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Wireless Interfaces for IEEE 1451 Sensor Networks

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Abstract

NIST started working with industry and the Institute of Electrical and Electronics Engineers (IEEE) in the mid 90's to develop a standardized interface to network smart sensors. With the spread of wireless technology, more industries are looking to incorporate wireless communications into their products and manufacturing processes. This paper discusses the IEEE 1451 standard interface for smart sensors, emerging wireless communication technologies, and possible solutions for creating a wireless interface for the IEEE 1451 standard.

1. Introduction

Sensors are an essential component of closed-loop control systems. They are used in all industries for all types of applications from monitoring a machine tool in a manufacturing plant to control of a process in a chemical plant.

Traditionally, using sensors meant that long cables were needed to connect each sensor back to a centralized monitoring or control station. Each cable may have contained multiple wires for both power and sensor data. When working with a small number of sensors, this may not seem like a daunting task to wire, but consider the number of sensors in some practical applications. For example, dozens of sensors may be used to monitor various thermal parameters in a manufacturing facility; thousands of sensors monitor the heat shield tiles on the Space Shuttle; tens of thousands of sensors monitor current naval vessel's condition and performance.

By networking sensors together similar to linking personal computers via a local area network (LAN), it is possible to connect many sensors via a single cable or bus. All sensor data can be sent through this cable using network communication protocols. Each sensor node on the bus, like a computer on a LAN, can easily be detached without affecting the other sensor nodes. This makes installation and upgrading the sensors much easier.

However, the conventional way of networking sensors means that the centralized controller polls all the sensors and processes all the sensor data in real time. Each sensor might only have a small amount of data to transmit over the bus, but if there are hundreds or thousands of sensors over the same bus, it can cause a bottleneck for the sensor data. By increasing the intelligence of the sensors, such as having them perform signal processing, algorithm execution, or decision processing, control functions are moved down to the sensor level. Taking this approach, only processed sensor data, control commands, and status information is transmitted over the bus. As a result, the amount of data on the bus is greatly reduced, decreasing the bandwidth requirements for the network or allowing more sensors to be added. This approach, referred to as distributed measurement and control [1], takes full advantage of the benefit of smart sensor networking.

NIST started working with industry and the Institute of Electrical and Electronics Engineers (IEEE) in the mid-90's to develop a standardized interface to network smart sensors. Last year, an exploratory project was initiated at NIST to study the feasibility of adopting wireless communication technologies and standards for networking wireless smart sensors.

2. Background

2.1 IEEE 1451 Smart Sensor Interfaces

In March 1994, NIST and IEEE's Instrumentation and Measurement Society's Technical Committee on Sensor Technology sponsored a workshop in Gaithersburg, MD to discuss smart sensor communication interfaces and the possibility of creating a standard interface. The response was to establish a common communication interface for smart transducers. Since then, four more workshops have been held and four technical working groups have been formed to address different aspects of the interface standard. The P1451.1 working group aims at defining a common object model for smart transducers along with interface specifications for the components of the model. The P1451.2

working group aims at defining a smart transducer interface module (STIM), a transducer electronic data sheet (TEDS), and a digital interface to access the data [2]. The P1451.3 working group aims at defining a digital communication interface for distributed multidrop systems. The P1451.4 working group aims at defining a mixed-mode communication protocol for smart transducers. This family of IEEE 1451 standards is designed to work in concert with each other to ease the connectivity of sensors and actuators into a device or field network [1].

2.2 Needs for Wireless IEEE 1451 Interfaces

Some people may ask "why do I need a wireless interface for my sensor if a wired one works so well?" Certainly there are some disadvantages to wireless sensors due to their complexity and the problems associated with radio transmission. However, the advantages could outweigh those in many cases. Some of the advantages include the absence of costly, time-consuming, and tedious cabling and verification, the lower infrastructure costs associated with sensor installation (i.e. no cables run throughout the facility), the ease of repositioning or removing sensors, the ability for wireless sensors to be deployed in extremely remote and hazardous locations, and so on.

Industry has shown interest in wireless sensor research and applications as can be seen by the number of Small Business Innovative Research (SBIR) and Defense Advanced Research Projects Agency (DARPA) funded projects in the U.S. Recently lawmakers in the U.S. Congress enacted H.R.5164 that calls for new cars and trucks to be equipped with devices to monitor tire pressure. These sensors must measure the tire pressure regardless of whether the vehicle is moving or stopped, in the mountains or desert, and new or old without being manually reprogrammed for all these different conditions. Wireless sensors will probably play a key role in fulfilling the requirements of this legislation for public safety.

Current manufacturing facilities use large numbers of fixed sensors mounted to each machine in a product line. By being fixed to the machines, these sensors do not offer a flexible manufacturing solution and often limit the work area of the machine due to mounting or wiring requirements. In addition, sensors are often duplicated to increase overall system reliability and for diagnostic purposes. With a wireless sensor system approach, a basic set of fixed sensors could be built into a machine and augmented with a host of wireless sensors on an as-needed basis.

Wireless sensors can be easily turned into mobile sensors. Wireless sensor standards could be applied to industries outside the manufacturing world like urban search and rescue (USAR) operations and environmental and hazardous waste cleanup. USAR operations after fires, earthquakes, or environmental disasters often require putting human beings in potentially hazardous situations. While searching for survivors after an earthquake, buildings are very unstable and could collapse at any time. Current technologies for search and rescue operations mostly use sonar or microphones to listen for people trapped in collapsed buildings. Rescuers drop microphones or other sensors into the structure with gravity as the only means of delivering a sensor deeper into the structure. Small mobile sensors (about the size of a mouse) could be deployed to "look" for survivors in an area under the supervision of a central control system. Rescuers could release many of these sensors into the building and search large portions of the structure at the same time. Mobile sensors with microphones, life detection, and global position system (GPS) capabilities could pinpoint the location of a survivor to be rescued.

The application of movable or mobile sensors could also make an impact in environmental disasters. Nuclear and toxic hot zones take a large investment in equipment and workers to clean up. Small, mobile sensors could be taken into the hot zones by a remotely operated "mother" and then released into the area. The "children" would then send back information about the concentration and extent of the contamination for a particular area.

A wireless communication system developed with MEMS technology and an IEEE 1451 sensor standard could be used as a "sensor skin" that could be painted onto any mechanism. Such a "skin" would remain passive until illuminated by a power source, such as a focused microwave beam. The activated sensors would then report back their current sensor readings.

2.3 Workshop on Wireless Sensing

The first Wireless Sensing Workshop was held on June 4, 2001 at the Sensors Expo/Conference at the Rosemont Convention Center in Chicago, IL. NIST, SENSORS magazine, Sensors Conference, and the IEEE Instrumentation and Measurement Society's (I&MS's) Technical Committee on Sensor Technology (TC-9) cosponsored the workshop.

In response to the industry's interest in wireless sensing, NIST initiated, cosponsored, and conducted this workshop to explore this interest. In addition, state-of-the-art, wireless communication technologies were examined. This workshop provided a good opportunity for representatives from industry, academia, and government to get together and discuss the possibility of a standard for wireless sensing in an open forum setting. Ninety people representing the manufacturing, process control, aerospace, home automation, automotive, and government sectors participated at the workshop. The ratio of attendees was approximately 4/2/1 for users/sensor vendors/network vendors, respectively.

The workshop opened with an overview of the IEEE 1451 standard. NIST's reference implementation of the IEEE 1451.1 smart transducer information model and the investigation of interfacing the 1451.1 model to the wireless world were discussed. Then various wireless technologies such as the wireless Ethernet standard (IEEE 802.11*x*) and

Bluetooth[1] were presented in detail. Following that, hardware and software tools that could help speed up wireless application development, as well as the application of wireless Bluetooth technology for sensors, were presented. One presentation proposed a wireless sensor interface standard, a potential IEEE P1451.5, using the IEEE 802 as a guideline for managing the IEEE 1451 framework [3].

After briefing the attendees on various communication interface standards, an open forum discussion began. Attendees provided input regarding their needs and general requirements for a wireless sensor communication interface. The results of the discussions are presented in the workshop proceedings [4].

3. Wireless Communication Technologies

Quite a few emerging wireless communication technologies are being developed today, such as IEEE 802.11*x* (wireless Ethernet) and Bluetooth [5]. These standards have been primarily developed for use by the personal computer (PC) industry or PC-related products, like personal digital assistants (PDA) and printers. The question that sensor vendors and users have is, “can these technologies be adopted for sensor applications?”

The IEEE 1451 standard provides a framework for setting up common interfaces for connecting smart sensors to a network. This will allow sensors “plug-and-play” access to microprocessor-based instrumentation systems and networks. The following sections provide a small subset of technologies that could be adopted by the IEEE 1451 standard for smart wireless sensors.

3.1 Low-Speed & Bandwidth Communications

Low-speed wireless communications have been around for decades. Spacecraft and satellites have been using this technology since their inception. For sensors, RS-232 has been the primary communication protocol for low-speed wireless technology. The carrier frequency used may be at tens to hundreds of MHz, however, the bandwidth of the data communications is typically between 9.6 kbps and 19.2 kbps.

Although this technology is old, there are still many valid uses for it. With the low-speed and low-bandwidth comes increased transmission range and reliability for the data. These signals can be transmitted over kilometers, where higher bandwidth signals may be restricted to several hundred meters or less. Another benefit is that low-speed communications can be used in much more rugged environments due to their higher noise immunity. Manufacturing plants may have large numbers of metal pipes, walls, electric motors, or other large equipment that may affect a wireless signal. With the increased transmission range, it is possible to bounce the signal off obstacles and reach places where high-speed communications could not go.

3.2 High-Speed & Bandwidth Communications

The most notable high-speed communication technologies currently used are IEEE 802.11*x* and Bluetooth. These technologies are gaining strength in the PC industry, and people in the manufacturing industry are looking for ways to use these technologies for their applications.

Ethernet, a thirty-year old technology, has migrated from the office to the manufacturing floor. Engineers have found it useful to be able to access a machine controller via Ethernet for remotely diagnosing problems, uploading software, and monitoring performance. With the increasing popularity of wireless Ethernet in the PC world, it is not surprising that more engineers are looking toward wireless Ethernet to solve some of their problems.

IEEE 802.11 [6] consists of multiple standards based on different physical media, transmission speeds, and frequency characteristics. The original 802.11 specification uses a carrier frequency in the Industrial, Scientific, and Medical (ISM) band of 2.4 GHz (2.402-2.480 GHz) with a data transmission rate of 1-2 Mbps. It is a direct extension of the IEEE 802.3 [7] specification to the wireless domain. This standard allows for three different transmission technologies: Frequency Hopping Spread Spectrum (FHSS), Direct Sequence Spread Spectrum (DSSS), or Infrared (IrDA). FHSS is a process where the 2.4 GHz band is split up into 79 separate channels each 1 MHz wide. Approximately once every 100 ms, the frequency shifts to another channel out of the 79 available. There are 22 different hop patterns used by the frequency controller, and all of them follow a pseudo-random sequence. FHSS is fairly good at avoiding specific noise frequencies due to this hopping characteristic. Instead of hopping between multiple channels, in DSSS, the signal is overlaid upon a particular sequence of 11 bits called a Barker sequence. Three sets of channels are assigned from the 78 MHz available in the bandwidth, each 22 MHz wide. These channels allow 11 MHz of data each to be transmitted instead of FHSS’s lower bandwidth of 1 MHz. IrDA uses infrared to transmit data between devices instead of the radio frequency (RF) energy used by FHSS and DSSS. IrDA is only available in the original 802.11 specification and is primarily used as an interface between portable computers and printers.

IEEE 802.11 also has multiple additional variations. IEEE 802.11a [8][9] promises speeds of 6-54 Mbps by using the 5 GHz ISM band (5.15-5.35 GHz). It also uses a different technology for transmission called Orthogonal Frequency Division Multiplexing (OFDM). This technology allows for multiple channels of data to be sent simultaneously, thus increasing the overall bandwidth of the signal. 802.11a is, however, not backward compatible with the original 802.11 specification since it uses a different frequency and transmission technology. IEEE 802.11b [10] uses the same 2.4 GHz ISM band that the original 802.11 specification uses but restricts the user to only using DSSS. With this restriction, the full 11 MHz of bandwidth is available to the device.

[1] The BLUETOOTH trademarks are owned by Bluetooth SIG, Inc., U.S.A.

Instead of being created by a formalized standards process, Bluetooth[1] was created by a consortium of companies, currently with over 1300 members. Bluetooth uses the same 2.4 GHz ISM band that IEEE 802.11 specifies, however, it uses FHSS with a hopping frequency of 1,600 hops/sec, where 802.11 uses about 10 hops/sec. Bluetooth has been designed mainly for use in Personal Area Networks (PANs). PANs allow devices in the same office to talk to one another without having to be wired to a network. This would allow situations like a PDA to talk to a printer or desktop computer, a computer to talk to a digital camera, or a laptop to connect to a presentation projector. Bluetooth has typically been designed for 1 mW output for a 10 m range, however, some systems have been designed to use 100 mW output power that would increase their range to 100 m.

Bluetooth is designed as a master-slave system. The "master" of the PAN establishes the hopping frequency and allows devices to join the network. "Slave" devices in a Bluetooth PAN can be in one of four modes of operation: active, hold, sniff, and park. Active devices are recognized as part of the network, have a network address, and remain synchronized with the hopping frequency of the master. In hold mode, the master will not send any packets to the slave device for an extended period. The slave device stops its synchronization with the PANs hop frequency and relinquishes its network address. This mode is typically used when a device needs to sleep for extended periods of time or when it is searching for other networks in the area. In sniff mode, the device stays in a semi-active mode, listening to the network at regular intervals to see if the master has sent a message. These devices remain synchronized with the hopping frequency and keep their address. If the master inadvertently sends data to a device in sniff mode while it is sleeping, the data will be lost. Another mode of operation available to the slave devices is park. This mode allows the devices to remain in synchronization with the hopping frequency, but does not maintain the network address. By remaining in synchronization with the hopping frequency, the time taken to return to the network is reduced significantly.

3.3 Low or Ambient Powered Wireless Sensors

Most sensors require an energy source, such as an electric power supply or battery, to power the sensing element and associated electronics. That means that a power cable or battery must be attached to the sensor. With today's microelectronics and MEMS-based sensors, size matters, and there may not be room for connectors or batteries that are many times the size of the sensor itself.

Low-power wireless sensors would be useful in locations where maintenance is performed regularly and batteries could be changed as part of that maintenance. These types of sensors would need to run for years on a small battery. The electronics for these types of sensors would need to be designed for extremely low-power usage in order to conserve battery life for as long as possible.

Another way to power sensors would be to have them draw power from their surroundings, hence the name ambient-powered sensors. A power conversion device would be designed to take energy from heat, light, sound, vibration, or any other source of energy available from the environment. Many devices using this type of technology are encountered in our daily life today. For instance, the security tags at some retail stores are basically simple RF sensors that take energy from a transmitter by the door of the store, modulate that energy, and retransmit it. A set of receivers, also located around the door, get this signal, and send out an alarm. While these are very simple sensors, they have become ubiquitous to most people. If technology could be developed to store up enough energy to transmit a longer range signal, it would be possible to use ambient-powered technology for wireless sensor solutions.

4. Potential Solution

In examining the IEEE 1451 architecture, as shown in Figure 1, for the most appropriate place to insert the wireless communication interface, two possibilities emerge. One, the wireless communication electronics could be integrated into the Smart Transducer Interface Modules (STIMs) as shown in Figure 2. STIMs, as defined by the IEEE 1451.2 specification [11], consist of sensors and/or actuators, signal conditioning circuitry, and digital data output. By incorporating the wireless communications at this low level, it would be possible to use these sensors virtually anywhere. As described earlier, cases like painted on MEMS devices or security tags would be extremely low-cost devices and would probably not consist of much circuitry other than a wireless transmitter. On the other hand, relatively high-cost sensors could absorb the extra cost for incorporating wireless communication electronics in their development.

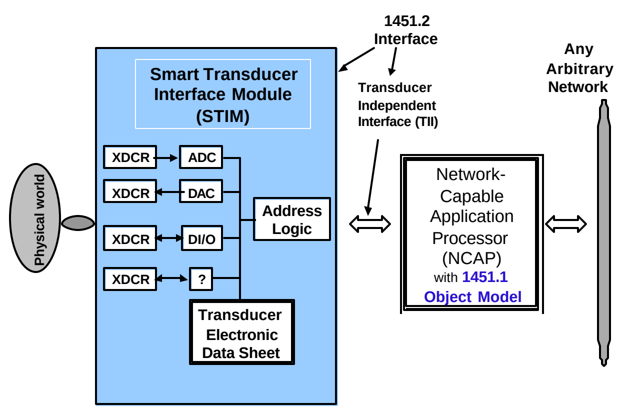

Figure 1 - IEEE 1451 System Diagram

The other possibility would be to have one or more STIMs hard-wired to a Network Capable Application Processor

(NCAP) node as shown in Figure 3. NCAPs are defined in the IEEE 1451.1 specification [12] as sensor network nodes. NCAP nodes allow multiple sensors to be attached to the network using one common point of access. These allow the communication portion of the sensor network to be taken out of the sensors themselves and distributed between multiple sensors via a separate piece of hardware. The STIMs would be hard-wired to the NCAP node similar to today's sensors. However, the NCAP node would have a wireless link to the main wired network through a gateway. By removing the wireless hardware from the STIMs, the overall cost of the sensor system would be reduced in many cases. The investment in wireless communications could be spread between all the sensors attached to each NCAP node. In addition to reducing initial investment costs, current manufacturing facilities could be retrofitted with these types of wireless links without having to replace all of the individual sensors in use. During the Workshop on Wireless Sensing mentioned above, an informal survey was taken as to how many sensors or STIMs should attach to any one NCAP node. Most people favored 8-32 sensors per node, with a very few people wanting as many as 256.

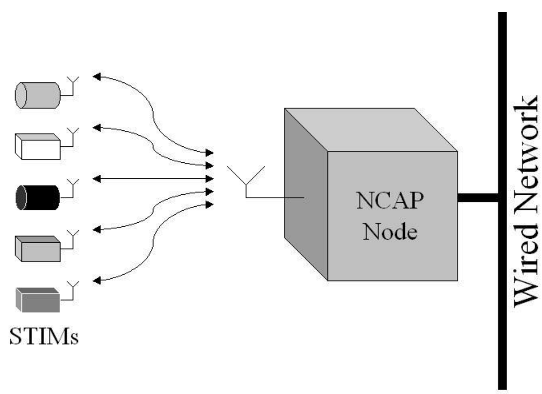

Figure 2 - Wireless STIMs

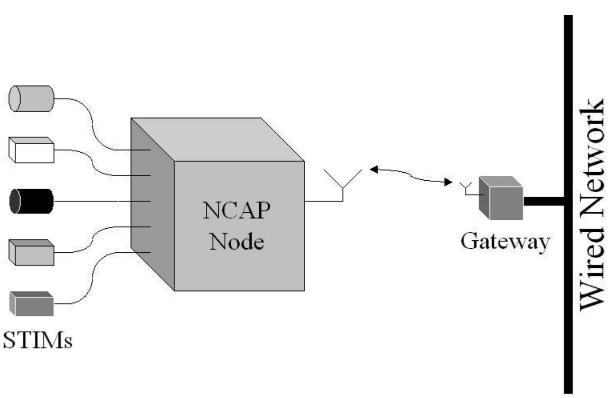

Figure 3 - Wireless NCAP Nodes

It may be necessary to look into whether multiple physical interfaces and protocols are needed in the 1451 architecture to meet industry's need for various data rates and bandwidths. There seems to be enough differences between the low and high-speed sensor communities that multiple standards within the IEEE 1451 framework may be necessary to meet the needs of the two worlds, unless there is a way to define the specification to accommodate the requirements of both groups. This can also be a way to break out discussions of power consumption as well, since the high-speed community may not have the same requirements for power consumption as the low-speed community.

5. Second Wireless Sensor Workshop

According to the manager of the Sensors Conference, the first Workshop on Wireless Sensing at the June 2001 Sensors Expo & Conference was an overwhelming success because the number of attendees was three times as expected. This wireless sensing workshop has created a significant amount of interest in the sensor industry. Workshop participants requested that a "follow-up" workshop be organized at the next Sensors Expo & Conference in Philadelphia, PA to further explore the appropriateness of a wireless interface standard for smart sensors. The second workshop will be held on Thursday, October 4, 2001.

At the second workshop, alternative wireless communication technologies for sensors will be examined. In addition, the workshop will focus on features necessary for inclusion in a wireless sensor interface standard. Finally, the workshop will consider the formation of an IEEE Wireless Sensor Interface Study Group and explore options for the next step in moving this technology forward into a standard.

6. Summary

Industry seems to be interested in incorporating wireless sensors and interfaces into their products and manufacturing processes. A wireless sensor interface is proposed to be integrated into the framework of the IEEE 1451 smart transducer interface standard. An IEEE study group will probably further explore this idea, along with wireless sensor interface requirements. Then a standard committee will probably be formed under IEEE I&MS TC9 to pursue the development of a set of wireless sensor interface specifications that would satisfy the needs of different groups of sensor users and manufacturers. In order to meet the needs of the emerging sensor market, the wireless sensor interface standard specifications may be done in a very timely fashion by incorporating multiple existing wireless protocols such as IEEE 802.11b, Bluetooth, and others into the IEEE 1451 framework.

7. References

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