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Executive Summary

The Honeywell Team's goal for the Wireless and Sensing Solution Advancing Industrial Efficiency award (DE-FC36-04GO14002) was to develop, demonstrate, and test a number of leading edge technologies that could enable the emergence of wireless sensor and sampling systems for the industrial market space. This effort combined initiatives in advanced sensor development, configurable sampling and deployment platforms, and robust wireless communications to address critical obstacles in enabling enhanced industrial efficiency. The program consisted of three components –

1. Design, development, and testing of an industrial wireless sensor communication network architecture in operational environments to offer a level of robustness and reliability not available in previous wireless sensor systems. This first component would lead to the opportunity for broader market acceptance of wireless solutions. The goal of the sensor network is to enable "pervasive sensing" for industries and factories to cost-effectively obtain increased levels of energy and operating efficiency through lower cost access to enhanced monitoring and information analysis.
2. Development and demonstration of an innovative technology for preconcentrating and analyzing the composition of gaseous process streams (PHASED – Phased Heater Array Structure for Enhanced Detection). PHASED is a Honeywell technology for high speed and sensitivity gas analysis. Robust gas analysis and the sampling required beforehand are the weak link in process control and automation. As described further below, PHASED is a micro-scale gas chromatograph consisting of a micro-fabricated gas concentrator/injector, a separator, and a micro-discharge device (MDD) detector. The individual components are designed to provide the robust analysis capability needed within process analytics.
3. Demonstration of PHASED gas sensing using a NeSSI (New Sampling and Sensor Initiative) sampling platform in operational process plant environments. NeSSI was designed to provide a standardized, modular, networked, and intrinsically safe format on which to put process stream sampling and micro-analytical systems. Due to delays in industry standardization of NeSSI Gen II and III specifications, this task's proposed scope was significantly scaled back during the program.

The combination of the three components promises reduced process upsets, reduced energy consumption, reduced environmental emissions, and enhanced economic competitiveness. However, as this report explains in more detail, each component met with a different level of success.

Briefly, the industrial wireless sensor communication network component was the most successful component. After the successful development and field trials carried out under this program, the network communication technology was commercially launched as Honeywell's OneWireless™ product portfolio [1]. These wireless activities fell under Task A of this project.

The PHASED gas analyzer development progressed through several design iterations. PHASED components were successfully integrated into laboratory and NeSSI-amenable prototypes. Laboratory evaluations of the prototypes consisted of simulating process stream environments and sampling the simulated streams with a NeSSI sampling manifold. Unfortunately, as the experiments more closely simulated actual process environments, they became less successful. The reasons for this are varied and detailed in this report. At the completion of this report Honeywell's field trial task of demonstrating a PHASED-NeSSI process stream sampling and analytical device is complete but technically unsuccessful. These PHASED and NeSSI activities fell under Task B of this project.

Task A: Wireless Network for Secure Industrial Applications

Introduction

The focus of Task A was to develop, demonstrate, and test leading edge wireless technology enabling wireless sensor systems for the industrial market space. The wireless technology developed will provide highly reliable and secure wireless communications for industrial applications, thus leading to broader market acceptance of wireless solutions.

Such wireless solutions can support industrial-specific requirements to produce increased levels of energy and operating efficiency through lower cost access to enhanced monitoring and information analysis. This wireless technology is applicable to petrochemical refining, pulp and paper manufacturing, power generation and distribution, and continuous process industries.

The technical barriers addressed in this project included achieving previously unmet industrial requirements of very high data reliability, long battery life, scalability up to 1000s of nodes, and security and latency management to ensure that data is received by the control system within a predetermined period of time.

The wireless network development was initiated with an extensive Voice of the Customer (VOC) analysis followed by a detailed requirements analysis reflecting the specific needs of the industrial marketplace and identification of the critical feature sets required to catalyze the market. Multiple wireless components using existing commercial solutions were evaluated for elements of robustness, interference rejection, and low-power consumption. These elements were combined into a network architecture that introduces enhanced data reliability, long battery lifetimes, scalability to large systems, and message latency guarantees. The success of the program rested on wide acceptance of the solution in the marketplace and its being available from multiple sources. The team engaged industry organizations such as WINA (Wireless Industrial Networking Alliance – [2]) and ISA (International Society of Automation – [3]) to ensure the requirements and proposed solutions have broad applicability.

Industrial wireless solutions impact energy saving through improved control of industrial processes leading to improved product quality and fewer process upsets, condition-based diagnostics and maintenance resulting in fewer unexpected shutdowns, monitoring of steam traps in industrial processes (steam production accounts for 34% of all energy consumed by industry, or 8,091 TBtu per year), monitoring steam injection devices used in oil production (oil fields that produce heavy crude account for 4 to 5% of the oil in the U.S; steam injection heats the crude and gets it to the surface more easily; over-injection of steam wastes energy without increasing production; by adding wireless monitoring to these steam injectors, energy savings of 5.3 TBtu/year can be achieved by 2020), and monitoring electric motors used in industrial processes (rotating machinery driven by electric motors account for 34% of the total energy usage by industry in the US—according to the DOE, this can be improved by 12%; wireless monitoring for vibration and temperature can identify inefficient operation and timely maintenance resulting in energy savings of 41 TBtu per year by 2020).

The payback for this wireless technology includes: enhanced ability to deploy additional process sensing in areas where sensor installation was not possible or excessively costly—leading to enhanced process control; the ability to install temporary sensors to diagnose process problems which were previously located with significant additional time and cost; and improved alarming and early identification of process problems—leading to reductions in process upsets and loss of material and improved product quality.

The wireless activities undertaken in this project and the wireless technology developed played a critical role in the development of the OneWireless™ solution that was commercially released in 2007. OneWireless is a second-generation, multi-functional wireless mesh network that supports wireless-enabled applications within a single wireless network to optimize plant productivity and reliability, improve safety and security, and ensure regulatory compliance. This network delivers a global solution with robust security, predictable power management, and multi-speed monitoring. The universal network supports multiple industrial protocols and applications simultaneously, providing a single wireless network that is simple to manage and efficient to operate. This solution has been further enhanced in the last two years with the addition of new features as well as the introduction of new wireless devices and applications.

Project team members participated in the ISA100 standards committee and played a crucial role in the development of the recently released ISA100.11a industrial wireless communications standard.

Background

In the past, industrial wireless sensor networks had limited acceptance due to high cost, non-deterministic unreliable performance, and setup and installation complexity. Factory owners had real and perceived fears of the loss of sensor data necessary to control their factory processes limiting wireless sensors from being used in advanced control situations. Consequently, wireless sensors were slow to gain acceptance and were largely marginalized to supplementary monitoring applications rather than being used in more impactful critical process control.

To increase battery life and signal reliability, mesh networks have gained acceptance for their ability to reroute messages through intermediate nodes when a primary communication path fails. However, this solution does not address the fact that critical control information is highly time sensitive. The wireless network must not only ensure that critical data is not lost, but, for smooth plant operation, data must arrive at the control system within a very narrow time window. Rerouting messages around failed nodes can affect the delivery of other messages being transmitted through the network, causing a localized communication failure to propagate into other sections of the wireless network. Wireless transmitters must use unlicensed frequency bands that are globally accepted. The frequencies are becoming increasingly cluttered with other wireless devices, resulting in additional interference and jamming. Each of these risks and barriers were addressed in the course of the project.

Earlier, Honeywell led the industry in successfully deploying a first generation industrial wireless sensor suite to assess market acceptance and gain experience in developing new application areas. This project has directly benefited from that “in the field” experience. Factory owners have clearly indicated a strong interest in wireless sensing technology particularly in 1) replacing old mechanical gauges that are now read automatically, 2) monitoring moving machinery that is difficult to monitor with wired gauges, and 3) low-cost, highly reliable wireless sensors that can be installed and operated at lower total cost of ownership than current wired sensors. Frequent process changes, difficult locations, lack of external power, and cost of wiring—as much as $10 to $40 per foot—are no longer obstacles to obtaining information. Armed with a broader range of consistent, accurate data, users can improve product quality, maximize uptime, reduce costs, and achieve regulatory compliance. Sensors of particular interest include gauge pressure, absolute pressure, temperature, tank level, ultrasonic noise (for detecting steam and gas leaks), and analog input interfaces for adding wireless capabilities to wired devices.

From this field experience and VOC data collected in the first part of the project, it was clear that the DOE Wireless and Sensing goal of achieving pervasive sensing depended on the ability to improve market acceptance of wireless technologies through:

- Significantly enhancing battery life
- Increasing sensor and wireless network reliability to be “as good as a wire”

- Improving data security against accidental or intentional disclosure of sensor data
- Expanding scalability from a few sensors to thousands of sensors in the sensor network
- Reducing total installed cost and total cost of ownership

Existing solutions had significant deficiencies with respect to these quality measures. If a new architecture did not address these key issues, the industry could reject existing standardized solutions and continue to experiment with custom, non-standard implementations that fail to gain wide-spread market acceptance. This situation would have led to a failure of the industry to embrace “pervasive sensing” and solutions that can directly impact industrial efficiency. Creating a solution that addresses factory owners’ concerns about wireless sensing in a standardized wireless infrastructure offered by multiple competing suppliers was paramount to realizing the benefits of this project.

This project addressed each obstacle to ensure a solution that meets the demands of the industrial marketplace. Key elements of the approach used were:

- Selection of leading industrial radio standards and solutions suggested by the technical community
- Critical analysis and evaluation of the leading candidates against the defined “Critical To Quality” measures defined through VOC surveys and experience in the wireless industrial sensor marketplace
- Participation in the industrial wireless sensor network standardization process helping to drive the community to a solution acceptable to industrial plant owners and installers
- Development of wireless network enhancements and extensions to address critical deficiencies in existing industrial wireless sensor solutions

Body of the Report

Voice of the Customer (VOC)

To develop an industrial wireless solution to meet the requirements of customers, the project team undertook a number of tasks to establish a baseline Voice of the Customer (VOC) through a series of on site interviews and assessments. An extensive VOC process was established for performing the assessments at each site. Experienced VOC assessors were used in the evaluation to ensure accurate and useable results. The assessment team was responsible for developing an extensive interview guide and questionnaire to be used in each of the assessments. Each interview was recorded to ensure accurate data capture.

We studied three facilities, each in a distinct segment of the industrial marketplace:

- A specialty materials plant in Virginia engaged primarily in the production of fertilizers and other chemical compounds used by a wide spectrum of other industries
- A coal-fired power station in Canada that produces electricity for the Edmonton area
- A California refining facility producing a variety of petrochemical compounds for automotive and industrial use

The answers to each of the questions from the interviews were categorized in a spreadsheet and organized by a number of response topic areas. Additional information collected in ad hoc informal discussions with participants were also documented and integrated into a final report. Finally, specific learnings from sales, marketing, and installation engineers involved with the first generation industrial wireless product (XYR5000) were included to form a final VOC report.

The cross-cutting applicability of industrial wireless technology is depicted in Figure 1.

Industries	Wireless Applications: people / asset tracking	safety shower monitoring	equipment health monitoring	automated field operator rounds	emissions monitoring	leak detection	process optimization via more I/O	process diagnostics
Petrochemical refining	x	x	x	x	x	x	x	x
Pulp and paper manufacturing	x	x	x				x	
Continuous process industries	x	x	x		x	x	x	x
Power generation and distribution	x		x	x	x		x	x
Pharma industries		x	x			x	x	
Aluminum	x		x	x	x		x	x
Chemicals	x	x	x	x	x	x	x	x
Glass			x	x	x		x	
Metal casting	x		x				x	
Mining	x		x				x	
Steel	x		x	x	x		x	x

Figure 1 Cross-cutting applicability of industrial wireless

Technical Requirements

The requirements development team reviewed the results of the VOC and integrated them into a comprehensive set of requirements for the industrial wireless market. The requirements development team consisted of technology leaders, product development leaders, and business development leaders with extensive knowledge of petrochemical, chemical manufacturing, power generation, and pulp and paper production processes. The integrated requirements were extensively reviewed and published as *Wireless Network for Secure Industrial Applications Project Requirements.* They were also presented to the ISA100 standards committee.

Industry acceptance required that the wireless solution offer:

- Reliable wireless communications robust to single-point failures, resistant to interference/ jamming, and which localize any network faults
- End-to-end latency control for message delivery within a time window of less than 50% of reporting period
- Capacity and scalability to support at least 1000 sensors serviced by 100 infrastructure nodes or access points
- Success rate for wireless communication of at least 95% of latency-controlled packets delivered on time
- Globally deployable based on an industry standard
- Coexistence with other wireless systems in industrial facilities such as IEEE 802.11b/g
- Multiple periodic reporting rates to support different types of sensors and different types of applications: 250ms to 1 hour or more
- Different quality of service (QoS) classes for different types of wireless communications: latency-controlled, high-throughput, immediate, and low-importance

- Wireless communication security covering: privacy, integrity, authentication, simple key management
- Ability to support diagnostics/alarm reporting
- Ability to auto-recover from power cycle
- Long battery life for battery-powered devices: > 3 years

Key challenges to delivering the solution included: industrial wireless devices cannot have batteries recharged as with traditional mobile devices; unreliable (intermittent) communications; existing systems suffer significant message latency or packet loss problems on scale-up; lack of user interface for security key deployment on wireless sensor devices; and lack of a standard industrial sensing solution that meets customer requirements.

Critical Review of Existing Technology

The team evaluated radio and networking technologies against the technical requirements. Two 2.4 GHz radio solutions were developed: one using direct sequence spread spectrum (DSSS) technology (Figure 2), and the other using frequency hopping spread spectrum (FHSS) technology (Figure 3). Both of these alternatives were augmented with key technology to increase their battery life, data security, network reliability, and scalability to large wireless networks.

An extensive testing strategy was developed to assess each RF solution for indoor and outdoor range, interference rejection with respect to accidental RF noise from devices such as portable phones and microwave ovens, and intentional interference from 802.11 b/g devices and access points. Assessments took into account both interference of 802.11b/g networks on the RF solution and the RF solution interfering with the correct operation of the 802.11b/g networks. RF blocking tests examined the sensitivity and interference blocking characteristics and analyzed the radios for a number of parameters with a high degree of accuracy that will emulate an operational industrial environment.

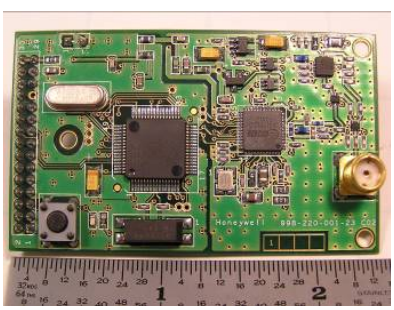

Figure 2 100mW DSSS evaluation board

Figure 3 100mW FHSS evaluation board

The testing (Figure 4) showed that the FHSS and the DSSS (IEEE 802.15.4) solutions were comparable technologies. Some differences were anticipated but could not be fully tested, including RF multi-path and scalability. Redundant connectivity, strategic spectrum usage planning, and a hybrid approach of using DSSS radios in a FH mode showed significant benefits.

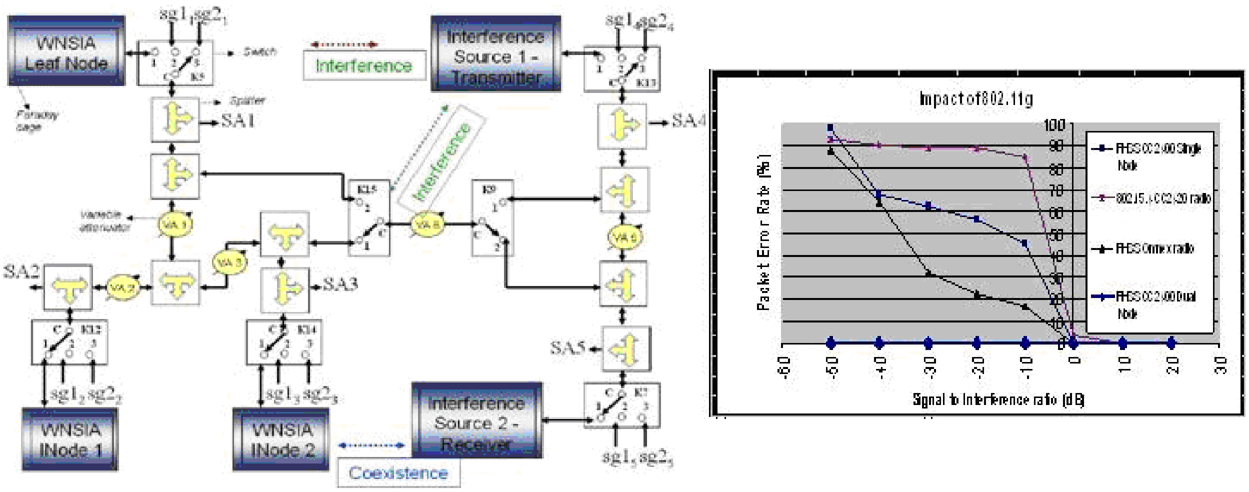

Figure 4 Radio testing and results sample

Range tests (Figure 5, Figure 6) proved the advantage of using radios with high transmit power and good receive sensitivity.

Indoor range test results (points sorted by # of floors/ # of walls)																																	
							802.15.4 LP 250 Kbps				FHSS CC2400 LP 250 Kbps				802.15.4 HP 250 Kbps				FHSS CC2400 HP 250 Kbps				FHSS Omnex HP 153 Kbps				HP* NB	802.11	
Location	Estimated Distance	# of walls / # of floors	Luna	Accutech 78.6	Axonn	Citronet	Channel 13	Channel 19	Channel 23	Channel 25	Mode 0	Mode 1	Mode 2	Mode 3	Channel 13	Channel 19	Channel 23	Channel 25	Mode 0	Mode 1	Mode 2	Mode 3	Mode 0	Mode 1	Mode 2	Mode 3	CC2400 1 Mbps	802.11b Ch#11	802.11g Ch#11
1	82	5/0					9	1.8	3.5		23	3.4		13	1				3	1.75	4.13	2.38			1.38		0.1	9.28	11.2
4	135	6/0					14	1.3	50	1.3									3.75	2.88	9.88	5.75	0.5	1	0.5	0.25	0.44	100	13.7
14	105	7/0											13		8	3	5		29.8	57.6	41.8	29.8	1.5	0.5	1.25	0.13	31		
2	107	8/0													4.5		9.8		2.5	9	16.5	8.5	3	6.5	0.75	0.88	2	100	
3	162	8/0													6	7.5	9	3			30	25.4	17.3	5.88	16.8	5.63	13	100	
13	156	12/0													11			2											
11	37	1/1					14	2.8	3	6					2.5				2	0.13	0.38	0.5			0.75		0.3	5	9.03
12	145	4/1										14				26		79	27.4			14.5							
5	160	5/1													23														
10	80	4/2														81		6			65.6								
8	150	5/2																		87.9									
7	157	6/2																											
9	185	7/2																											
6*	172	8/1																											
15	170	9/2																											
Statistics			250mW 900MHz	30mW 900MHz	100mW 900MHz	100mW 2.46 GHz	1 mW								100 mW												100 mW 2.461GHz	50 mW 2.462GHz	10mW 2.462GHz

Key: Works (PER < 6%) | Borderline (PER < 20%) | Fail (PER > 20%) | Unavailable

* Used Projected PER, see 2400HP; Narrowband

Figure 5 Indoor range testing

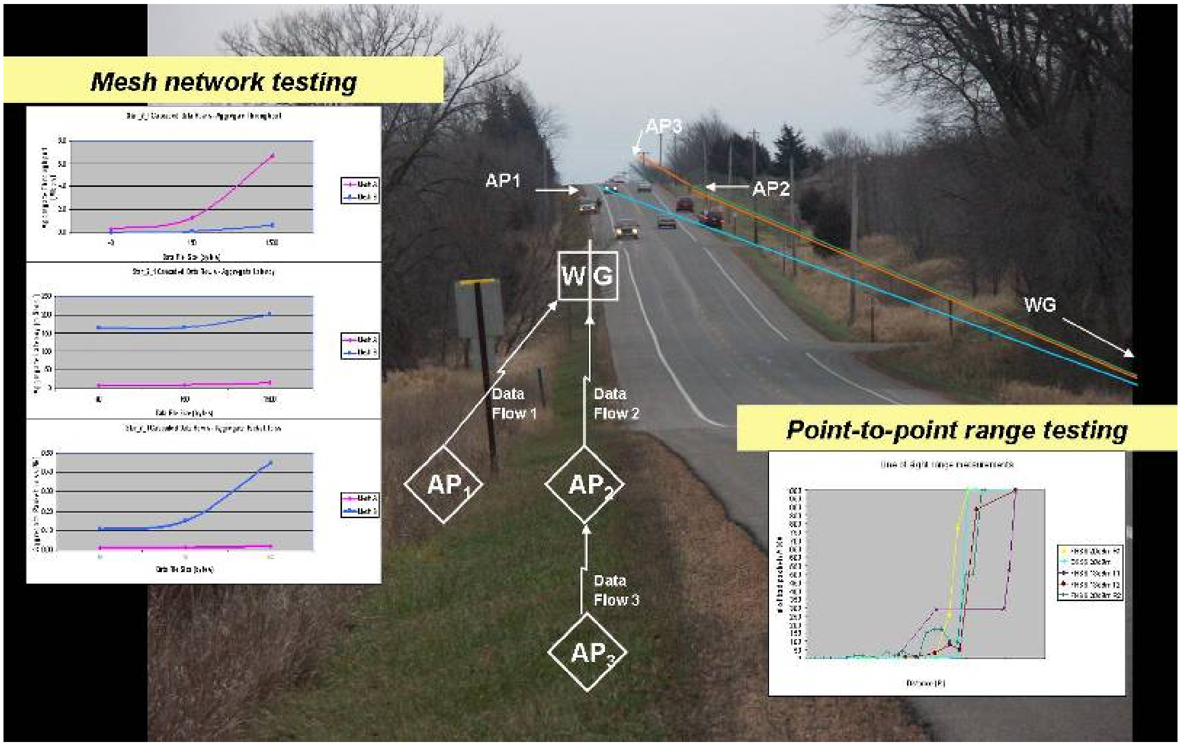

Figure 6 Outdoor testing

Extensive testing of the commercially available networks, based on both proprietary and ZigBee protocols, were conducted. The results (Figure 7) showed significant limitations in such networks with respect to range, latency control, and throughput. These limitations were due to significant bandwidth limits on the intermediate nodes leading to message bottlenecks in the system. In addition, they also demonstrated very poor latency control primarily due to the way message retries were done. Assessments showed that these networks could make use of only a small portion (<10%) of the total available bandwidth because of inefficient message handling.

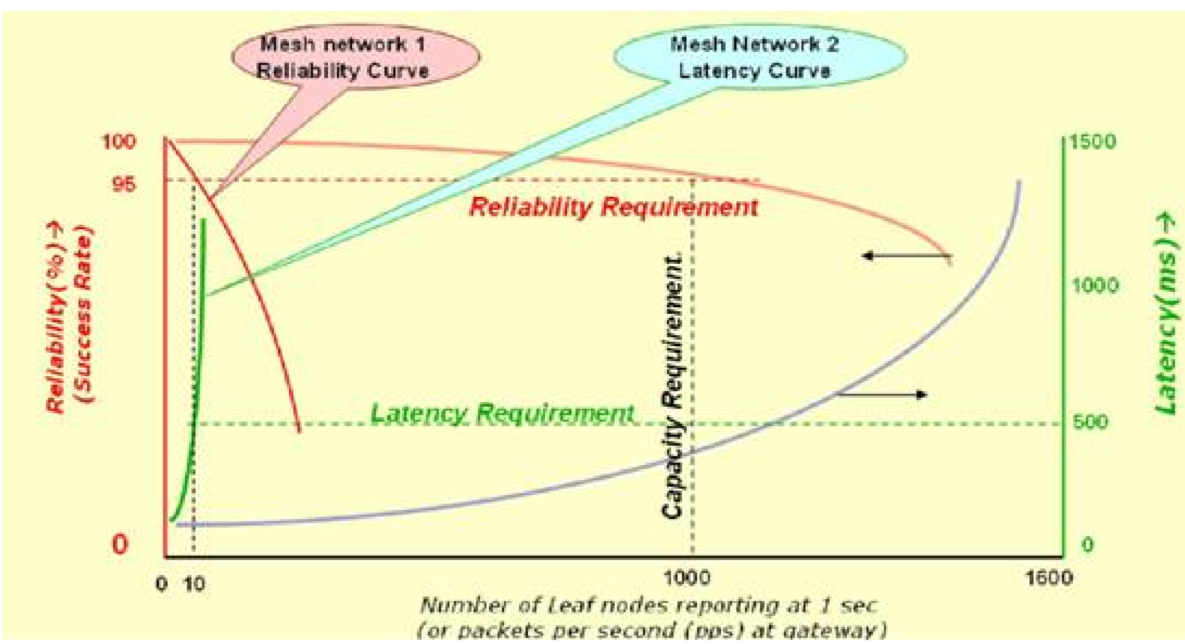

Figure 7 Network testing results

Modeling and Simulation

The project team developed several stochastic network models for evaluating the system throughput—particularly when the network became stressed from large numbers of nodes in a small area or with sensors requiring high reporting rates. The models provided significant insight in the data rates that the intermediate nodes must support and the network topologies that must be used. Conclusions using these models further strengthened the conviction that existing systems provided insufficient scalability and robustness. The project team also developed a number of performance simulations that identified the details of radio performance, how the network would respond in the presence of node failures, and total system capacity limits. These simulations helped conceptualize a design with significant flexibility, resilience to failures, and scalability to allow the system to grow to very large wireless networks. Figure 8 shows examples of the modeling and simulation activities the project team carried out.

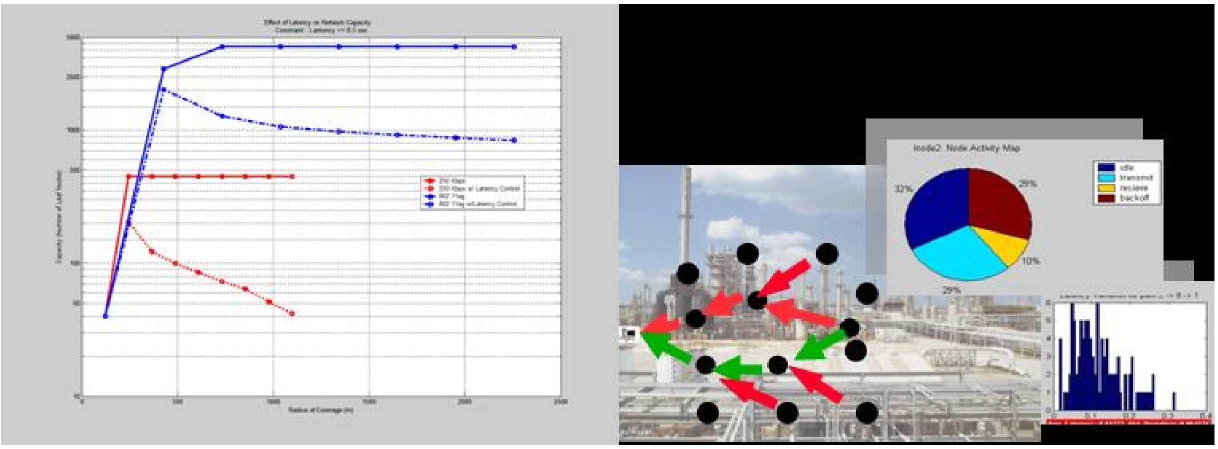

Figure 8 Modeling and simulation of industrial wireless networks

System Design

The project team designed the next-generation industrial wireless architecture (WNSIA: Wireless Network for Secure Industrial Applications) that emphasizes scalability, stability, reliability, and security. The system components included leaf nodes (i.e. wireless sensor nodes that are typically battery-powered), infrastructure nodes/Inodes/multinodes (i.e. line-powered router nodes that relay the traffic from these Leaf Nodes to the final destination), Gateways (i.e. multinodes that connect the wireless system into the wired control system), and a server to manage the network performance and maintain its security. This architecture later evolved into the OneWireless^{TM} architecture shown in Figure 9 and described in detail below.

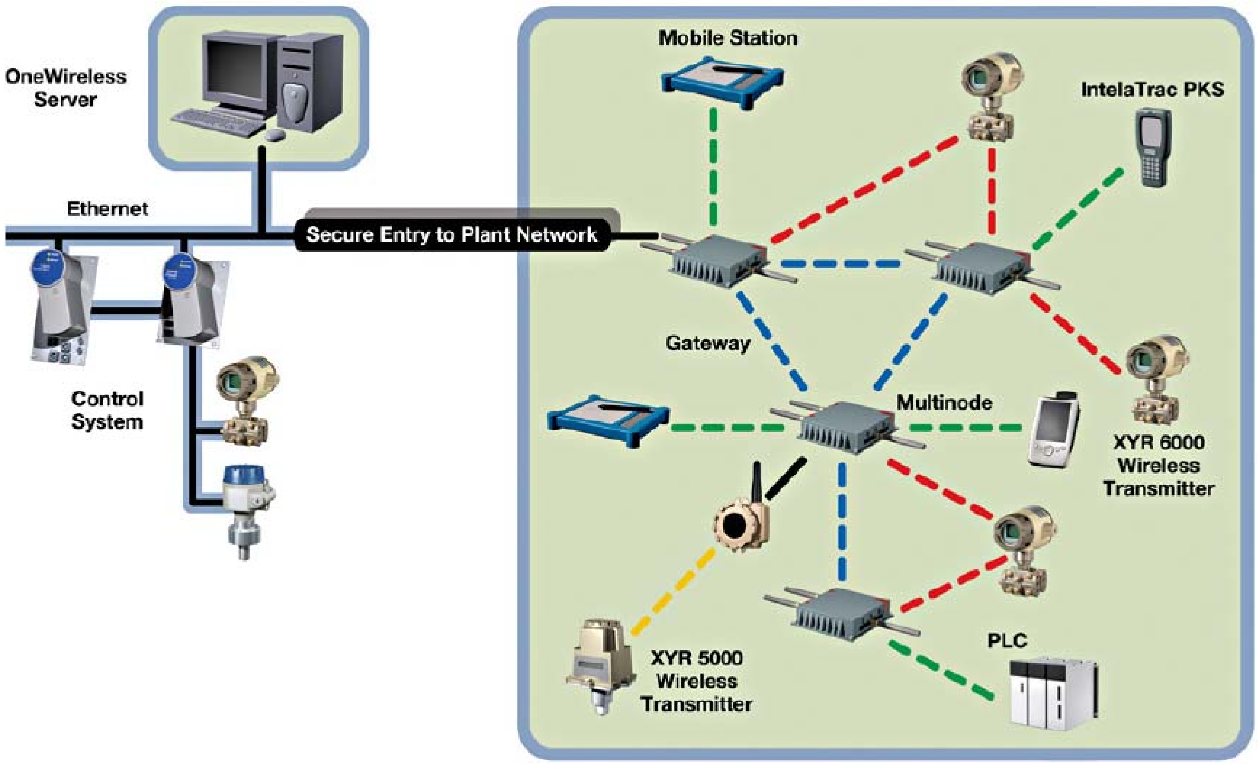

Figure 9 OneWireless architecture

The radio design went through several iterations (Figure 10) before being finalized. Both FHSS and hybrid FH-DSSS radios were developed to obtain superior RF performance while maintaining low power operation. Several tests confirmed radio behavior.

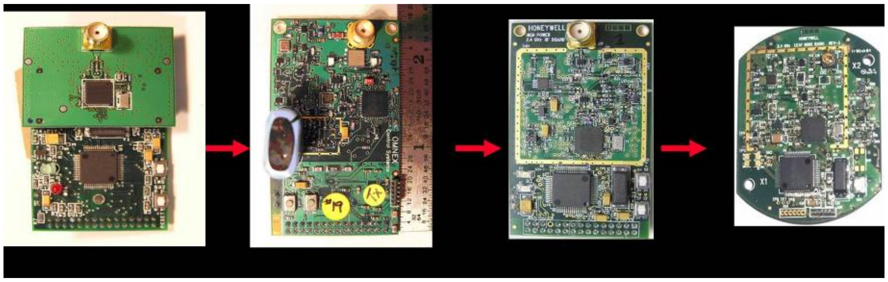

Figure 10 Radio design progression

A low-power FH-based medium access control (MAC) protocol was developed that offered extremely high reliability through redundant connectivity. Battery-powered sensors used this MAC to connect to redundant multinodes. Testing ensured that the design met the requirements discussed above for industrial wireless sensors. The battery power management of the wireless sensors was analyzed. Battery life is a complex function of sensor type, ambient temperature, analog conversion rate, RF transmit rate, number of analog inputs, etc. About 3 to 10 years of battery life was estimated and verified through testing and extrapolation.

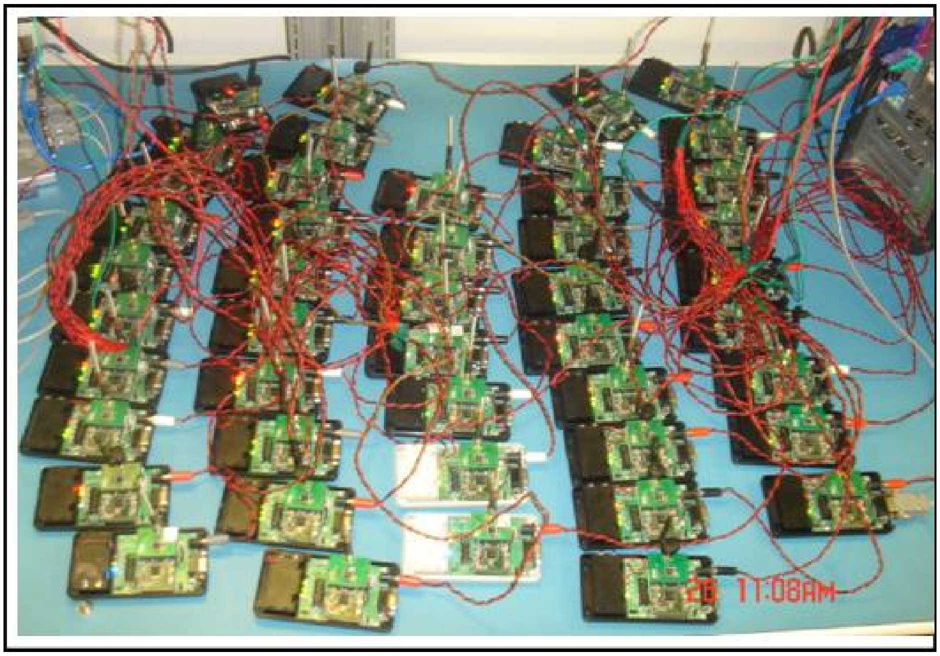

Figure 11 Scalability testing for wireless sensors

After extensive testing and evaluation, a Wi-Fi based mesh network (testing shown in Figure 12) was selected for the multinode network. This multinode network provided the high-speed backbone for covering an entire plant and supporting the communication needs of battery-powered sensors. This network also supported other Wi-Fi based devices such as laptops and PDAs. The wireless protocol software for the various OSI layers was developed and tested thoroughly using regression tests. Time synchronization—important to maintain the FH-based communication and support sequence-of-events based applications—was verified.

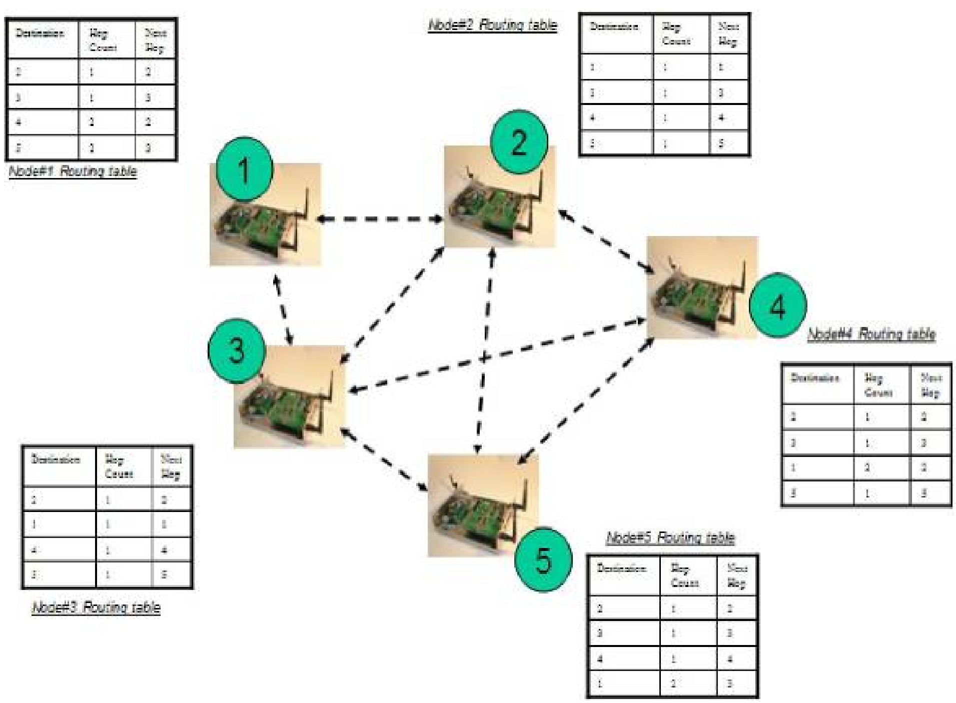

Figure 12 Mesh network development and testing

The team placed particular emphasis on designing a highly secure system without adversely affecting the battery life of the wireless sensors. The detailed design of the security architecture (Figure 13) and the strategy for distributing security keys to the wireless sensors and multinodes was reviewed by leading commercial and academic experts. This design maintained the integrity of the system, was resilient to external threats and attacks, yet remained easy for the end user to setup and maintain.

The comprehensive end-to-end security architecture (WPA2, AES-based device authentication, FIPS 140-2 based encryption) provided confidentiality, integrity, source authentication, protection against replay attacks, resistance to denial-of-service attacks, and convenient key management.

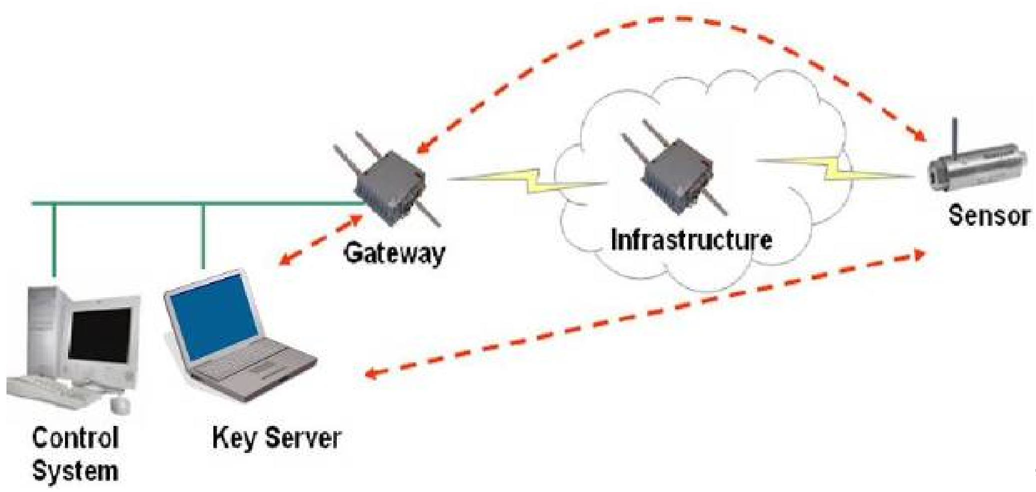

Figure 13 Security architecture

Device management and system management are critical for the proper operation of a wireless network. Device management is related to the local configuration and management of the resources within a device while system management is related to the management of various communication resources across the network. These features were implemented and tested. The tests verified system behavior during the joining and leaving of devices in the network, reporting of faults that occurred in the network, configuration of communication resources to support application needs, maintaining time synchronization throughout the network, monitoring the operation and health of every device in the network, monitoring the network performance and optimizing the resource allocation, and maintaining end-to-end security throughout the network.

SNMP based network management tools and data collection tools were developed and used to provide the diagnostics and performance metrics from system tests and field demonstrations. User interfaces were developed for these tools (Figure 14 and Figure 15) as well as for the key server, which manages the entire security architecture in the system.

Extensive functional- and system-integration (Figure 16) tests were conducted throughout the project to verify system features and confirm that the system met the technical requirements.

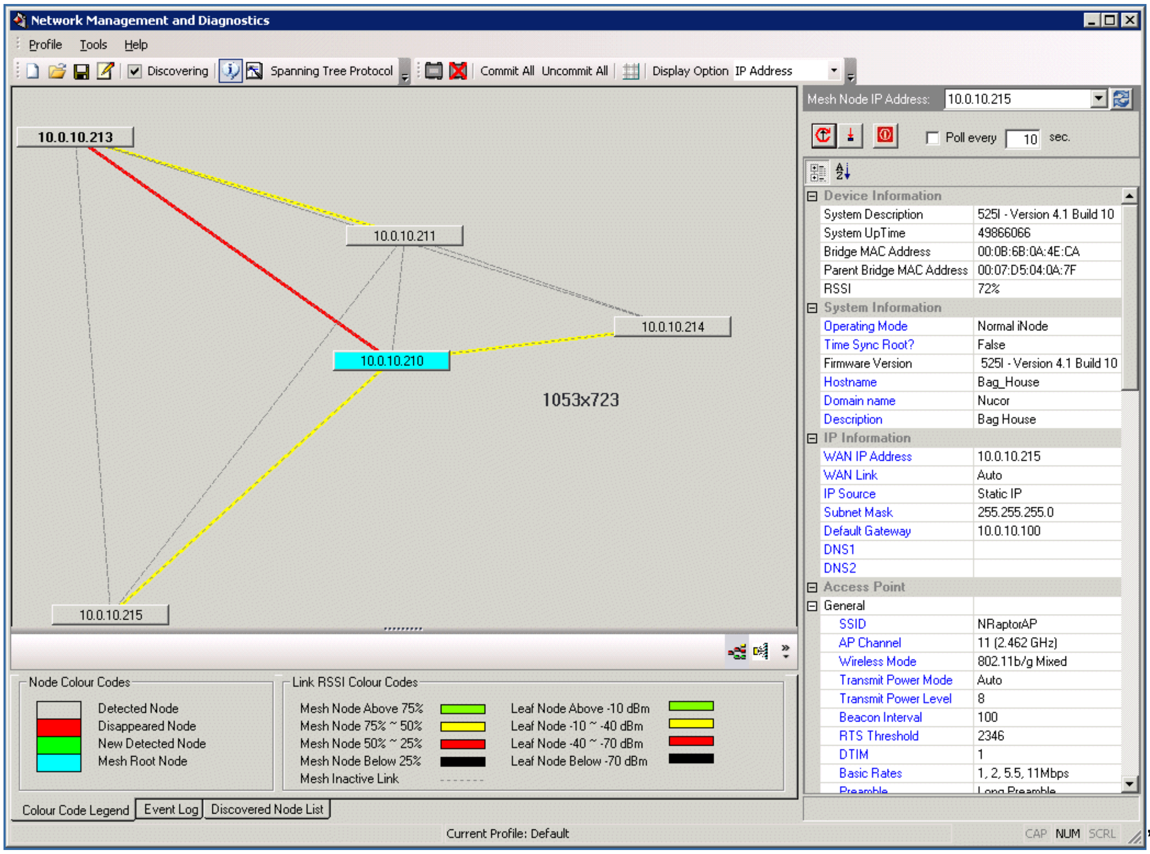

Figure 14 Network management and diagnostics tool

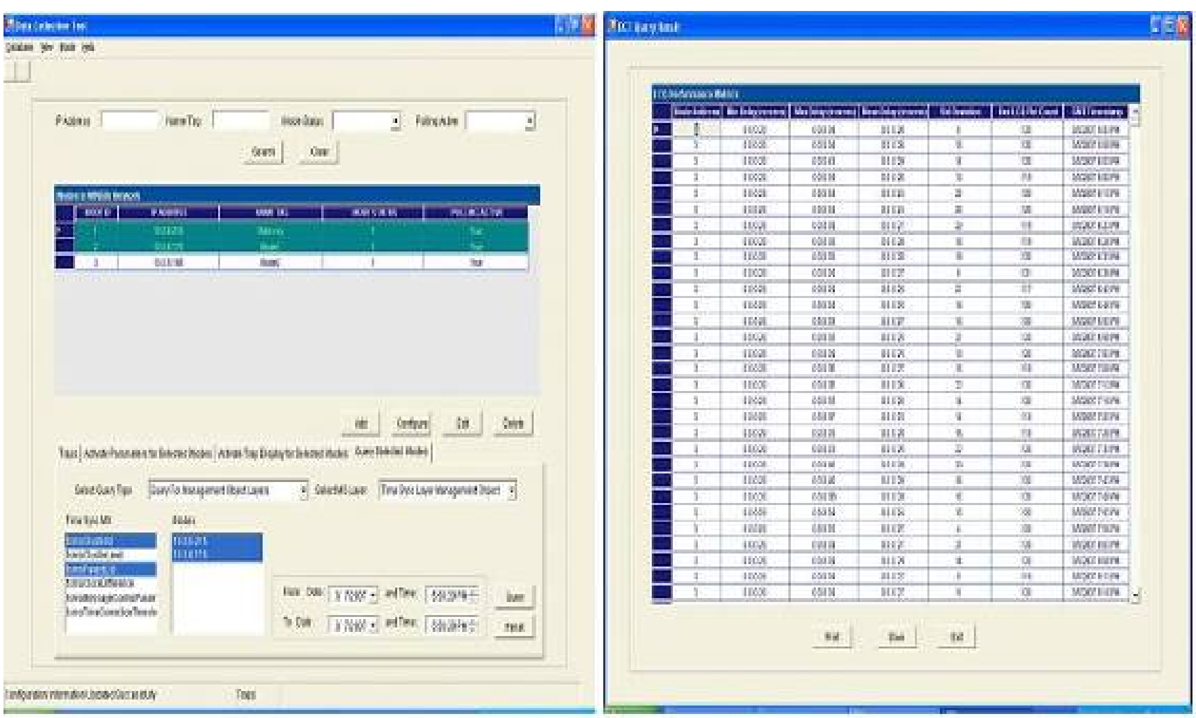

Figure 15 Data collection tool user interface

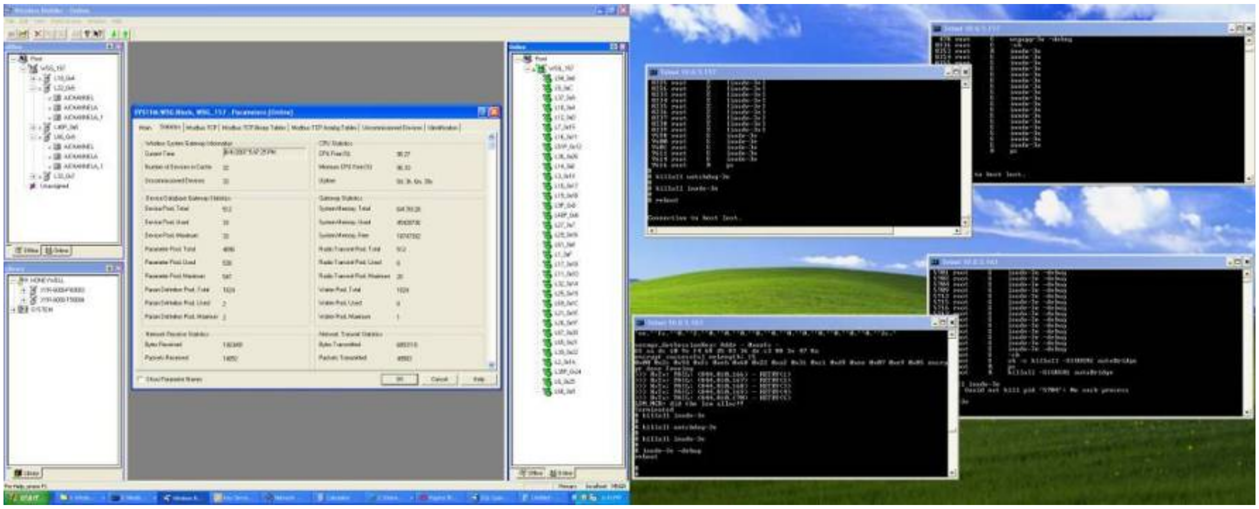

Figure 16 System integration testing

Field Trials

Field trials of the industrial wireless system were conducted at two industrial sites with unique RF environments. The first site (Figure 17) was a steel recycling/production facility where the wireless system was deployed both inside and outside large factory buildings where it would experience high temperatures and significant electro-magnetic interference. Significant RF noise and interference was observed through a spectrum analyzer.

Figure 17 Field trial at industrial site #1

The second site (Figure 18) was an oil refinery with tank farms. The wireless system was deployed in an outdoor environment with a collection of tanks and inter-connecting pipes. Significant multi-path fading effects were expected at this site. All aspects of the system including the wireless communication links between the sensors and the multinodes, multi-hop routing, network-wide time synchronization, low battery consumption by the wireless sensors, and security were tested.

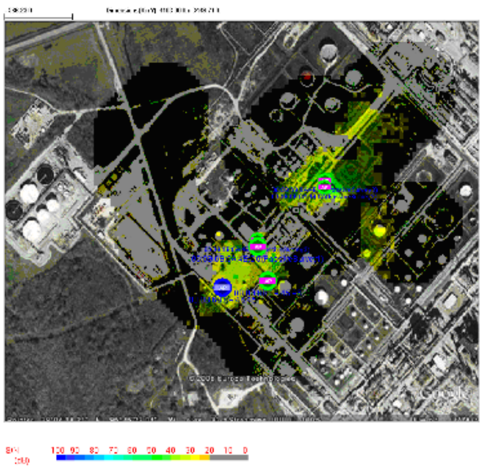

Figure 18 RF site survey at industrial site #2

Figure 19 Field installations of wireless sensors and multinodes

The team analyzed the data from both the field trial systems and addressed issues arising from these tests. Site surveys examined the RF environment at both the sites.

In addition to collecting metrics such as packet error rates, received signal strength and retransmission percentage, the field trial systems also tested the actual sensing components and the battery power consumption. Table 1 shows samples of some of the collected data.

Table 1 Sample of field trial results for wireless system

	Sensor_P_18	**Sensor_A_08**	**Sensors_T_01**
Antenna Type	**Integral**	**Integral**	**Integral**
Average Primary RSSI	-80.36	-53.54	-27.07
Average Secondary RSSI	-68.96	-64.52	-65.43
Average # of Retries Over 100 Packets	0.52	0.03	0.0048
Dual Connect %	99.4569%	100.0000%	100.0000%
Client-server reliability	99.7673%	99.8966%	100.0000%
Initial TX Success	99.5565%	99.9935%	99.9952%
First Retry Success	97.6401%	99.4005%	100.0000%
Aggregate TX Success	**99.9250%**	**99.9935%**	**100.0000%**

The two field trial systems ran successfully for more than six months, during which several firmware upgrades were performed on the running system. The firmware upgrades were conducted over-the-air from the control center and did not require any physical interaction with the devices. End users discovered unique and innovative applications based on wireless sensing. These systems continued to remain operational in the field to verify long term operational stability, scalability, and security. The built-in redundancy of the wireless system significantly improved the message reliability in harsh RF environments. Sensor latency-controlled data success rate was observed to be beyond 99%. Low-battery power consumption of the wireless sensors was validated.

A few problems were identified and resolved: poor RF signal between some multinodes due to mesh hardware problems (including antennas) were identified and addressed; placement of multinodes significantly affected system performance and site survey and installation tools helped determine the multinode locations; degradation of mesh due to RF fluctuations (mesh was re-forming due to RF fluctuations—mesh software was upgraded to tolerate fluctuating RF links); metal tanks and pipes obstructed RF communication paths (sensors placed below tanks and below collection of pipes experienced poor RF links—we replaced integral antennae with external high gain/directional antennae as appropriate).

Wi-Fi based location tests (Figure 20) were conducted at an industrial site in an attempt to leverage the existing Wi-Fi infrastructure to provide location services.

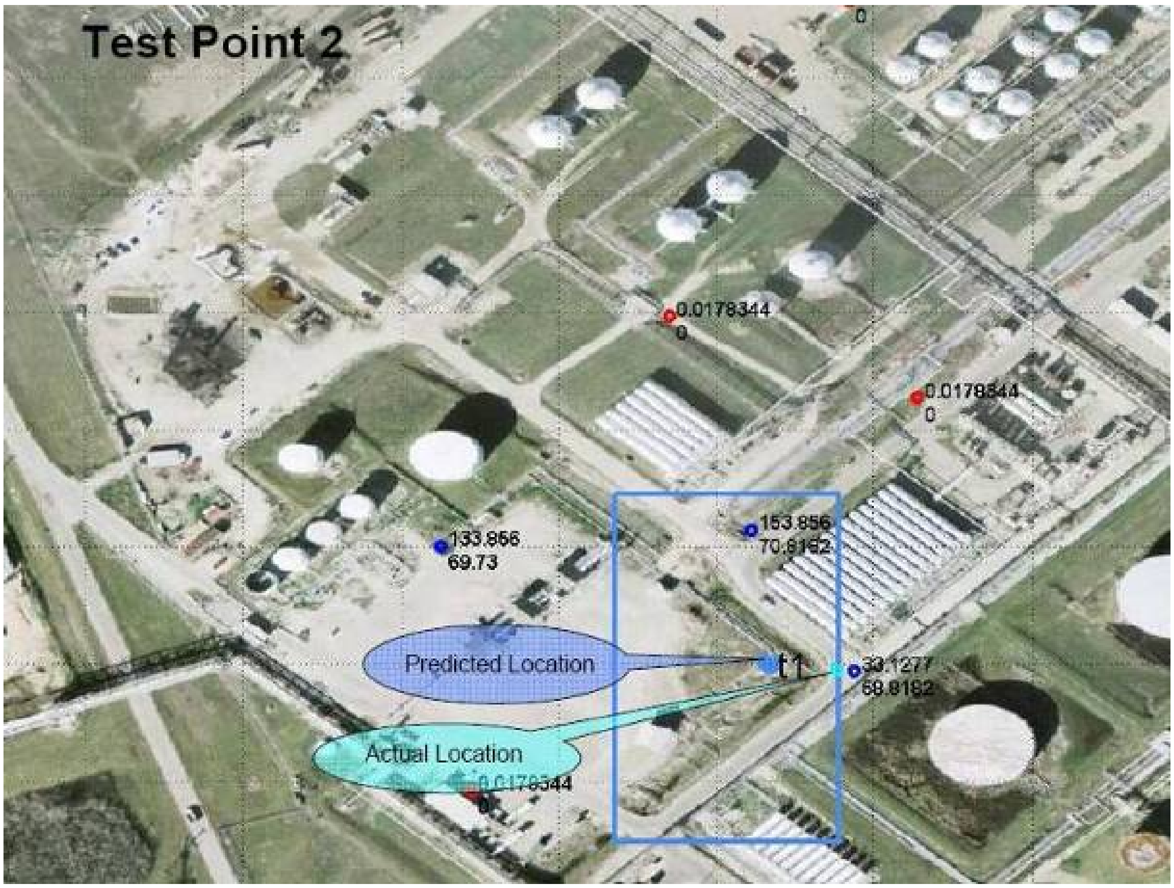

Figure 20 Location testing

Applications and Energy Savings

(Note: information regarding energy use, production efficiency, economic impact, etc, is usually considered proprietary and confidential data that end-users typically do not disclose; all the information given below is available on public websites; please contact the project team if any further details are required)

Improve steel mill performance using wireless

The wireless system was installed in a hot-rolled-coil and cut-to-length plate steel mill (Figure 21) that manufactures carbon and high-strength, low-alloy steels for structural and pressure vessel applications. This steel mill needed to improve process operations on a furnace used to melt and recycle steel. To help support an increase in production levels, operations staff searched for a reliable way to monitor temperatures around the furnace in areas not previously monitored. The ability to gather this data would facilitate a furnace upgrade and subsequent increase in production. A key requirement was to be able to instantaneously know what temperatures were in the furnace (which can reach more than 1,000 deg F,) to protect from a production upset if temperatures were to get too high. Another concern was the huge magnetic field around the furnace, a result of running over 120,000 amps to the furnace, and its impact on transmitter functionality.

Figure 21 Wireless application in steel mill

The wireless system made it possible to safely obtain accurate and reliable temperature readings on the furnace. The end user and the project team developed a solution that included the placement of wireless transmitters just a few feet from the base of furnace flames. The transmitters were installed on the cooling circuits for the furnace and encased on specially built protective boxes to withstand the extreme heat. The steel mill realized the following benefits:

- Increased production of 15 % through furnace upgrade
- Improved production efficiency through more accurate data
- Improved safety through greater ability to measure process status
- Faster, more reliable access to data
- Improved quality of data to enable better decision making
- Reduced maintenance requirements compared to wired transmitter alternative
- Provided foundation to expand wireless efforts across the mill and enhance process reliability
- Increased energy savings up to 10 % possible due to availability of data real-time

Reduce energy usage in compressed dry air systems with wireless

A factory in Ohio had a 750 hp compressor driving the compressed dry air (CDA) system at a supply pressure of 125 psi to operate pneumatic tools and equipment. The compressor ran at an average duty cycle of 50%. The annual cost of electricity to operate the compressor was about $123,000. Over the years, the plant production mix changed, and some production was moved to other locations offshore. The plant manager believed that it was no longer necessary to operate at a supply pressure of 125 psi, since there was less equipment with lower flow rates required, and lower associated pressure drops. In fact, he believed that he could safely reduce the supply pressure to 85 psi and still operate acceptably.

Reducing the supply pressure from 125 psi to 85 psi was expected to save about $39,000 per year in electrical energy costs (at 5 cents per kWh) (see Table 2) and could also reduce the wear and tear and associated maintenance on the compressor.

Table 2 Energy savings calculation for lower compressor pressure

750 hp compressor power consumption	560 KW
Hours in one year	8760 hours
Duty cycle of compressor	50%
Energy used per year	2,450,610 KWh
Cost of electricity	5 cents per KWh
Energy cost per year (125 psi setting)	$122,531
Estimated savings (85 psi setting)	32% lower energy use
Estimated savings in cost (85 psi setting)	$39,210

The compressor supplied compressed air to 18 different downstream branches with multiple tools and equipment on each branch connected to the CDA line. The plant had a batch type production process, which meant that different equipment cycled on-and-off at different times to produce batches. Depending on the combination of equipment that was operating at a given time, the air flow and the pressure drops may vary by 25 psi or more at different branch locations. The CDA energy savings opportunity was identified at a corporate level as a high priority project to reduce energy costs. To get started on this project, the main work required was to install a monitoring system to characterize the operating modes and pressures and a notification/alarm system to ensure that maintenance staff was alerted if pressures fell too low. The plant staff wanted the monitoring data to be tied to the existing automation system. Monitoring points were needed on each CDA branch line (18 locations total--Figure 22 shows an example), distributed across 30,000 sq-ft of manufacturing area. The existing system had controller and I/O panels around the perimeter walls of the manufacturing area. Most of the monitoring points were about 60 to 100 feet away from the nearest automation system I/O panel. Some of the I/O panels did not have spare analog input cards and could not accommodate any more points.

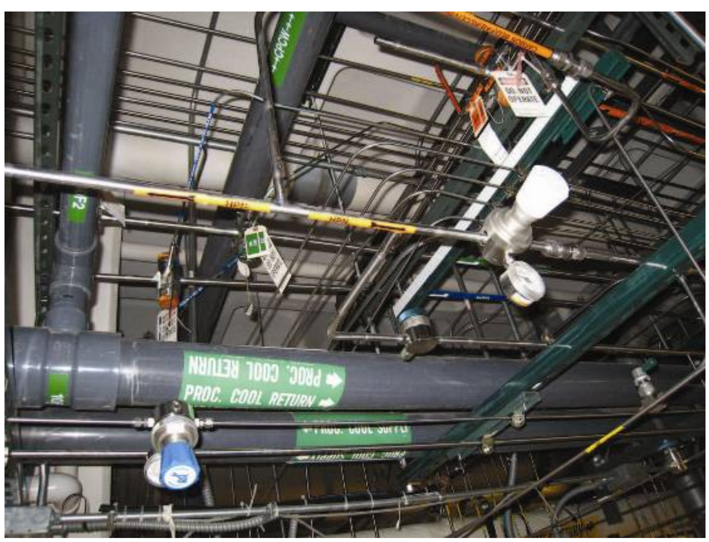

Figure 22 Typical branch line with manual gauge and pressure regulators

The plant manager considered two options for implementing the monitoring system:

Option 1: Install traditional wired transducers by adding pressure ports on the branch lines and running conduit for signal and power lines from the transducers to the nearest automation system panel. Install additional I/O cards or modules as necessary to accommodate the new points. Plant operators could monitor values and receive alarms via the automation system. Estimated time to install this system was 170-man hours, over 1.5 calendar months.

Option 2: Install wireless gauge readers by clamping them onto existing manual dial gauges at branch locations. The units were battery powered (3-5 year life) and did not require power or signal cabling. Readings could be transmitted wirelessly to a central receiver/server and optionally passed on to the automation system via an industry standard OPC interface. Plant operators could monitor values and receive alarms via this system or via the built-in web interface and cell/pager notification system. Estimated time to install this system was 15 man-hours over two calendar days. The plant was running at close to maximum capacity, which meant that any need to shutdown equipment affects production and plant revenue, was very costly.

Table 3 shows the comparison of the upfront costs for implementing the two options.

Table 3 Upfront cost of wired vs. wireless

	Wireless gauge reader	**Wired transducer**
Transducer/sensor	$1,200	$400
Install/wiring, leak check labor	$50	$1,000
Drawings, reviews	$0	$400
I/O panel / termination	$0	$300
Process downtime	$0	$1,700
Total cost (per point)	**$1,250**	**$3,800**

Table 4 shows the payback analysis for the two options. The wireless gauge reader option would achieve a payback in 7 months, while the traditional wired transducers would achieve a payback in 1.7 years (21 months).

Table 4 Payback period calculation

	Wireless gauge reader	***Wired transducer***
Total cost to implement monitoring (18 points)	$22,500	$68,400
Energy savings achieved	$39,210	$39,210
Payback period (years)	***0.6***	***1.7***

Reduce energy consumption and improve monitoring of refinery and petrochemical utilities systems: *(due to proprietary and confidential considerations, only qualitative information is provided below)*

While it is relatively common for process streams in refineries and petrochemical plants to have sufficient instrumentation, the utilities systems that support production are often not as well instrumented. This situation can make it impossible to determine where unnecessary consumption or leaks are occurring. Wireless solutions can provide essential information for identifying utility consumption and enable strategies that save energy and improve efficiency.

To compete in an environment with high energy costs, refiners and petrochemical producers are looking for ways to improve energy efficiency and reduce unnecessary energy costs. It is difficult to improve energy consumption if it cannot be measured. Utilities systems are characterized by a branched piping network, sending steam, air, water, lube oil, fuel gas, fuel oil, and electricity to and from the process units. Often, only the network's main headers and branches are instrumented, which leaves many areas unmeasured. This limited coverage may help calculate the overall consumption and identify the main suppliers' and consumers' performance, but it does not help close the material balance or identify possible leaks or wasted use. Engineers also do not have enough information to optimize the usage of these utilities across the site.

Wireless transmitters can be combined with any flow element to quickly and cheaply provide flow information to as many additional branches of utilities systems as are required to adequately map all the suppliers and consumers. These wireless transmitters can provide one second or greater reporting intervals and use self-contained batteries that can last up to 10 years. Wireless transmitters can operate effectively over a range of 6 miles when used in conjunction with high gain antennae. Therefore, even the largest utility system networks can be covered with one wireless network so that all information can be integrated into the control room for energy monitoring applications.

Wireless technology can enable improved monitoring and reduced energy usage in several ways:

- Many of the multiple header steam systems suppliers and consumers across a site do not have sufficient flow measurements to know where the steam is being used. Installing wireless flow transmitters on the main branches can help identify where the consumers are and provide information about where steam is being wasted either through broken steam traps or inefficient operation. Steam balancing applications can then help reduce header pressures and close let down valves, resulting in improved energy efficiency.
- Column steam reboilers are sometimes controlled using a tray temperature directly to control valve. Inserting a wireless flow transmitter would support more efficient steam consumption strategies such as using the tray temperature to control a steam/feed ratio controller.
- Fuel gas headers do not have a high surge capacity, so they need to consume what is provided or the excess will be blown down to the flare stack. Most major consumers such as furnace fuel gas lines have wired flow meters. However, the off-gas into the fuel gas system from light ends columns, for example, are not monitored. Fuel gas consumption can be improved by installing a wireless flow meter on a column off-gas vent and, as additional fuel gas is available, the base-load of fuel oil consumed in a dual-fired furnace can be automatically adjusted.
- Lube oil circuits ensure that rotating equipment remains in optimal operating condition. Although the total consumption of lube oil is commonly measured, the flow to individual pieces of equipment may not be. Adding wireless flow meters to measure each major user's consumption can help identify where unexpected amounts are being used due to leaks into equipment or, worse, where a blockage is preventing lube oil reaching a machine.
- Instrument air compressors, while vital to a plant's safe operation, are not usually monitored unless they fail. Typically, companies run multiple compressors to the same header with a pressure valve on each compressor venting to the atmosphere to prevent overpressure. Installing a wireless flow meter on the vent might highlight the opportunity to safely turn off one of the compressors or reduce its speed to save electricity.

Wireless solutions can eliminate the economic barriers that normally prevent sufficient monitoring of utilities. As a result of better monitoring, companies can reduce energy consumption and improve energy efficiency.

Accomplishments

As per the goals and objectives of the project, all the technical requirements for an industrial wireless solution were met through the development of the WNSIA architecture. All the milestones of Task A were met as planned. Successful field trials demonstrated the wireless technology and convinced the project team to proceed with commercialization as well as standardization activities. The activities are described below.

Commercialization

On June 11th 2007 Honeywell announced the product launch of the OneWireless™ solution. This second-generation multi-functional wireless mesh network supports wireless-enabled applications within a single wireless network to optimize plant productivity and reliability, improve safety and security, and ensure regulatory compliance. The technology that went into this industrial wireless solution was developed as part of this project and it delivered a global solution with robust security, predictable power management and multi-speed monitoring. Industrial strength wireless XYR™ 6000 transmitters (temperature, pressure, analog input, corrosion, etc) were introduced. As a single network supporting both sensors and IEEE 802.11-based applications, OneWireless also supports mobile worker devices, such as Honeywell's IntelaTrac PKS and Experion Mobile Station, and can improve plant safety by helping customers quickly locate employees. Figure 23 shows OneWireless transmitters and multinode.

Figure 23 OneWireless industrial transmitters and multinode

On November 27th 2007 Honeywell introduced OneWireless™ Equipment Health Monitoring (EHM). OneWireless EHM wirelessly transmits complete spectral information—including vibration amplitude and operating parameter information—from the field to the plant control room, helping reduce equipment failures and improving plant performance through lower maintenance costs. This EHM solution can be installed in less than four hours on a pre-installed OneWireless network.

On June 16th 2008 Honeywell announced an updated version of its OneWireless™ industrial wireless network equipment that was designed to be compatible with the end-user driven ISA100.11a industrial wireless communication standard. This OneWireless release (R110) was the process industry's first mesh network with ISA100-ready hardware. It can be easily upgraded to the ISA100.11a standard through an over-the-air software update. The release also extended Honeywell's product line of transmitters with a new XYR™ 6000 digital input wireless transmitter. In addition, this OneWireless release expanded the interface capabilities of the system, supporting the HART protocol. HART is commonly used by asset management applications such as Honeywell's Field Device Manager. OneWireless system management software makes any XYR 6000 transmitter communicate to existing HART-enabled applications in the same manner as to a wired HART device. This continuous evolution of the OneWireless platform highlighted the multi-protocol capabilities of the Honeywell system.

On April 28th 2009 the OneWireless™ Gauge Reader was added to the OneWireless family of wireless solutions for industrial manufacturers. The product wirelessly monitors manual gauge readings from existing dial gauges, allowing operators to analyze critical equipment health and process information and make decisions to improve plant operations. It integrates into the OneWireless mesh network designed to simultaneously accommodate thousands of field devices and multiple industrial protocols.

On May 28th 2009 Honeywell added two discrete-input transmitters to the family of XYR™ 6000 wireless devices. The STXW 500 and the STTW 401 transmitters can convert any measurement device with a contact-closure switch input into a wireless input, enabling manufacturers to decrease costs and improve efficiency by wirelessly monitoring more processes at their plants. The transmitters are ideal for applications such as wirelessly monitoring level switches, pump status and system alarms.

On June 16th 2009 Honeywell introduced the latest version of the OneWireless™ industrial mesh network solution for manufacturing facilities. OneWireless R120 features the process industry's first redundant wireless system gateway (WSG), a critical prerequisite for wireless process control. The new WSG manages data between wireless field instrumentation and the plant's process control network (PCN). It serves as a backup gateway to ensure that data is always delivered even if the main gateway malfunctions or fails. Paired with existing OneWireless redundancy features, this approach created the first industrial wireless system with complete hardware and radio-frequency redundancy from the field instrument to the PCN connection. Additionally, unique failure recovery features help prevent data loss and the network can recover in less than two seconds from any field hardware failure. OneWireless R120 included several other enhancements that improve the network scalability and reliability such as adaptive transmit power control for XYRTM 6000 field instruments. This feature saves battery power and minimizes radio interference by enabling field devices to use the least power possible to transmit signals to OneWireless multinodes.

On June 16th 2009 Honeywell also introduced the OneWireless™ XYR™ 6000 Valve Position Sensor, which allows remote, reliable valve position monitoring in a variety of applications to avoid the time and safety risk of manually monitoring valves in hazardous areas and remote installations.

On August 11th 2009 Honeywell released the first ISA100.11a-ready wireless radar gauge that helps process manufacturers monitor tank levels and prevent hazardous incidents in their plants and terminals. The FlexLine Wireless Radar Gauge improves operator awareness by capturing a wide array of tank measurements and quickly transmitting them via the OneWireless network to control rooms. This setup reduces overall operating costs and improves safety by eliminating the need for manual data collection.

More information about the OneWireless solution can be obtained at [1].

The value proposition of wireless to the end users is described in Appendix – Wireless. In certain applications, 10 % or more energy savings can be achieved by the end user through the use of industrial wireless technology. Energy savings as well as economic impact of wireless are described in Appendix – Wireless.

Publications & presentations

S. Huseth, "Wireless Architecture for Industrial Systems", EPRI Wireless Working Group, Comanche Peak, TX, Jan 20, 2005.

P. Gonia, "Scaling in Large Sensor Networks – How Large is Too Large?" 3rd Annual IEEE COMSOC Conference on Sensor and Ad Hoc Communications and Network (SECON), Reston, VA, Sep 27, 2006.

S. Kolavennu, R. Budampati, P. Gonia, "Secure and Reliable Wireless Architecture for Process Monitoring, Control and Diagnostics," 23rd International Forum on Process Analytical Technology (IFPAC), Baltimore, MD, Jan 28, 2009.

Patents & filed applications

R. Budampati, P. Gonia, S. Kolavennu, "Latency Controlled Redundant Routing".

R. Budampati, P. Gonia, "Wireless Communication System with Collision Avoidance Protocol".

R. Budampati, P. Gonia, S. Kolavennu, "Wireless Communication System with Channel Hopping and Redundant Connectivity".

R. Budampati, "Redundant Wireless Node Network with Coordinated Receiver Diversity".

R. Budampati, A. Mathur, "System and Method for Optimizing Power Suplies in a Wireless Transceiver".

D. Foo Kune, P. Gonia, T. Phinney, J. Kimball, "Secure Wireless Instrumentation Network System".

D. Foo Kune, K. Mahadevan, "Method and Computer Product to Increase Accuracy of Time-Based Software Verification for Sensor Networks".

K. Driscoll, P. Gonia, J. Kimball, T. Phinney, "Cryptographic Key Sharing System".

P. Gonia, S. Kolavennu, A. Mahasenan, R. Budampati, "System and method for time synchronization in a wireless network."

R. Budampati, P. Gonia, S. Kolavennu, A. Mahasenan, "System and method for merging clusters of wireless nodes in a wireless network."

Standards activities

Project team members from Honeywell actively participated in the ISA100 and WirelessHART committees for development of industrial wireless sensor network standards. In May 2006, Honeywell along with a group of other companies issued a press release: "*Honeywell, Adaptive Instruments, Endress+ Hauser, Flowserve, OMNEX Control Systems, 3e Technologies*

International (3eTI) and Yokogawa announced they have joined the Instrumentation, Systems, and Automation Society (ISA) SP100 working group to support the committee's efforts to create an open industrial and multi-functional wireless standard. This industry group will work towards a joint solution that will enable industrial plants to use a single wireless network architecture to support a wide range of applications from low-rate monitoring to process control to wireless worker functions."

The project team presented the technical requirements obtained from this project to the ISA100 committee; these requirements were incorporated into the technical requirements document that was used by ISA100. Members of this project team were selected by ISA to take on the role of technical editors for the development of the ISA100.11a standard. These editors actively participated in the definition of ISA100.11a Principles of Operation (PoO), generation of three drafts of the specification (D1, D2a and D2b), and comment resolutions throughout the standard development process. The final draft (D2b) was released on July 8th and was approved by the ISA100 committee on July 23rd 2009. This draft was approved by the ISA Standards and Practices (S&P) Board on Sep 9th, 2009 as a standard: ISA-100.11a-2009: Wireless Systems for Industrial Automation: Process Control and Related Applications.

More information about this standard can be obtained at [3].

Conclusions

During the critical review of existing wireless systems, the project team quickly realized that no existing systems could meet the technical requirements; the team also realized the importance of conducting a thorough VOC process to ensure that a solution would be designed that end users would accept and adopt.

An industrial wireless sensor network that offered a level of robustness, reliability, security and power management was acceptable to industrial users if it could be deployed globally, coexist with other wireless systems already in the plant, and provide a multi-functional infrastructure that could be used for other purposes besides supporting wireless sensors. The project team put in significant effort to ensure that these criteria were met by the developed solution. To satisfy these needs, the team designed the system to coexist with other wireless systems and to strategically manage spectrum utilization in the plant.

While most of the end users did not understand the technical details of state-of-the-art security designs, they did understand the need to deploy a system that they could trust was secure enough. The project team not only designed a secure wireless system, they also made sure that the security design was critically reviewed by both commercial and academic experts.

While the industrial wireless solution developed in this project does not require a RF site survey for normal operation, the project team realized that every industrial plant is unique and carefully planned deployment of the network can ensure reliable performance that is critical for sustaining long-term benefits. Some key observations include: sub-optimized use of limited bandwidth can impact reliability and scalability; industrial wireless networks are extremely secure when properly configured but may not be very secure if improperly implemented; device placement, antenna selection, frequency tuning and power output configuration can dramatically reduce interference and signal leakage while increasing reliability; too many extraneous devices increase up-front and maintenance costs while lowering performance due to interference and additional hops; too few devices may not provide high enough signal quality to ensure reliable operation over the long term; no matter what type of wireless system is used, it is important to carefully assess the site requirements and to design the network with both current and future needs in mind.

After the introduction of Honeywell's OneWireless^{TM} solution, which is a multi-functional mesh network that supports multiple applications with a single network, end-users have been coming up with new and innovative applications based on their interaction with this wireless solution. Some of these applications are listed in Appendix – Wireless. The significant end-user interest generated by this solution has led to the development of supporting wireless devices that can be connected to this single wireless network. While some end-users have only used the wireless system for monitoring applications, others have started experimenting with non-critical control applications. As end-users gain more confidence with wireless, control over wireless will become more common. The latest OneWireless version (R120) is designed to meet this need and provides the necessary redundancy features for wireless process control.

A significant barrier for wide-spread adoption of industrial wireless was the lack of a user-driven standard that met their needs. This barrier was removed by the recent approval of the consensus-based ISA100.11a:2009 standard. The project team realized the importance of this user-driven standard and played a key role in developing the technical specification for this standard.

Recommendations

The recently approved first industrial wireless standard, ISA-100.11a-2009: Wireless Systems for Industrial Automation: Process Control and Related Applications [3], meets all the technical needs of the end users and ensures multi-vendor device interoperability. Hence, DOE should actively promote ISA100.11a and encourage end users to deploy wireless solutions that are compliant with this standard. Compliance will lead to widespread adoption of industrial wireless, which can ensure that DOE's goals of improving energy savings and efficiency in industries can be met.

The recently formed ISA100 Wireless Compliance Institute (WCI) [4] is as an industry group within the Automation Standards Compliance Institute (ASCI). Its mission is to assure that the ISA100.11a standard is applied effectively and consistently, i.e. wireless products developed by member vendors are compliant with this standard. The testing and approval process undertaken by WCI will ensure performance as well as interoperability of certified products. These are both critical to assure that users build and maintain confidence in wireless technology.

DOE should encourage vendors offering industrial wireless solutions to join WCI and develop ISA100.11a compliant products. DOE should also educate users about the benefits of insisting on WCI approved products to guarantee performance and interoperability.

A key aspect of DOE's Save Energy Now initiative [5] is the energy assessment performed to identify energy-saving opportunities in industrial plants. Such assessments can be improved significantly through the use of wireless energy assessment kits. Such kits can be based on the ISA100.11a standard and provide the low-cost means for faster, more efficient energy assessments. Due to the lower cost and ease of installation of such wireless kits, more assessments can be completed leading to more energy savings. DOE should consider funding a project to develop such wireless kits with portable devices and demonstrate their benefits in industrial plants. Another project that DOE should consider funding is inferential process control using wireless systems; wireless systems that offer a high level of reliability and deterministic behavior can support such control. Also control strategies that take into account the inherent nature of wireless communication need to be developed for ensuring predictive control of product quality.

DOE should also consider funding a showcase site for demonstrating the DOE-funded wireless technologies. An industrial site that offers a continuous, in-process application of these wireless technologies for energy savings and is accessible to DOE-approved visitors can be a compelling tool for spreading awareness among the broader industrial community and help the industrial plants to realize the energy-saving-benefits offered by wireless. It can drive them towards the DOE goal of 25% or more reduction in energy intensity in 10 years.

The technical features of ISA100.11a are relevant not only for process industries but also for the Smart Grid. As a result, ISA100 was cited in the recent NIST Roadmap for Smart Grid Interoperable Standards [6]. DOE should continue to push for the broader adoption of ISA100.11a as well as the various technologies that make up this standard.

Task B: Microanalytics for Process Control Solutions

Introduction

This program supported the development of a micro-scale gas chromatograph (GC), PHASED, tailored for a sampling and communications manifold, NeSSI. These two technologies were expected to give industrial users access to chemical composition information more frequently and in more locations throughout a process chemical plant. Increased process knowledge provides more opportunities for process control and optimization. Optimized processes produce the same quantity of product with significantly lower amounts of raw material and energy.

The PHASED concept is to replace each component of a macro-scale GC with a micro-scale counterpart based on MEMS technology. The PHASED concentrator/injector is based on a large linear array of thermally isolated, individually addressed, gas adsorption-desorption heating elements. The separation column can be either a MEMS structure or a traditional micro-bore capillary column for isothermal separations. The PHASED detector is the micro discharge device (MDD), an orthogonal/complementary detector based on photon emission of plasma excited gases. The unique design of PHASED allows robust valve-less operation at low power consumption and fast analysis times. NeSSI provides the sampling interface to the PHASED concentrator injector. Its responsibility is to representatively sample process streams and condition them for PHASED analysis.

The specific problem that the PHASED-NeSSI combination proposes to solve is the inadequacy of the current state-of-the-art gas sampling and sensing systems. The inadequacy has been stated by several leading industry groups. The Technology Roadmap for the U.S. Petroleum Industry lists the need for real-time measurements of chemical composition as a top priority. The Glass Technology Roadmap identifies “robust” gas sensors and “smart” sensors as a priority for process control. The Roadmap for the Forest Products Industry assigns a high priority to the development of reliable, affordable real-time sensors to measure non-process contaminants. The modular aspect of the NeSSI sampling system, the valve-less PHASED operation, and high resolution chromatographic data address many of these inadequacies.

The potential applications for a fully developed and deployed PHASED-NeSSI system are very diverse and realized energy savings can be large owing to the PHASED approach which replaces each aspect of a traditional GC within a MEMS counterpart. Moving to a MEMS package has advantages in size, sensitivity, speed of analysis, power consumption, ease of use, and reliability. However, a large draw-back is the significant development time required for each variation of a micro-scale GC in terms of MEMS integration, scale-up, and refinement. This development time makes a fairly straightforward macro-scale GC process, such as column changing, rather complex in the MEMS-GC. For PHASED, changing the column requires development of a new stationary phase and deposition procedure and may require new column dimensions. These modifications could impact the resulting flow rate and timing sequence of the integrated PHASED micro-GC. The diversity, availability, and relative ease of switching macro-scale GC injectors, columns, and detectors make them applicable to a wide variety of process applications. This ease of switching is not available to the micro-GC world.

Honeywell’s focus in the later months of the program was to work with industrial partners to find one particular process chemical application for PHASED-NeSSI. Applying PHASED-NeSSI to this process would provide value to the customer by increasing yields while lowering raw material and energy costs for production. The magnitude of the predicted energy savings within this one application is a realistic and near-term achievable savings compared to the theoretical savings of a fully developed NeSSI-PHASED that has market presence across every process chemical application. A commercial plan will be developed depending on the results of the discussions with the industrial partners.

Background

Real-time, automated, and continuous online monitoring of chemical processes is an area of general interest in industrial controls and represents an important capability for issues of efficiency (i.e. cost), quality control, and safety. Unfortunately, sampling and composition sensing technologies are widely viewed as the weak links in most process control and automation instrumentation.

The inadequacy of the current state-of-the-art in compositional sensing has been put forth by several leading industry groups. For example, the *Technology Roadmap for the U.S. Petroleum Industry* lists as a top priority the need for real-time measurements of chemical composition. In addition, the *Glass Technology Roadmap* identifies "robust" gas sensors and "smart" sensors as a priority for process control. The *Roadmap for the Forest Products Industry* assigns a high priority to the development of "reliable, affordable real-time sensors to measure non-process [contaminant] elements in harsh pulping, bleaching and recovery processes." The *Year 2000 Separations Roadmap* for the chemical industry lists the need for improved sampling methods and process gas chromatographs. Together, these and other such industries represent a significant component of the U.S. and world economy, and therefore even modest efficiency and productivity gains would have a significant economic impact worldwide.

In many industrial sensing and measurement applications, it is possible to trade speed or accuracy for cost. This tradeoff is not typically the case in chemical process control where the complexity of the compositional measurements drives reliance upon expensive, analytical instruments as opposed to discrete, low-cost single or multi-analyte sensors.

Principal among the analyzers of choice is the gas chromatograph. The gas chromatograph is considered the most versatile and accurate analyzer available for the identification and quantitative measurement of complex, possibly unknown gas and chemical mixtures. Such systems find widespread use in the pharmaceuticals, petroleum, industrial processing, and general laboratory research industries.

Unfortunately, GC instrumentation suffers from several significant drawbacks that prohibit the technology from penetrating areas that could benefit from their high levels of utility and functionality such as:

- Systems are typically large (~1,000-10,000 in^3) and not portable. They therefore must be centrally located to spread the cost across multiple low usage applications, or be specially facilitized for on-site accommodation in single, high-use applications.
- GC instruments are delicate systems requiring specialized training, care in handling, and frequent calibration, factors which not only play into the portability issue, but lead to high operating costs and limits deployment to relatively "clean" environments.
- At a typical price of >$100K per installation, GC analyzers are among the most expensive instrumentation a facility may require, relegating them to a limited number of installations in a shared environment, with dedicated installations being supported only in mission critical control loops.
- GC systems draw 100s to 1000s of Watts during operation and require consumable carrier gases such as helium and hydrogen adding to the cost of installation and use.
- GC analyses occur over minutes to tens of minutes. Already slow by most standards, this actual analysis time may be only a small fraction of the total measurement cycle. A typical procedure may involve either 1) long sampling lines to a shared GC or 2) a human operator

physically taking a sample, transporting it to the GC instrumentation, performing the measurement, interpreting the data, and then initiating any indicated actions. Thus, a measurement cycle may take as long as many minutes to hours.

Clearly, industrial process monitoring needs are not being addressed by currently available technology. To address these issues, we proposed the concept of the PHASED micro-GC; a robust, low-cost, compact analyzer with the full functionality of a bench top GC. This instrument would directly address most, if not all, of the issues outlined above. When packaged in a standard NeSSI sampling module, the PHASED micro-GC would enable cross-industry deployment of such sensors, concentrating the characterization power where it is needed most; at the pipe and in the flow stream.

Body of the Report

Technical Approach

The approach of the PHASED concept replaces the large injector, column, oven, and detector components with their micro-scale counterparts based on MEMS technology. Rather than using a high-pressure consumable carrier gas with plumbing and storage issues, the PHASED approach can utilize ambient air or process gas as the carrier gas, and a compact pump to draw the gas through the PHASED chip. In place of the stainless steel injection valve, we proposed a novel, coherently additive electro-thermal injection mechanism not only to generate an extremely narrow injection plug (leading to high-speed analyses and excellent peak resolution), but also to yield high preconcentration of the sample for increased measurement sensitivity. The separation column could either be a MEMS channel structure or a traditional capillary column. The integration of thin-film heater membranes within the MEMS column structure would eliminate the need for an external oven and radically reduce power consumption, size, and analysis time. Finally, the replacement of traditional detectors with the MDD maintains or improves overall sensitivity and selectivity while improving size, cost, power, and analysis times.

It is estimated that 70-80% of analyzer outages can be traced to the sample system. Therefore, Honeywell’s approach to developing MEMS-GCs for chemical process monitoring would be incomplete without a sampling system. Sampling systems limit the deployment and sensing points of many process analytical devices. The beginning of this program saw the emergence of a potential solution to the sampling problem, the NeSSI platform. NeSSI is designed to make chemical composition analysis of process streams more representative by standardizing the sampling interface. It provided an ideal platform for Honeywell’s PHASED technology.

NeSSI was and is being developed by an open community of process analytical vendors and users. To be widely applicable across the processing industries, NeSSI was developed as an "open" architecture for sampling with three stages of development: NeSSI Generation I (Gen I) provided a standardized (ANSI SP-76) means for the fluid-mechanical design for process stream sampling. Gen I NeSSI systems and components were commercially available at the onset of the program. NeSSI Generation II (Gen II) extends the platform to include a means of electronically networking NeSSI components using a sensor actuator manager (SAM) with the control room. The Gen II standard was recently agreed to in 2009. NeSSI Generation III (Gen III) focused on creating micro-analytical capability to the gas sampling platform in a smart, safe, and plug-and-play fashion. This last generation of NeSSI focuses on bringing analytics to the sampling point and integrating the analytical signals with the SAM and is in its infancy. The PHASED NeSSI system developed in this program is an example of a Gen III system.

Experimental Methodology, Test Procedures, Characterization Methods

Due to the ground-breaking aspects of the PHASED NeSSI systems, Honeywell focused the experimental methodology on proof-of-principle bread-board and brass-board prototyping and experimentation. The proposed design of the PHASED system is shown below in part A of Figure 24; its final prototype used for testing and evaluation is shown in part B.

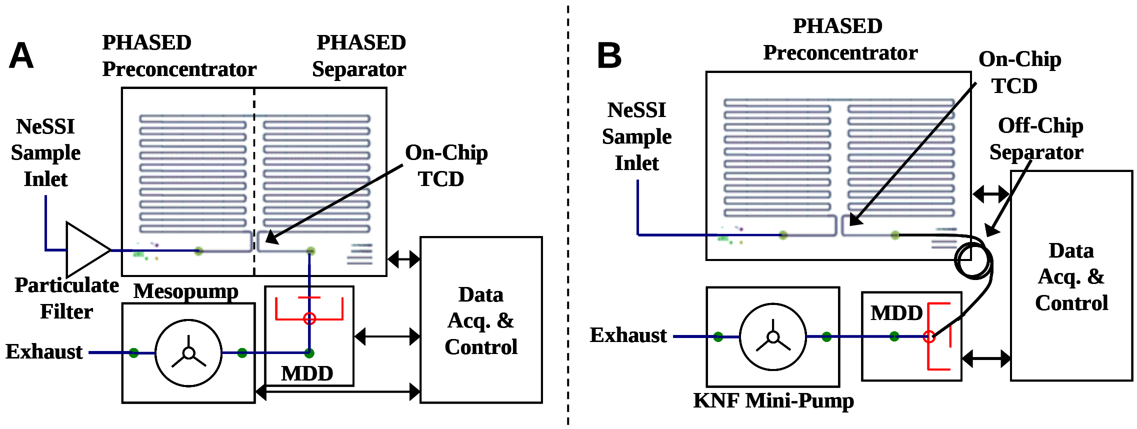

Figure 24 PHASED design schematics: A) as originally proposed; B) modified design used in testing and evaluation

The changes made to the proposed design during the course of the program were done to minimize time before the system could be tested and evaluated. The main design differences are the lack of a particle filter and use of commercially-available separation columns and vacuum pumps. These differences reduced development time without sacrificing performance within the scope of the planned field trials.

The proposed PHASED NeSSI effort was a complex development and integration of several break-through technologies. As such, Honeywell's management strategy was to break the final PHASED-NeSSI system into manageable subsystems during prototyping, testing, and evaluation. The program covered four major tasks:

1. PHASED Materials Development
2. Micro-Detectors for Gas Sensing
3. PHASED NeSSI Systems Integration
4. Test and Evaluation

The results of each subsystem development are discussed below, where appropriate, further details of the approach methodology and testing procedures are also provided.

1. PHASED materials development

Two key PHASED developments were performed under this task. The first was the design and fabrication of the PHASED MEMS chip itself. The second was to develop adsorbents to perform the preconcentration and separation of the analyte gases.

MEMS design and fabrication of PHASED chip: The majority of the PHASED fluidic and thermal designs were carried out under a separate program, ORNL subcontract 4000015922, ORNL contract with DoE No. DE-AC05-00OR22725 [7]. Briefly, the chromatographic performance of various channel designs was modeled using certain assumptions about applicable flow rates, resulting injection widths and corresponding chromatographic peak capacity. Merging the need for high flow rates, low pressure drop, and high chromatographic efficiency led to the selection of roughly 100x100 micrometer square channels.

Adsorbent or stationary phase development: The importance of this development cannot be underestimated. The adsorbents within PHASED have many, sometimes conflicting, responsibilities. They need to strongly interact with every analyte gas during preconcentration. However, the interactions must be not too strong to allow rapid desorption upon heating for the phased injection. After injection, the chromatographic adsorbent must provide unique weak interactions with the analytes for effective separation. Moreover, the adsorbents must be amenable to MEMS processing. This requirement ensures the entire fabrication process for the PHASED devices is low cost. The early approach was to look for a single adsorbent that could perform the preconcentration and separation roles for target analytes equally well. The target final target analytes at the two test sites were: HCl, light hydrocarbon; and CO, CO_2, CH_4, N_2, O_2 in He.

A rapid adsorbent screening methodology was developed to streamline Honeywell's adsorbent development task. Selected adsorbents were evaluated experimentally using Honeywell's quick test vehicle (QTV). QTVs allow the rapid deposition of adsorbents within MEMS fluidic channels for rapid prototyping. QTVs typically take two working days to fabricate. They allow for high throughput empirical evaluation of MEMS processing strategies and resulting adsorption properties of the adsorbents.

Honeywell modeled or empirically studied many adsorbents throughout the program. They included: Ogano-Silicates, EpoxyNovolac, PDMS, Graphites, Adamantyl-Arylene, and Tetrafluoroethylene. Some more familiar adsorbents, or stationary phase, material evaluated include Haysep "T," Teflon, SU-8, and Carbon Nanotubes. Haysep "T" is a molecular sieve material. Two sources of material were evaluated. However, the MEMS processing did not result in a sufficiently uniform distribution of its particulate matter. This non-uniform distribution led to problems with wafer bonding. Both Teflon and SU-8 were straightforwardly deposited on the QTV channels but yielded poor retention and separation characteristics. Lastly, carbon nanotubes were evaluated under a separate project. Considerable effort was expended at merging the growth recipe for the CNTs with the PHASED fabrication process. The result was a CNT phase that exhibited very strong retention of hydrocarbon analytes grater than C5. Unfortunately, the CNT-analyte interaction strength dramatically slowed the necessary thermal desorption process. This resulted in wide injections and poor chromatographic resolution.

Three adsorbents exhibited a combination of qualities that were attractive for PHASED NeSSI application. Those three are included in Table 5.

Table 5 PHASED adsorbents developed to highest level of maturity

Adsorbents	Maturity Level	MEMS amenable	Adsorption Characteristics
Nanoglass™	High	Yes	High surfaces are broadly adsorbent, good separation characteristics for light compounds.
"Nanozeo"	Mid	Yes	Hybrid zeolite phase for preconcentrating small analytes; holds promise for separating permanent gases.
OV-5	Mid	Yes	Preconcentrates low vapor pressure gases well, good separator for >C5.

Although each phase exhibited some ideal qualities, none of the evaluated adsorbents met all of the requirements for both preconcentration and separation. As a result, the Honeywell team modified the original design. The second design used the on-chip channel for preconcentration only. In this design, the separation is performed isothermally at near-room temperature by an off-chip chromatography column. Refer above to Figure 24 for a graphical representation of the difference. The Test and Evaluation section below presents the results obtained for calibrating PHASED NeSSI responses to target analytes. The adsorbent used in all trials was nanozeo, with an off-chip separator and MDD detector. The detectors investigated during this program are detailed further in the next section.

2. Micro-detectors for gas sensing

This subsystem involved the design, fabrication, evaluation, and integration of the required thermal conductivity (TCD) and MDD detectors. The TCD detectors were the baseline approach as they were more technically ready at the onset of the program. The TCDs are based on Honeywell's microbridge flow sensor technology. As the project progressed, the TCDs could not meet the required sensitivity because of the similarity of thermal conductivities between target analytes and the carrier gases in which they were present. As a result, the micro discharge device (MDD) detector, originally planned to demonstrate enhanced selectivity detection, became the baseline approach. The early MDD detectors were jointly developed by Caviton, the University of Illinois, and Honeywell. However, late in the program the development was moved completely within Honeywell to decrease the iterative design, prototyping, and evaluation timelines.

The MDD detector is an optical, multi-channel detector providing added analyte selectivity. This selectivity allows analytes that overlap chromatographically to be quantitatively resolved with a variety of mathematical procedures generally referred to as chemometrics. An MDD produces an electrical discharge in the gases to be analyzed. As the gas composition varies so does the optical emission spectrum of the breakdown or discharge. The emission can be monitored via a variety of optical detectors. The optical spectrum can be analyzed and calibrated for a variety of analyte specific information. Chemicals with different elements or functional groups can show unique signature wavelengths.

The early MDD detectors were jointly developed by Caviton, the University of Illinois, and Honeywell. However, late in the program the development was moved completely within Honeywell to decrease the iterative design, prototyping, and evaluation timelines. Honeywell's re-designs of the MDD detector began with the goal of increasing the device's sensitivity to the target analytes. To this end, three changes were made. First, the detector's dead volume needed to be decreased to maintain peak shape. Second, the gases needed to interact with the most intense region of the discharge field to maximized excitation and emission. Third, the optical fiber used to collect the light needed to be self-aligned with the breakdown to ensure best coupling efficiency, reproducibility and manufacturability.

Honeywell's proprietary MDD detector design incorporates all of these aspects. It continuously operates for several days in an air or N2 carrier gas and several months in He or Ar carrier gases. It was the main detector for the PHASED NeSSI system. The optical spectrometer linked to MDD detector and Honeywell's data collection software can collect a complete emission spectrum (from 200–1100 nm) every 1 ms. As described in the Test and Evaluation section, this integration time varied depending on the target emission's wavelength and intensity.

3. PHASED NeSSI systems integration

A sample conditioning system makes it possible to interface the sample from the process line to the PHASED NeSSI GC. Figure 25 is a schematic for the complete unit built as a prototype of the PHASED NeSSI micro GC for UOP field test unit. This unit has three input streams, the process gas stream, the dilution stream, and the calibration stream. The flow through the micro GC is controlled by mass flow controllers and monitored by flow and pressure sensors. A small local PC (a brick) controls, and monitors the operation of the system, and also, collects, and analyzes the measured data locally. The electronics that control and monitor the flow are located in a small box within the system enclosure. It communicates flow data back and forth to the local PC. The PC synchronizes the operation of the micro GC with the mass flow controllers. Figure 26 shows the Air Products complete field test unit for testing impurities in Helium.

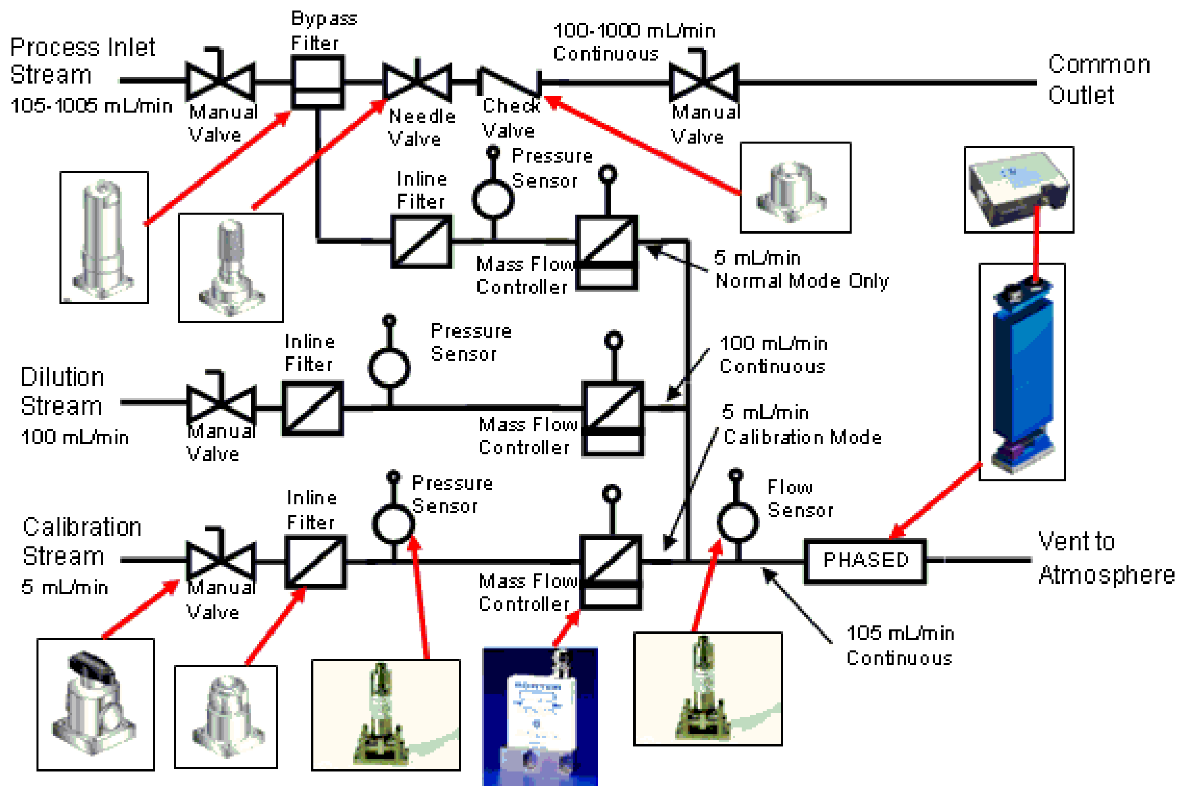

Figure 25 NeSSI system schematic

The GC microsystem, shown in Figure 27, occupies two standard 76 NeSSI blocks. The micro GC consists of the PHASED chip, which has the concentrator and separator, the MDD detector, and all there driver electronics. It has two connectors, an electrical, and an optical one. The electrical connection carries the power and the communication to and from the GC. GC with the microprocessor that controls the concentration, and separation processes, and detector (MDD) high voltage driver The optical connection, via a fiber that collects the emission within the MDD, couples the MDD signal to an optical spectrometer. The output is collected and analyzed by the PC in the unit.

The analyzed data is communicated to the sensor actuator manager (SAM) through an Ethernet connection.

The final design of the electronics has been deployed and tested in the lab under conditions similar to those in the field.

The design of the total PHASED software architecture was completed, including the software in PHASED, in the SAM associated with NeSSI and in the data analysis PC. The data provided by the MDD required additional data analysis software. This software has been developed, but it has been tested only in the lab environment.

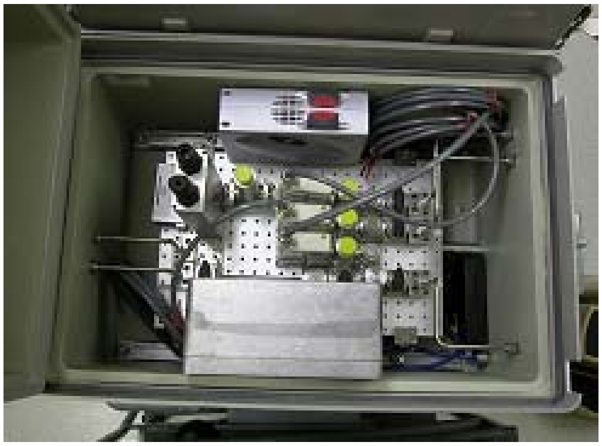

Figure 26 Air Products field test system

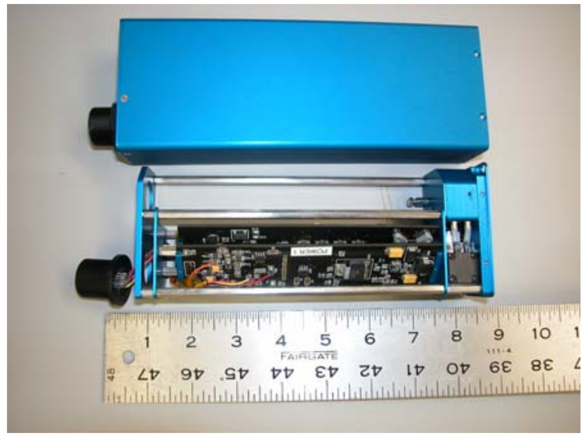

Figure 27 Microsystem GC for NeSSI system platform

4. Test and evaluation

The proposed program was supported by 12 industrial partners who, at the time of the proposal, were willing to take PHASED NeSSI prototypes into their processing plants for evaluation. As mentioned earlier the rapid standardization of NeSSI Gen I specifications was followed by several years before the NeSSI Gen II standard was agreed on (SAM). This is a critical aspect of NeSSI in many users' minds. It provides guidelines to component manufacturers for making sensors and actuators able to be remotely controlled and interrogated. During the Gen II standardization process very few components were available for remote operation. These circumstances reduced the excitement for NeSSI within the industrial community. As a result, ten of the twelve industrial partners lost interest and support for the program by the program's end. The remaining two industrial partners were Air Products, and UOP. The progress towards meeting these two collaborators' specifications are presented separately below.

Air Products Application

The Air Products application was to detect permanent gas impurities within an He production stream. The target impurities were Ar, N_2, O_2 CO, CO_2, Ne, and CH_4; all were to be measured at or below 2.5 ppm. Of the three available adsorbents, none were well suited to preconcentrate these analytes. Without preconcentration, the PHASED system cannot perform injection and subsequent separation of the analytes. Therefore, to detect each analyte individually, the MDD needed to be able to record specific emissions for each gas.

The Air Products gases were tested at various concentrations between 500 and 5000 ppm (v/v). The goal of the testing was to record data sufficient for identifying each of the five test gases by their MDD spectra alone. The five gases tested were supplied individually at ~5000 ppm in a helium buffer gas. Nitrogen, methane, argon, neon, and hydrogen were all evaluated. Completely selective emissions were located for all 5 test gases. The emissions were found by recording the helium background spectrum and subtracting that spectrum from the sample's spectrum. This helium subtraction creates the negative peaks seen in some of the emission spectra below. The selective emissions are summarized in Table 6 and the graphs in Figure 28. The individual helium subtracted spectra that shows the selective emission appear below in Figure 28. Part A shows the selective emissions for Neon, Hydrogen, and Argon; Part B shows the selective emissions for Nitrogen and CH_4.

Table 6 Selective wavelengths of 5 Air Products gases

Analyte	Selective wavelength(s) in nm
Nitrogen	336.8, 357.4, 315.6
Methane	431.2
Neon	704.0, 585.4, 725.3
Hydrogen	657
Argon	751.2, 812.3, 764.5

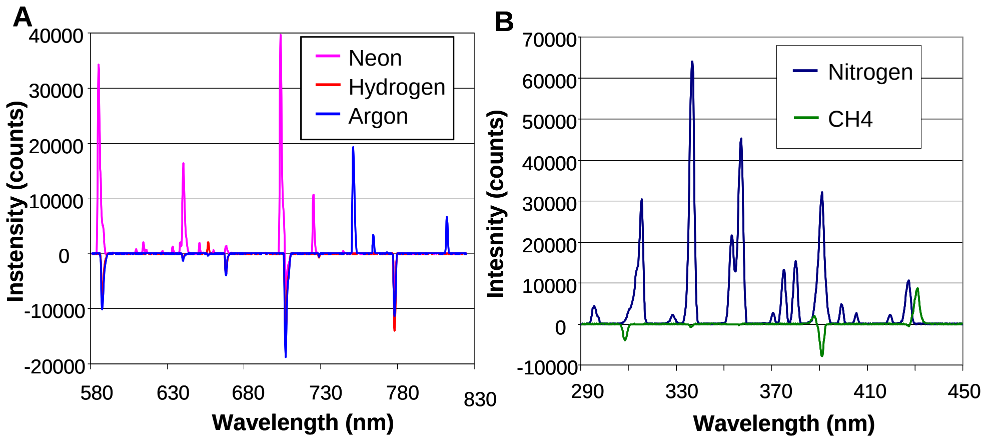

Figure 28 Zoom-ins showing selective emissions

Looking a little more deeply into the data presented above, two observations can be made. The first is that the MDD provides high selectivity to the Air Products target gases and is extremely sensitive to nitrogen. Table 6 lists the three most prominent nitrogen emissions. However, there are many more visible in part B of Figure 28. This sensitivity is contrasted by the MDD's sensitivity to hydrogen. The selective emission for hydrogen shown in red above is quite small. Quantifying that emission is made more complicated by is location in a crowded area of the spectrum.

The high sensitivity to nitrogen presented its own challenges in the laboratory PHASED NeSSI evaluations. When nitrogen is present, the helium emissions are diminished. The extreme sensitivity to nitrogen makes purging the NeSSI system and any connective tubing of atmospheric nitrogen very critical. If nitrogen dominates the emission, many of the purely selective emissions for other analytes do not appear. The hypothesized reason for this is that the helium emissions that typically couple energy into the excited states of the target analytes are not nearly as populated when nitrogen is present (as evidenced by the lower intensity helium emissions). In the laboratory demonstrations, atmospheric nitrogen contamination was present. For ease of presentation of the data, the testing performed in this study used an integration time of 2ms.

The data presented in Figure 28 is at a high concentration, greater than 500 ppm. The high concentrations were used to ensure that any selective emissions were visible. Unfortunately, producing dilutions of the 5000ppm gas standards to concentrations lower than 250ppm was not possible with the available NeSSI amenable mass flow controllers. Additionally, a limited number of analytical gas cylinder standards were available. The only other concentration available at the time of testing was a mixture of all Air Products analytes (CO_2 being the sixth) at 2.5 ppm. When using the 2.5 ppm mixture and a 2 ms integration time, the above signals were not visible with the exception of nitrogen (which was easily visible) and one emission from argon. The argon emission was confirmed by increasing the integration time to 10ms. At 10 ms the argon emission was significantly above the baseline noise. Neon and methane emissions were approximately equal to the baseline noise at 10 ms but could not be quantitatively identified at this integration time.

Although not expressly stated before, the apparent limit of detection (LOD) of the MDD can be lowered by increasing the integration time. The increase however has the potential drawback of high-intensity emissions swamping the nearby low-intensity emissions. With that concept and the Air Products data in mind, Honeywell was confident of the following assertions:

- The LOD for nitrogen is well below 2.5 ppm at a 2ms integration time
- The LOD for argon should be approximately 2.5 ppm at 2ms and lower at higher integration times
- The LOD for methane and hydrogen should be on the order of a few ppm with longer integration times 10ms
- The LOD for hydrogen is expected to be significantly greater than 2.5 ppm at any integration time (as it is in a crowded section of the spectrum)

The above predicted sensitivities are worse than expected for a complete PHASED NeSSI analyzer due to the lack of an appropriate adsorbent for preconcentration. Without the added sensitivity gain from such an adsorbent, the system was unable to meet the LOD requirements for the Air Products application. Air Products remains supportive of the technology and interested in evaluating a PHASED NeSSI system in the field. However, the program's remaining time and budget resources were redirected to locating a near-term application that would have a high probability of successful improvement in process monitoring and show useful energy savings to the DOE.

UOP Application

UOP is the second industrial partner in this program. UOP has a considerable number of industrial processes that are refined within their pilot plants every year. For the vast majority of this program, the UOP application focused on monitoring hydrogen chloride gas (HCl) contamination in a hydrocarbon stream. The hydrocarbon was the only other gas present in the stream. Originally, this carrier was butane, C_4, but switched to pentane, C_5, as the program progressed. This change did not impact either PHASED or the NeSSI sampling system greatly. Nanozeo, the second adsorbent in Table 6, was developed to support this application. The hypothesis, subsequently supported by experiment, was the Angstrom-scale pores within the zeolite could effectively adsorb the HCl gas for a period of a few seconds until thermal desorption/injection was desired. The nanoglass material was needed as a binder to secure the zeolite to the heater structure.

Experiments evaluated the nanozeo PHASED system's ability to monitor HCl within a simulated UOP process stream. The first goal was to establish the adsorbent's ability to preconcentrate, and therefore inject, HCl. The preliminary experiments produced HCl within a helium carrier gas. The HCl concentrations were generated by passing various flow rates of He over a 20% aqueous solution of HCl and merging that headspace stream with additional pure He to equal a total flow rate of 100 sccm. This dilution was performed with a combination of standard and NeSSI fluidic components. The output of the NeSSI system was pushed through the PHASED analyzer. The results of these early experiments are shown below in Figure 29.

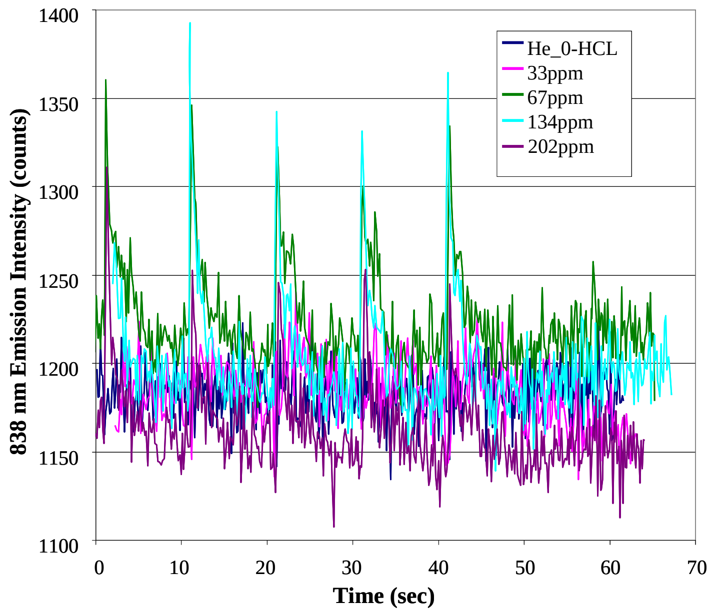

Figure 29 HCl injection and detection at 838nm wavelength

The data in Figure 29 show peaks indicative of HCl preconcentration and injection. The signals were recorded using the MDD detector. The MDD detector was set to an integration time of 20ms, a 50Hz sampling rate. The manner in which the HCl vapor was generated created both water and HCl vapors. Testers observed that the overall brightness and resulting signal intensity of the MDD was significantly lower after the HCl and water vapor streams were introduced. Fortunately, this diminished signal still allowed HCl specific signal to be recorded. The data in Figure 29 show the average emission at 838 nm. This wavelength was chosen as it appeared only when HCl was introduced to the PHASED analyzer. Four replicate injections were performed and the 838 nm region of the emission spectra recorded.

These early experiments showed effective preconcentration and injection of HCl vapor. However, the data were not without oddities. For example, within Figure 29 there is a gradually increasing signal intensity of the 838nm wavelength emission from 0 ppm through 134 ppm, as expected. However, at 202 ppm of HCl the signal intensity decreases. At the time of the experiment, this was hypothesized to be due to the increased presence of water vapor. Water vapor was known to reduce the intensity of the optical discharge and thus all analyte signals. The UOP specification was a minimum detection level of 600 ppm. The data above provided evidence of PHASED-NeSSI system's capability to meet this specification. As such, the program focused on moving towards a more realistic calibration.

The next phase of development began several months after recording the data presented in Figure 29. When the experiments resumed, the PHASED preconcentrator fluidic channels were realized to contain several leaks. The PHASED-NeSSI system was disassembled and the PHASED chip delaminated to investigate the source of the leaks. Two silicon substrates combine to form the fluidic channels of PHASED. The two chips are hermetically sealed with an indium solder. Figure 30 below shows the direct comparison of the delaminated leaky chip that had been exposed to HCl and H_2O vapors and a virgin delaminated PHASED device. The left half is a virgin device; the right half is a leaky device that was previously exposed to HCl and H_2O vapors.

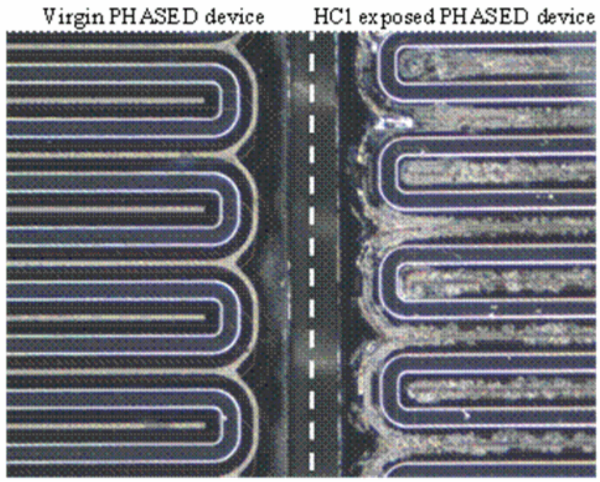

Figure 30 Side-by-side photographs of delaminated PHASED devices

Upon investigation of the delaminated devices, we hypothesized that corrosion of the indium solder by a combination of HCl and H_2O caused the leaks. The photographs above and others clearly reveal additional materials around the bond areas on the chip that was exposed to HCl and H_2O vapors. Closer observation revealed an opaque residue, which may be a residual "salt" from a reaction with the HCl, H_2O, and the metals used the PHASED device. Interestingly, the nanozeo adsorbent was not observed to have changed appearance after the HCl exposure. Although the degradation of the PHASED devices was concerning, the team moved forward with the application testing. The team reasoned that the corrosion of the PHASED device was caused by a combination of HCl with water vapor; however, a deployed system would not contain any water vapor. From the early experiments, the apparent sensitivity to HCl and speed of response met all of the specifications.

The early experiments were fairly qualitative owing to the method of producing HCl vapors and the large differences between the laboratory gas stream compositions and those that exist in the actual UOP process. Honeywell's next step in development was to more closely approximate field conditions within the lab to evaluate the PHASED device. The main means of approximating the true process stream was to create a high concentration of pentane within the gas. Several difficulties emerged when increasing the pentane content of the analyzed stream. At high concentrations (% level) of gaseous pentane in He, the MDD detector's optical signal began quenching dramatically. An investigation into the cause was carried out, as examined below.

At pentane concentrations of 9000ppm (0.9%), the MDD's discharge began quenching. This was manifested in an approximately 90% lower intensity signal than in He alone. Furthermore, the signal sporadically changed 10-20% in amplitude within a second. This change was not reproducible or predictable. The end result was a near complete elimination of signal within 30-40 minutes of introducing the high pentane concentrations to the MDD detector. This behavior was not accompanied by any change in the electrical characteristics of the MDD detector. The intensity could be temporarily restored by adjusting the drive frequency, duty cycle, or applied voltage of the MDD detector. The increase in intensity was quickly followed by another progression through the quenching cycle. Interestingly, once the MDD quenched subsequent investigation revealed an increased pressure drop across the MDD. This drop would be indicative of a narrowing of the fluidic channels through the MDD. Several methods of opening the fluidic channels were attempted without success. One method that worked was to draw air through the MDD while driving the discharge with a higher voltage than in normal operation.

After several hours, of this process the pressure drop decreased but never recovered to the level of a newly assembled MDD.

This data supported a hypothesis that the cause of the MDD quenching was the gradual build up of partially oxidized pentane. The low oxygen, high temperature environment of the MDD could create soot that gradually accumulated in the ferrule or exhaust port, eventually blocking flow, increasing the pressure, and quenching the electrical discharge. The dramatic reduction of signal intensity of quenched MDD prevented successful HCl detection—the team focused on preventing the quenching process.

If partial oxidation of the pentane caused the flow restriction and subsequent quenching, then complete oxidation might solve the problem. To this end, laboratory streams were created that approximated the UOP stream but with varying amounts of O_2. The early results with high pentane concentrations (9000 ppm) in He with 20% O_2 proved promising. The MDDs did not quench after greater than 12 hours of continuous operation. The optical signal from the plasma remained high. With the quenching apparently solved, specific HCl emission lines within a mainly He carrier gas were recorded. The specific emissions of HCl recorded on a 2500 ppm concentration in an He carrier gas are below if Figure 31.

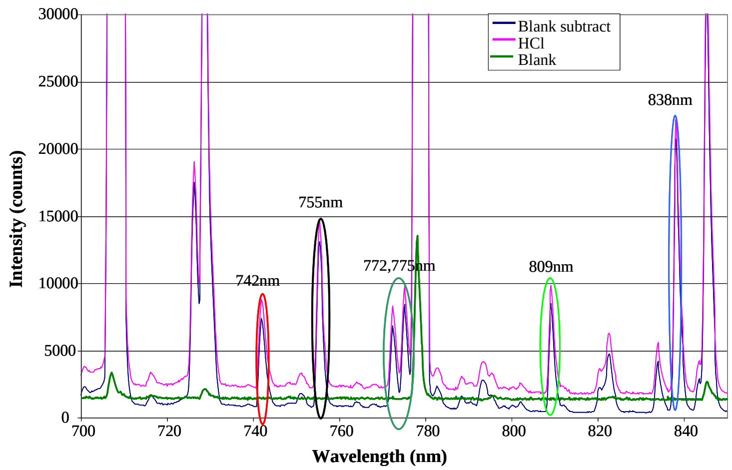

Figure 31 Specific emissions for HCl in He recorded with the MDD detector

The emissions that are specific to HCl are circled at 742, 755, 727.7, 809, and 838 nm in Figure 31. Each has a good signal to noise ratio that suggests an overall sensitivity able to meet UOP specifications. These promising results convinced the team to begin calibrating the PHASED NeSSI device using high concentrations of background pentane, to more closely approximate field conditions, and added oxygen to prevent quenching. The results of this calibration are below.

The signals from the HCl specific emissions were dramatically quenched when introducing even small flows of pentane and oxygen. In an effort to discover more about the MDD's behavior, a design of experiments was performed to determine the HCl emission's sensitivity factors to the presence of oxygen and pentane. The first set of experiments maintained the ratio of two of the three gases in the stream while varying the third. The results revealed that the HCl emission intensity was highly sensitive to the relative amounts of oxygen and pentane present. This results in a dramatically higher limit of detection for HCl contamination in pentane when oxygen was present than recorded without oxygen in the stream. One calibration curve is presented in Figure 32, below.

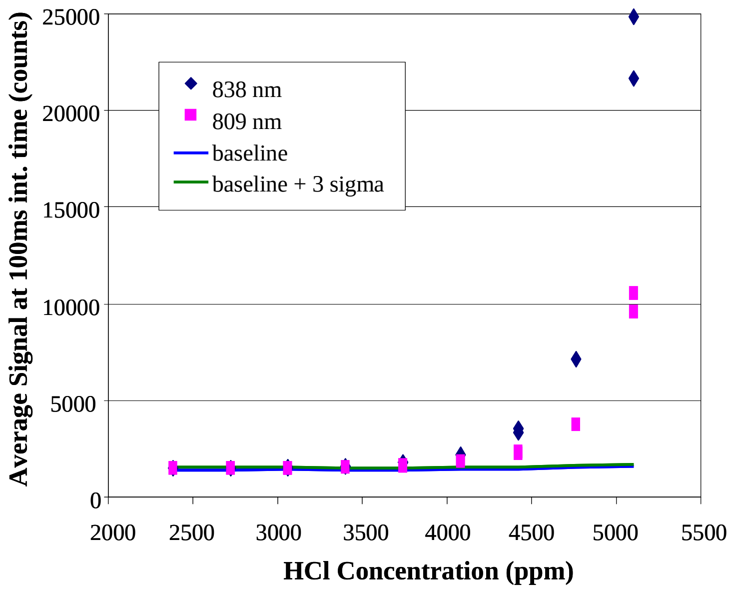

Figure 32 Optical intensity vs. concentration of HCl at 1:1 9000 ppm pentane to oxygen flow rate; resulting LOD is 3750 ppm, much higher than recorded without the addition of oxygen

The non-linearity of the calibration is likely a result of the combined quenching effects of the pentane and O_2. The data presented in Figure 32 is an average of ten emission intensities recorded at a 100 ms integration time. These measurements were taken one after the other; therefore, the standard deviation of the measurement is over a short time period and is not indicative of the true standard deviation of a deployed system. The standard deviations of the signals were left off of Figure 32. The baseline noise around the emission peak (higher and lower in wavelength) was measured peak-to-trough at several locations. That peak-to-trough noise intensity was assumed to represent 5 standard deviations of the noise. This value was used to calculate the baseline and 3 times the baseline standard deviation. Using this approximate 3x standard deviation of the baseline, a limit of detection of 3750 ppm can be supported.

As examined above, the LOD for PHASED-NeSSI in monitoring HCl within a pentane stream gradually worsened as the laboratory experiments more closely approximated real-world conditions. When adding oxygen to prevent system clogging, the resulting sensitivity was too poor to warrant field testing at the UOP site. UOP remained strongly supportive of the PHASED NeSSI program and worked with the Honeywell team to determine if a more appropriate process stream could meet program objectives.

The alternative process application identified by UOP and Honeywell was monitoring impurities in a hydrogen stream. The impurities of interest were CH_4 and CO/CO_2 at concentrations of 1 ppm. The Honeywell team had previously recorded CH_4 and CO_2 emissions from the MDD within an He carrier gas but had not evaluated an adsorbent that could effectively concentrate and inject these light analytes. The approach used the MDD detector alone to measure these analytes.

The first experiments were designed to evaluate the ability of the MDD to create a discharge or plasma within an H_2 stream. The plasma was evaluated according to the relative energy needed to spark the plasma, and the optical signal produced from that plasma. The MDD detector has two electronic control boards. The main difference in the boards is the voltage and frequency supplied to the electrodes to create the plasma. The lower voltage and higher frequency MDD driver was not successful in igniting plasma in 100% H_2. The higher power driver was successful. However, with the higher power required for the plasma to form, the shorter lifetimes as seen in air and N_2 plasmas was hypothesized to exist. Moreover, the optical intensity of the plasma was very low, which makes sense because of H_2 has a limited number of excited states.

The team decided that the lifetime issues could be dealt with if similar signals resulted as with earlier He-based plasmas. Rather than ordering and waiting for analytical standards of CH_4 or CO/CO_2 to arrive, the team used the nitrogen in compressed air as an analyte. When small amounts of He are added to a N_2 stream, the nitrogen emissions are greatly enhanced. Similar enhancements were witnessed for CH_4 and CO_2 in the AirProducts application. An H_2 enhancement of the air emissions would support the ability to meet the required sensitivities in the H_2 stream. The results of this enhancement experiment are shown in Figure 33.

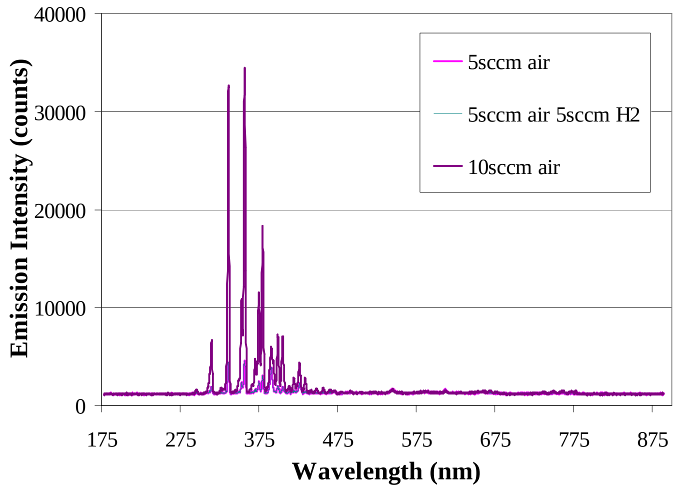

Figure 33 MDD emission spectra indicating hydrogen's lack of signal enhancement of the nitrogen emission lines from air

The data in Figure 33 show that flows of 5 and 10 sccm of air produce very different MDD emission intensities. If H_2 exhibited enhancement effects similar to He, the addition of 5 sccm of H_2 to 5 sccm of air would produce more intense emissions that than of 10 sscm of air alone. Unfortunately, the blend of 5 sccm of air and 5 sccm of H_2 yields a lower emission intensity level (small green trace peak maxima of approximately 4000 counts). This lack of signal enhancement due to the presence of H_2 did not support further effort at investigating if the MDD detector had 1 ppm sensitivities to CH_4 and CO/CO_2.

The three process applications, one from AirProducts and two from UOP, were investigated within the laboratory to evaluate and calibrate the PHASED NeSSI system before field trials. Unfortunately, these tests encountered many difficulties in meeting the required specifications. The chief difficulties were the inability to maintain high analyte sensitivity as the laboratory experiments more closely approximated field conditions. Rather than use the remaining time and funding to deliver the NeSSI system to industrial partner sites and perform field tests that had a very low likelihood of showing the potential energy savings of a deployed NeSSI-PHASED system, Honeywell and our DOE sponsors decided to use the remaining program time and funding to focus on identifying target applications that provided useful energy savings to DOE, was a good technological fit for PHASED NeSSI, and provided additional value to the end customer. For this reason, the Test and Evaluation task was discontinued. An update on the progress of the application identification task is provided in the recommendations section below.

Accomplishments

This program has supported the successful PHASED system development from early design and paper studies through laboratory prototypes and preparation for field testing. Moreover, during execution of this program, NeSSI progressed from a general mechanical layout specification (Generation I), through the recent standardization of remote communications to control NeSSI actuators (Generation II). Of the many PHASED adsorbents evaluated during this program, three have progressed through early prototyping and significant experimental evaluation: Nanoglass, Nanozeo, and OV-5. Each has applicability to a different class of target analytes, detailed above. The off-chip PHASED detector, the MDD, was developed under this program. This multivariate detector has proven to be very versatile. It can be used in He, Ar, N2, or air carrier gases to detect gaseous TICs, TIMs, and organics at ppm or lower levels. As a chromatographic detector, it is capable of adding selectivity to a chromatographic system and opening up higher ordered data processing techniques. The PHASED NeSSI system has proven to be sensitive to a wide variety of process analytes. The originally proposed field demonstrations were not carried out for a variety of reasons. Chief among those was the delay in agreeing to NeSSI Generation II standards, and the mismatch between the current PHASED capabilities and the energy intensive processes of most interest to the DOE. Honeywell and several large partner companies continue to support PHASED development. At the writing of this report, the teams continue to investigate new chemical processes that stand to substantially reduce energy consumption via advanced control and optimization enabled by PHASED NeSSI systems.

Publications & presentations

U. Bonne, R. Higashi, K. Johnson, N. Iwamoto, R. Sacks, R. Synovec, “Stationary phase films for microanalytical measurements”, PittCon 2005, Orlando, FL, USA, 27 Feb.–4 March 2005.

U.Bonne, R.Higashi, T.Marta, F.Nusseibeh and T.Rezachek (Honeywell Labs), and C.Herring, D.Kellner, K.Kunze and M. Castelein (Caviton, Inc), "MicroGas Analyzer for NeSSI and DHS: Measurements and Simulations," PittCon 2006, Orlando, FL, 13-16 March 2006.

N.Iwamoto and U.Bonne, "Molecular Modeling of Analyte Adsorption on MEMS GC Stationary Phases Eurosime, Como, Italy, 24-26 April 2006.

Patents & filed applications

T. Marta, R. Higashi, F. Nusseibeh, A. McBrady, “Micro Discharge Device Capable of Low Voltage Discharges in a Variety of Carrier Gases for Detection and/or Ionization”.

U. Bonne, L. Hilton, “Plug and Play NeSSI Component Lock”.

Conclusions

When proposed, this program was acknowledged to be of grand scope and challenge. Many of the challenges were met successfully. The OneWireless line of Honeywell products speaks to this success. Some challenges, such as the rapid development and acceptance of NeSSI Gen II and III standards, proved significant for the gas sensing portion of this program. As these standards are implemented throughout the various NeSSI deployment sites, PHASED and other NeSSI amenable GCs will continue to be of active interest and R&D pursuit within the industrial marketplace.

One of the main lessons learned during this program is the trade-offs between full-scale and micro-scale GCs. The highly integrated nature of many MEMS GCs provides advantages in terms of chromatographic efficiency, power use, sensitivity, and cost of manufacture. However, the highly integrated nature makes some simple macro-scale processes difficult or impossible at the MEMS scale. One example is changing the stationary phase to address a different range of analytes. Typically, this process takes a matter of minutes within a COTS GC. However, an integrated MEMS GC would likely need to be replaced entirely, and may require significant phase development research to allow the varieties of new stationary phase to be amenable to MEMS manufacturing processes. These considerations can drastically reduce the available market for a MEMS GC.

MEMS-enabled GCs and NeSSI compatible GCs still provide many realized and potential benefits in terms of speed sensitivity and increased ability to perform chemical process control and optimization. Honeywell's contribution to DARPA's PACT, a high throughput gas sensing program relies on PHASED injectors to meet the 300,000 samples per day goals. Additionally, the level of NeSSI and NeSSI GC acceptance continues to expand. Analyzers such as C2V, a NeSSI-compatible mini-GC, are now priming the process chemical markets for wider deployment of Gen II and eventually Gen III NeSSI analyzers.

Recommendations

Honeywell and our DOE sponsors decided to use the remaining program time and funding to focus on identifying target applications (most likely light petrochemical liquid refining) that provided useful energy savings to DOE, was a good technological fit for PHASED NeSSI, and provided additional value to the end customer. Although very supportive, the discussions with potential customers to find the most appropriate process application for PHASED NeSSI has lacked in quantitative information needed to predict accurate energy savings forecasts. The most promising application is that of analyzing cracked gas from olefin plants.

Olefin cracking furnaces are the most promising application for PHASED NeSSI to enter into the petrochemical refining market. The process stream consists of H_2, CH_4, ethylene, ethane, acetylene, propylene, and propane. Current analysis is typically carried out by a process GC-MS at a 6-minute cycle time. One instrument is centrally located and is responsible for monitoring several crackers. This approach results in a relatively slow point-to-point measurement time for one cracker. Olefin cracking furnaces are typically 50 MW furnaces and each plant has several furnaces. If the rapid sampling rates of the PHASED NeSSI system (4 sec cycle time) enabled better process control and optimization, an improved process yield of 1% should be possible. Under such a situation, a substantial energy savings per unit of product could be realized. Moreover, the olefin cracking process monitoring has many other customer centric divers that support PHASED NeSSI systems. Currently, the downtime in the analytical system is nearly 100% attributable to the sampling systems that direct the sample from multiple crackers to one centrally located analyzer. These sampling lines are typically 50 meters long and get blocked frequently. Moreover, the lines and process sampler at the cracker represent about 40% of the analytical system cost. This high cost and high down time sampling system would be replaced by individual PHASED NeSSI systems at each cracker.

Honeywell continues to participate in NeSSI forums held at the Center for Process Analytical Chemistry, and the International Forum for Process Analytical Chemistry. Honeywell's industrial partners involved in the PHASED NeSSI developments to date, as well as some not directly involved in earlier developments, are moving rapidly towards more modularized, wide-spread, and at-stream process monitoring paradigms. As such, the application possibilities and ease of performing PHASED NeSSI field trials are growing. However, many new classes of analytes require a significant adsorbent development. The relatively new market alone is insufficient to support the high risk adsorbent development. At these conferences, workshops, and subsequent teleconferences Honeywell continues to refine plans for future programs designed to rapidly field test a PHASED NeSSI system using already developed adsorbents. Due to the necessity of extensive participation and buy-in from industrial partners, these future programs are envisioned provide support for both Honeywell development and industrial partner field testing and energy savings calculations. As these conversations and plans become more concrete, Honeywell will continue to involve DOE sponsors as information resources, scientific collaborators, and potential program sponsors.

References/Bibliography

[1] Honeywell OneWireless™ website: http://www.honeywell.com/ps/wireless

[2] WINA documents page: http://www.wina.org/WireSol/Documents/Forms/Default.aspx

[3] ISA100 website: http://www.isa.org//MSTemplate.cfm?MicrositeID=1134&CommitteeID=6891

[4] WCI website: http://www.isa.org/Content/NavigationMenu/Technical_Information/ASCI/ISA100_Wireless_Compliance_Institute/ISA100_Wireless_Compliance_Institute.htm

[5] DOE's Save Energy Now initiative: http://www1.eere.energy.gov/industry/saveenergynow/

[6] NIST Smart Grid interoperable standards project: http://www.nist.gov/smartgrid/

[7] Industrial Wireless PHASED Sensor Phase 1. Feasibility Demonstration, ORNL Subcontract 4000015922 (performed under ORNL Contract with DOE, No. DE-AC05-00OR22725); contact project team or ORNL for more information

Appendix – Wireless

Value Proposition of Wireless to End Users

- Up to 10:1 reduction in capital expenditure
  - No signal wiring or conduit for new points
  - No marshalling area space or termination assemblies
  - No additional I/O cabling into automation system
  - No I&E documentation for wiring and termination interconnect
- Modest reduction in operational expenditure
  - No budget for wiring and conduit maintenance
  - No spares for termination assemblies
- Easy addition of more sensors
  - Significantly improved process operations
  - Additional coverage when primary sensors fail
  - Better process diagnostics
  - Suitable for temporary placement during unit troubleshooting
- Usable where wired connections are infeasible
  - Due to long distance (e.g., piers and quays, pump houses)
  - Due to large common-mode voltage differences (e.g., motors, tank farms)
  - Over water or non-owned obstructions (e.g., roadways)
  - On vibrating, rotating, or moving machinery (e.g., large motors, fans, cranes)
  - Great height: stacks, towers, tanks (e.g., for monitoring emissions)

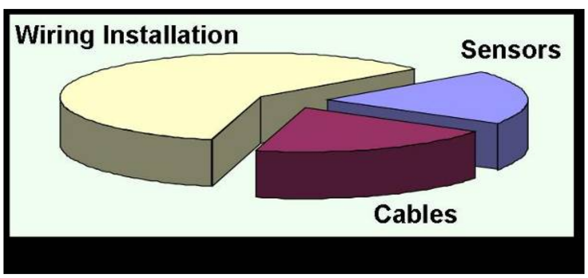

Figure 34 Industrial sensor installation costs

How Energy Will be Saved

- Improved industrial process control leading to improved product quality and fewer process upsets
- Monitoring of steam traps in industrial processes
- Monitoring steam injection devices used in oil production
- Monitoring electric motors used in industrial processes
  - Faster introduction of new sensor and analytical technology
  - Condition-based diagnostics and maintenance resulting in fewer unexpected shutdowns
  - Ability to deploy temporary sensing to solve in efficient control problems

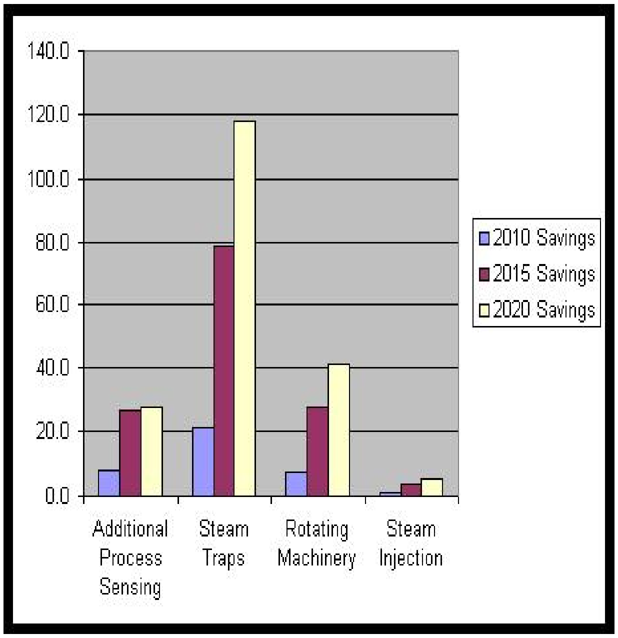

Figure 35 Estimated energy savings

Economic Impact of Wireless

Inventory management – wireless offers 6.1 month payback with ~4x impact.

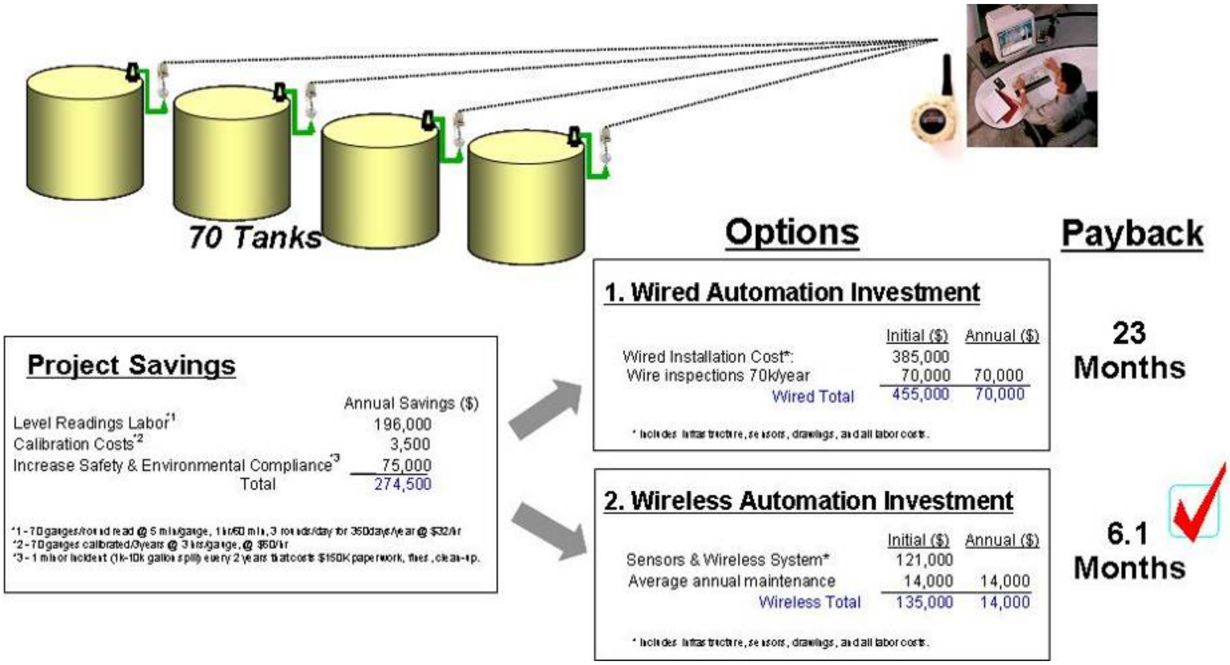

Figure 36 Wireless economic impact

Remote safety shower monitoring –

- Required by OSHA First Alert Response guidelines
- Estimated wired system installed cost $1.5M
- Estimated wireless system installed cost $50K

Pipeline pressure monitoring –

- Wireless provides 37% cost savings over wired system
- 50% reduction in maintenance costs
- Increased data and measurement reliability with the elimination of data transmission faults

Bearing temperature monitoring –

- Temp monitoring critical to predict compressor bearing failure
- Wireless eliminates thermocouple failure previously present due to moisture in wiring conduits
- Reduces process downtime and prevents possible employee injury

Rotating equipment temp monitoring –

- Temp monitoring inside rotating lime tunnel kilns needed for product quality
- 60-80 rotations/hour, 500degF—significant time and energy cost savings possible
- Wireless helps avoid scrap product

Wireless Applications Enabled by OneWireless

Note: the bullet points below are hyperlinks. Description of these applications can also be found at [1].

Safety

- Location and Mustering
- Remote Video
- Safe and Reliable Operations
- Safety Showers
- Smoke Detection
- Employee Safety During Project Staging

Reliability

- Cement Rotating Kiln
- Compressor Motor Bearing Temperature in an Alki-Unit
- Corrosion Monitoring
- Equipment Health Monitoring Solution Helps Protect Employees and Improve Productivity on a Floating Tanker
- Gas Consumption Monitoring
- Leak Detection and Repair for Fugitive Emissions
- Monitoring Bearing Temperatures in a Tandem Cold Rolling Steel Mill
- Remote Analytical Measurements

- Rotating Drier Monitoring
- Rotating Kilns
- Steam Trap Wireless Monitoring Solution for Steam Leak Detection
- Steel Mill Applications
- Tank Farm Automation
- Temperature Monitoring in the Pharmaceutical Industry

Efficiency

- Aircraft De-Icing
- Employee Efficiency
- Energy Efficiency
- Extend the Wired Network
- Improve Advanced Control
- Leach Pad Monitoring
- Plant-wide Wireless Network Assessment and Installation
- Power Generation Industry Applications
- Project Staging Area Efficiency

Success Stories

Success stories in the following industries can be found at http://hpsweb.honeywell.com/Cultures/en-US/Products/Wireless/ProvenSuccess/default.htm

- Chemicals
- Life sciences
- Metals, mining and minerals
- Refining
- Oil and gas
- Others