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Wireless Industrial Monitoring and Control using a Smart Sensor Platform

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Abstract— **A wireless smart sensor platform (based on patent pending technologies [1, 2]) targeted for instrumentation and predictive maintenance systems is presented. The generic smart sensor platform with 'plug-and-play' capability supports hardware interface, payload and communications needs of multiple inertial and position sensors, and actuators, using a RF link (Wi-Fi, Bluetooth, or RFID) for communications, in a point-to-point topology. The design also provides means to update operating and monitoring parameters as well as sensor/RF link specific firmware modules 'over-the-air'. Sample implementations for industrial applications and system performance are discussed.**

I. Introduction

INTELLIGENT wireless sensor-based controls [3] have drawn attention of the industry on account of reduced costs, better power management, ease in maintenance, and effortless deployment in remote and hard-to-reach areas. They have been successfully deployed in many industrial applications such as maintenance, monitoring, control, security, etc [4]. In this research, the focus is on the issues of portability, reliability, flexibility and robustness while using wireless connectivity in industrial applications such as instrumentation and predictive maintenance, and to design a workable solution. This paper extends our earlier work [5] by expanding the scope of the applications; investigate design choices for the proposed system, and presents detailed experimental results of the implementations with their analysis.

The proposed Smart Sensor Platform is an attempt to develop a generic platform with 'plug-and-play' capability to support hardware interface, payload and communication needs of multiple sensors, and actuators. An RF link (Wi-Fi, Bluetooth, Mote or RFID) facilitates communications in a point-to-point topology. The design also provides means to update operating-, monitoring- parameters, operational thresholds, and sensor and RF link specific firmware modules 'over-the-air'. It is composed of two main components – a sensor-wireless hardware interface and system integration framework, which facilitates the defining of interaction between sensors/actuators based on process needs. The intelligence necessary to process the sensor signals, monitor the functions against defined operational templates, and enable swapping of sensor and RF link, resides on the microcontroller of the hardware interface. A variety of industrial sensors (position, accelerometers, gyros, temperature, shock etc.) and actuators (motors) have been interfaced and successfully tested with the platform. The key contribution of this work is the versatility of the developed system and its ability to be configured for diverse applications. The system built using COTS components is modular, extendable and cost effective.

The organization of this paper is as follows. Section 2 covers potential industrial applications to benefit by wireless connectivity. Section 3 is the discussion on sensor networks related work, and specific initiatives for industrial automation. Section 4 describes the application scenario in detail, and discussion of the proposed intelligent wireless sensor architecture constitutes Section 5. Implementation details, snapshots, simulation and experimental results of the current implementation are presented in Sections 6 and 7. Finally, Section 8 reports the conclusions.

II. Potential Industrial Applications to Benefit by Wireless Connectivity

The following are some of the industrial applications of interest for testing the smart sensor platform.

Instrumentation applications are open/closed loop control applications, involving sensors and actuators, where the objective is to control certain parameters (e.g., speed and position), or state of the system. All the system elements may always be in communication with each other, requiring real-time performance and their effect on the control parameters is defined. They also require in-built fault-tolerance capability to tackle communication/physical node failures.

Predictive-maintenance involves tracking the state of equipment/machine/system, and to take action, if they enter a disallowed state. The state could be a diverse set from mechanical parameters (speed or position) to physical parameters (temperature, pH level, etc.). To conserve energy, these applications are not active all the time. They can be further categorized based on their payload transmission intervals into - event-based monitoring, periodic monitoring and store-and-forward systems.

In event based monitoring, a strict violation condition is specified and breach (an event) of which 'wakes' the system to perform a pre-defined action such as recording the violation and/or issuing an alert. Rest of the time it remains in a passive or power save mode.

In periodic monitoring, the state of equipment is periodically determined and a pre-defined action is performed - typically used to monitor equipment use or wear and tear profiles, keeping machine down-times low and help locate the problem before the machine breaks down.

In, store and forward applications, the communication link is not available all the time and the system has to store the data and forward it when the link is available. The link unavailability can be due to channel problems - interference, noise, etc.; or to improve overall system performance - scheduling in a group to prevent data collision in an open-access channel or for improving battery life by buffering the transmission data.

The applications above employ different types of sensors and actuators (mentioned earlier), having different capabilities, interfaces, and supporting different protocols for data and communications. Formation of systems from such diverse distributed sensor elements entails versatile control modules. In addition, the operational challenges are exacerbated when different RF links have to be used to satisfy the requirements of bandwidth, payload, delay, jitter, range, noise immunity and others (including cost) for communication.

III. Related Work

The field of automation has continuously evolved- starting from early days of register level programming for data acquisition and point-to-point wired links for communication, to the current virtual instrumentation and Ethernet, a wired communication paradigm for networking industrial systems. Developmental efforts in this area can be broadly classified as:

A. *Industrial Initiatives*

Include the design of industrial open protocols for wired communication also known as field buses like CAN, DeviceNet and ControlNet; proprietary system formation tools - Virtual Instruments from National Instruments, Factory solutions from ABB, etc. Further development involved open data exchange or messaging framework, for e.g. OPC foundation which is trying to establish a standard data exchange standard so that interoperability among products (hardware and software) from different manufacturers is achieved [6, 7]. Strong potential for wireless is envisaged in enterprise-wide asset monitoring and maintenance on an open protocol for communication like ZigBee. Industrial initiatives, though, have focused on the system formation issues, but have been unable to exploit the advantages of wireless technology.

B. *Academic Initiatives*

Early work in the field of wireless sensor networks was started with DARPA’s military surveillance and distributed sensor network project, low-power wireless integrated micro-sensor (LWIM) and the SenseIT project. The Wireless Integrated Network Sensors (WINS) project and NIMS project [8] at UCLA in association with the Rockwell Science Center, deals with ad-hoc wireless sensor network research, with a focus on building micro-electronic mechanical sensors (MEMS), efficient circuit design, and design of self-organizing wireless network architecture. These projects are oriented towards environmental and military applications, involving tens of thousands of nodes, and use nonstandard RF communication technology.

The Motes and Smart Dust project [9] at UC, Berkeley focused on creating low-cost micro-sensors, with emphasis on the development of sensors and an embedded operating system, TinyOS. ’nesC’ a product of this project has been utilized for sensor characterization. The project is node-centric, rather than system-centric.

The Pico-Radio [10, 11] project group at UC, Berkeley has developed a power-efficient wireless node using an integrated SoC based hardware implementation for the sensor interface. The aim of the project is to achieve ubiquitous data acquisition from sensors at very low power by using mesh networks.

The field of wireless sensor networks has matured, but the focus has been on environment monitoring, military and homeland security applications. Though viability studies have been conducted for using wireless communication in industrial applications, not much impetus has been given over full system deployment. Application-specific wireless implementations [12] have been proposed but a generic system building approach has not been investigated.

Abstraction of different system elements, a natural step for top-down system building, has been attempted in technical literature. In [13], Mr. Yu et al., have proposed methods to abstract the communication link. In [14, 15], the authors have proposed a unified wireless application interface called Sensor Network Service Platform (SNSP) that abstracts the sensor, and through use of two tools Rialto and Genesis a system can be designed based on application needs. The design presented is novel and effective but is tailored for query/response applications only.

Several research efforts have concentrated on the design of middleware for sensor network applications too. In [16], the authors have proposed a middleware, called MiLAN, which is generic enough to operate using any wireless technology, Bluetooth, WiFi or other. The targeted applications, however, are environment surveillance or data acquisition applications. The Cougar project [17] and Mate project [18] consider the sensor network as a database and have developed query/response based models. Though they do bring in the concept of distributed queries and hierarchical data aggregation, implementation of instrumentation applications using the techniques developed is not feasible. For more details on the issues faced by a sensor network middleware please refer to [19].

Deployment of wireless infrastructure in industries will occur incrementally and interoperability (between different systems) and extendibility (different application needs) will form the requirements of prospective solutions. This smart sensor platform research initiative is an attempt to develop such an end-to-end solution with support for incremental deployment, extendibility and scalability.

IV. Typical Application Scenario

The sensor network that we envisage for industrial applications differs from the conventional definition of a sensor network as considered in majority of the technical literature. Reliability of the nodes and lower routing redundancy are key departures from the conventional view of sensor networks in industrial automation scenarios. Another difference is that nodes, although power efficient, often have access to power sources, which facilitates providing different levels of service - enhanced support for sensing and communication for time-critical data, or to be able to ignore this feature for non-time-critical data. The sensor network that we envisage can be compared to "fixed-wireless", where the equipment is static, but uses wireless technology for communication. Design issues of such a sensor network for industrial applications are:

- **Scalability:** Though the number of sensors/actuators etc. which need to be interfaced is less than in a typical sensor network application; scalability still remains an important issue. The idiosyncrasies of the different components of the system have to be carefully examined and considered. For e.g., Bluetooth can support only a maximum of seven connections per device in a piconet setup.
- **Multiple interface requirements: C**ost sensitive; and performance and range present a tradeoff - it may be required that performance be sacrificed for range and vice-versa.
- **System building:** A modular and hierarchical system building technique enhances the system flexibility, robustness and reliability.
- **Fault tolerance:** Level of service guarantee is required from the communication system - in the form of a confidence level for latency in a command/query message.
- **Interoperability:** Interoperability with existing legacy solutions is required. This can be achieved by using open and customizable message passing and network architecture.
- **Energy efficiency:** Though, energy-saving is not critical in system setup and organization of the applications under consideration, the system viability must reckon energy minimization.

V. Smart Sensor Node Design

The motive of the smart sensor project is to create 1) a general purpose hardware interface for diverse sensors and actuators, which can be customized for an application through over-the-air firmware downloads and 2) create a data processing infrastructure at the backend to implement applications. The proposed solution consists of a collection of sensors, and actuators communicating with the central control unit using standard RF-links. The basic scenario is shown in Figure 1. The sensors are directly connected to the central control unit (workstation here) through a RF link, which can be Bluetooth or WiFi.

Each sensor or actuator is equipped with a reconfigurable generic wireless or *smart sensor interface* (SSI). The interface extracts data from the sensors, commands the actuator, and provides a data communication interface to the central control unit. A sensor/actuator coupled with smart sensor interface is termed as a *smart sensor node* (SSN).

A. *Smart Sensor Node: Hardware Design*

The sensors/actuators found in industrial applications can be classified by analog, digital, or serial (or combination of these) signals used for data communication. The SSI interprets sensors/actuators' signals, and converts it into digital data/commands. For this purpose, a 14-bit 200ksps ADC, 8 channel 10-bit 9.6ksps ADC, 4 DACs, 16 GPIO, SPI, and USARTs are used. The hardware design is shown in Figure 2.

B. *Smart Sensor Node: Software Design*

The digital data extracted by the hardware interface has to be bound by a context and processed to convert it into useful information. For example, a reading of 0x1fff of a 14-bit ADC from a linear position sensor may denote 4mm displacement, which may be the information required by the end application and hence communicated. This intelligence of attaching a context is provided by the software that resides on the SSI.

The software design of the node is shown in Figure 2. The software module stack on the smart sensor interface consists of three layers. The bottom layer is the device driver which directly interfaces with the hardware interface and extracts digital data. The device manager (middle layer) interfaces with the device drivers and exposes a multiple-data channel interface to the firmware layer. In the software framework, each sensor/actuator is composed of a combination of digital, analog or serial channels. Establishment of context to the extracted channel data is done at the firmware layer. The firmware layer (top layer) synthesizes the sensor by combining data from multiple data channels. It also implements the application specific functionalities like real-time performance, data communication protocol with central control unit, smart sensor node management, etc.

This separation of data acquisition tasks across three layers in the smart sensor interfaces helps support functionalities such as over-the-air update of parameters, plug-n-play of sensors, multiple sensor support, multiple wireless technology support, universal data interface, etc. As noted in section 1, these features play a key role in making the system portable, extendable and flexible to implement most of the applications.

C. *Application Integration Software*

The application integration software resides on the central control unit and handles application-specific customization of the smart sensor nodes. Based on the Java Beans framework, the software enables formation of systems from discrete smart sensor nodes. Specific description for real-time and predictive maintenance applications is provided in the implementations section.

VI. Implementation

D. Real-Time Control

The objective of this implementation is to demonstrate the non-deterministic real-time performance of the smart sensor node. Deterministic real-time performance cannot be achieved with the smart sensor node as wireless communication is used, which is prone to errors. In order to achieve near real-time performance the smart sensor node tracks the traffic of wireless channels and uses a simple TCP-like congestion control scheme (increase packets linearly and drop exponentially) to regulate the traffic. Once the node senses congestion, high traffic, or connection loss, it brings the node into a "safe-state". The node then simply waits for the central control unit to reconnect or signal degradation to abate.

The system built for demonstration was a proportional gyro-motor-encoder system (Figure 3) where each sensor/actuator pair is connected to a smart sensor interface and uses Bluetooth to communicate with the central control unit. The gyro senses the angular tilt and communicates it to the central control unit, which in turn sends appropriate command to the motor. Further, the encoder attached to the motor tracks the position of the motor. In this application the safe state of the system is to bring the motor to a halt.

E. Predictive Maintenance

A typical factory environment is considered, where the health of the machinery/equipment is regularly monitored and any digressions/violations from the tolerable behavior during operation are recorded. The recorded information of a machine typically consists of information like threshold violations, time of the event, extent of the event, etc. The status of machines is typically checked by a qualified machinist who inspects the machine when the main power has been switched off. Any proposed solution should thus operate passively and data should be stored locally.

In the current implementation, smart sensor nodes, equipped with sensors to monitor the status of a machine, store the health information in a RFID tag. RFID tag is used as a plain wireless non-line-of-sight data storage [9]. In this mode, the maintenance personnel can retrieve the required health information by querying the tag even when the central computer has been switched off, using a handheld RFID reader.

To demonstrate the capabilities, we record every threshold violation of the linear sensor with timestamp. The threshold parameters are set through the application software module during deployment. We use ISO 15693 (13.56 MHz) tags for storing data. These tags have memory ranging from 256 bytes to 2KB. A handheld reader connected to a PDA is used to read tag data. On the PDA, the records are presented in a tabular format. Snapshots of the current implementation are shown in Figure 3. To emulate factory settings, the linear sensor was displaced to violate the set threshold several times. The system was then switched off and using a handheld RFID reader, the violations recorded on the tag were read.

F. Store and Forward Application

Cold-chain monitoring is a supply chain application where certain strict conditions on the physical state of the commodity have to be maintained while it is in transit. Further, physical profile like temperature, humidity, shocks and location data may have to be provided upon delivery or while in transit. For the purpose of this application, GPS (for location), acceleration (for shocks), temperature and humidity sensors will be interfaced with the smart sensor interface. For the wireless interface, GPRS will be used for communication as neither Bluetooth, nor WiFi may be available on highways. The software to use these new sensors and wireless interface can easily be programmed on the smart sensor board.

Further, a host of application scenarios can be considered with this smart sensor node. For example, a simple scenario would be that the node will periodically "wake up" after small intervals (1 min for e.g.), sample the sensor data and update it at one central location, provided GPRS connection is available. In another scenario the sensor data can be just recorded on the on-board flash memory and retrieved later or uploaded at much larger intervals (like 4 times a day).

VII. Experimental Results

Experiments were conducted to study the relevant performance metrics such as link delays, bandwidth with varying distance, traffic and packet bursts. These parameters have a significant effect on the system/application fidelity and responsiveness. Consequently, the parameters will also determine the feasibility of using the wireless platform for specific applications. For example, several systems will not operate correctly if the delay bounds are not met.

Delay performance studies for Bluetooth and WiFi were conducted using an echo-scenario. The CCU (the workstation here) sends a packet to the node and the node echoes back the packet. For Bluetooth, the serial port profile is used hence single-slot packets are sent. The payload is 1 byte. For WiFi, a TCP packet with 1 byte payload is sent. The time difference between transmission and reception of the packet is the round trip delay (or plainly delay). Delay was calculated over varying packet burst size, distance and competing traffic. The results for Bluetooth and WiFi are presented in Figures 4-9.

Varying Packet burst size will determine how the system will respond to bursts in traffic whether it is suitable for large traffic loads or otherwise. For the experiment, packets were sent from the PC and the PC waited till each packet was received back from the node. The overall time elapsed divided by number of packets is the round trip delay of each packet.

Competing traffic is also an important parameter affecting the system performance. Competing traffic can be changed by adding and removing sensor nodes from the system.

To summarize, the effects of the following parameters on delay of Bluetooth are:

- Distance: With increasing distance, the delay becomes larger and jittery.
- Traffic: No considerable effect

- Packet Bursts: Mild effect with performance degrading with more packets per burst

For Wi-Fi

- Distance: Performance degrades with distance, delay increases and becomes jittery.
- Traffic: Performance worsens with increasing traffic. The effect is more pronounced at larger distances.
- Packet Bursts: As time to access channel is constant, bigger payloads experience less per-byte delays

Thus, Bluetooth seems to fit better in industrial application scenarios where limited bursts of data need to be delivered in real-time in a noisy environment. Wi-Fi seems to fit better in scenarios where huge amount of data need to be transmitted in a less noisy environment.

RFID Experiments: Simple experiments were performed to test the reading/writing range of RFID tag and to ascertain whether it can be used in certain industrial conditions. The results are shown in Figure 10. As can be seen from the experimental results, the writing range is always less than or equal to the reading range, and any interference (presence of metal, obstructions, water, etc.), degrades the performance of RFID.

Another important parameter for RFID applications is the reading and writing rate of the tags. Though extensive tests still need to be performed, simple tests yielded a reading rate of ten tags per second, where only the tag-Id was read. Writing rate of 20 bytes/second was achieved on the same tag with data written in blocks of 4 bytes.

VIII. Conclusions

The design and implementation of a wireless smart sensor platform targeted for instrumentation systems and predictive maintenance was discussed and presented. Tests were carried out to determine system performance for both the instrumentation and maintenance applications, and as the results suggest were quite satisfactory. The experimental results show that a sustained near-real-time system can be set up with the smart sensor nodes, and the versatility of the smart sensor interface allows implementing diverse applications.

Future work for the smart sensor platform entails development of multi-hop networking capability among the heterogeneous-radio-equipped smart sensor nodes. A hierarchical network with gateway nodes, network aggregators and end-sensor-nodes is envisaged [20].

Zigbee with its excellent low-power capability provides an excellent alternative for Bluetooth and RFID in terms of power and performance. Support for Zigbee is currently being added and will be reported separately.

Store-and-forward applications like cold-chain monitoring require a long-distance wireless link with network coverage over its entire operation area. GPRS with its wide-area/long-range connectivity and reasonable bandwidth, thus, forms a suitable candidate. Support for GPRS is also being added and will be reported separately.

Acknowledgements

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He has a Doctorate degree from Carnegie Mellon University (CMU), a Masters from Cornell University and a Bachelors degree from IIT Kanpur. He has taught as a visiting researcher at UC Berkeley, has been an Assistant, Associate and Full Professor at University of Wisconsin-Madison, and did his sabbatical as a visiting researcher at Stanford University for a year. He has over 125 papers in journals, conferences and technical magazines, three patents granted and three patents in application.

Dr. Asad M. Madni *is President and Chief Operating Officer of BEI Technologies, Inc., located in Sylmar, California. Prior to joining BEI in 1992 he was with Systron Donner Corporation (A Thorn/EMI Company) for 18 years where he served in various senior level technical and executive positions, eventually as Chairman, President and CEO. He received the A.A.S. degree from RCA Institutes, Inc., B.S. and M.S. degrees from Univ. of California, Los Angeles and the Ph.D. degree from California Coast University, all in electrical engineering. He is also a graduate of the Certificate Program in Engineering Management at the California Institute of Technology, the Executive Institute at Stanford University and the Program for Senior Executives at MIT Sloan School of Management. Dr. Madni is an internationally recognized authority with over 30 years of experience in "intelligent" system design and signal processing. He is credited with over 100 refereed publications in archival journals, conference proceedings and book chapters; over 100 research reports and internal publications; over 100 keynote addresses, invited lectures, chairs and panels; and 34 issued patents and 31 patents pending resulting in numerous "industry firsts". He has served as a director on the board of six technology companies and serves on the advisory boards of several professional and academic organizations including California State University Northridge (CSUN) College of Engineering and Computer Science, CSUN College of Extended Learning, UCLA Electrical, Mechanical and Aerospace Engineering Departments, UCLA Wireless Internet for Mobile Enterprise Consortium (WINMEC), UCLA WINMEC Radio Frequency Identification (RFID) Group, UCLA Engineering Alumni Association Board of Governors, USC Electrical Engineering Advisory Board and the Journal SENSORS. Dr. Madni is also the recipient of numerous awards and national honors including, the 2005 IEE Achievement Medal, the 2004 Alumnus of the Year Award from the UCLA Henry Samueli School of Engineering and Applied Science, the 2004 Distinguished Engineering Achievement Award from the San Fernando Valley Engineers' Council, the 2003 George Washington Engineer of the Year Award from the Los Angeles Council of Engineers and Scientists (LACES), the 2002 UCLA Professional Achievement Award Medal, IEEE Third Millennium Medal, Joseph F. Engelberger Best Paper Award at the 2000 World Automation Congress, California Coast University Distinguished Alumni Award, Association of Old Crows (AOC) Gold Certificate of Merit, and is listed in all the major Who's Who publications including Who's Who in America. He is a Chartered Engineer, Fellow of the Institute of Electrical and Electronics Engineers, Fellow of the Institution of Electrical Engineers (UK), Fellow of the Institute for the Advancement of Engineering, Fellow of the New York Academy of Sciences, Fellow of the American Association for the Advancement of Science, Lifetime Associate Fellow of the American Institute of Aeronautics and Astronautics, and Life Fellow of the International Biographical Association. He is also a Life Member of the Association of Old Crows, and Member of the Society of Automotive Engineers.*

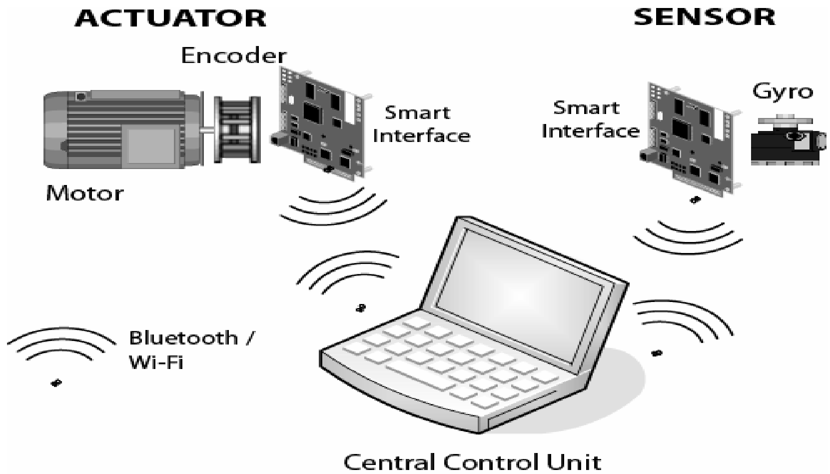

Figure 1.General Application Scenario

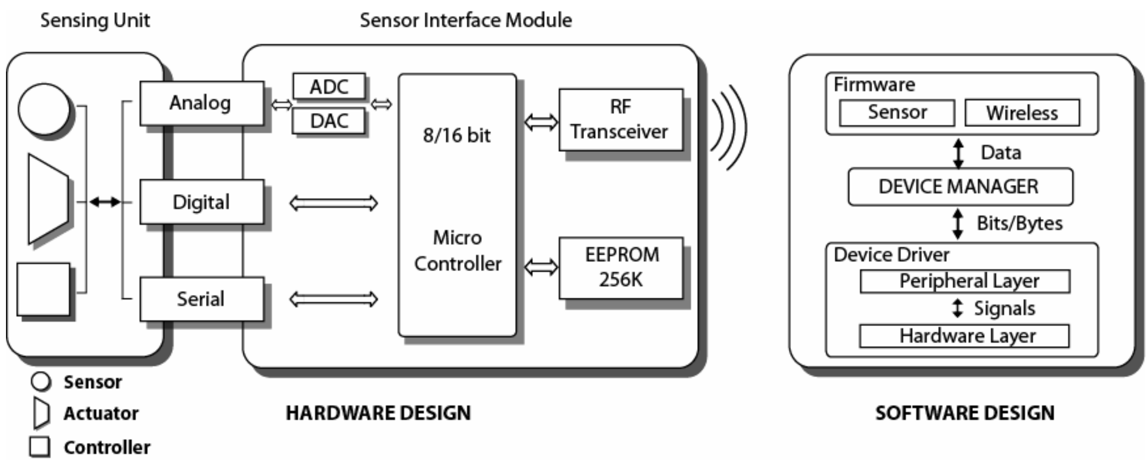

Figure 2. Smart sensor node design

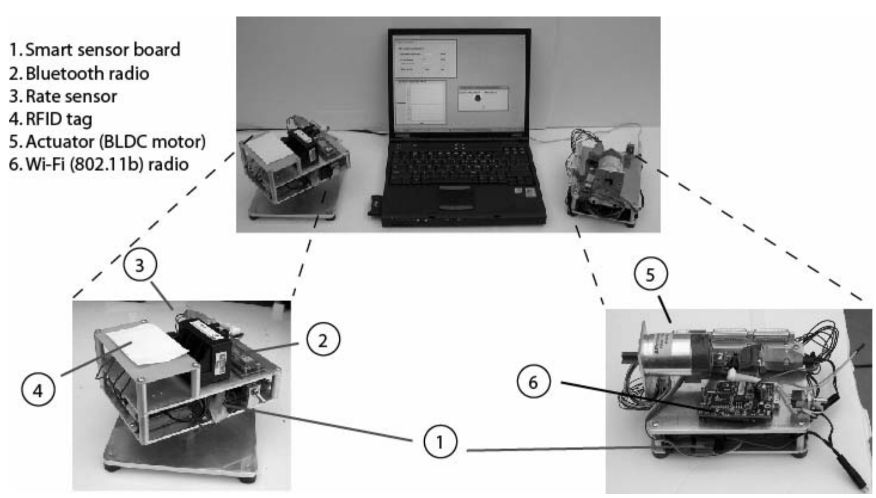

Figure 3. Smart sensor platform test setup

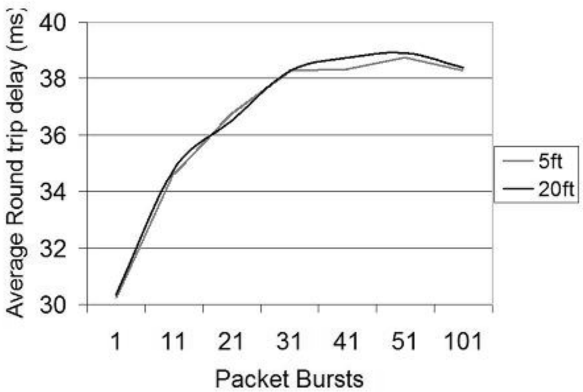

Figure 4. Average round trip delay with varying packet bursts for Bluetooth

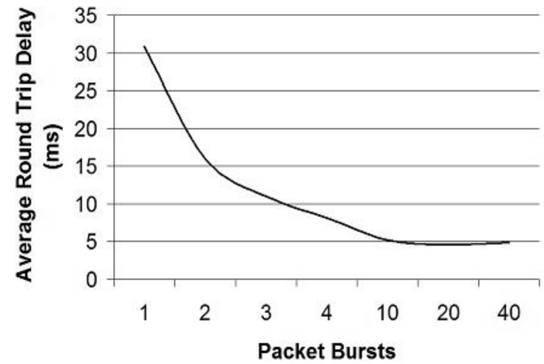

Figure 5. Average round trip delay with varying packet bursts for WiFi

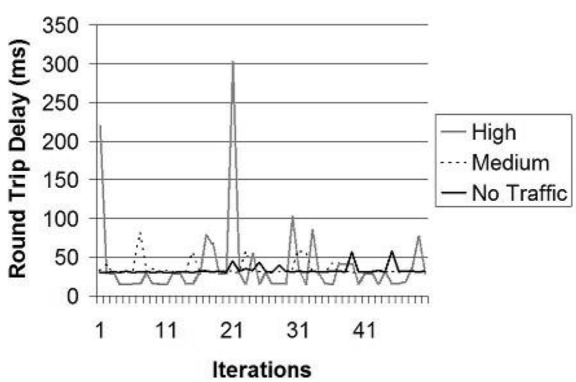

Figure 6. Round trip delay with varying traffic for WiFi at 20ft

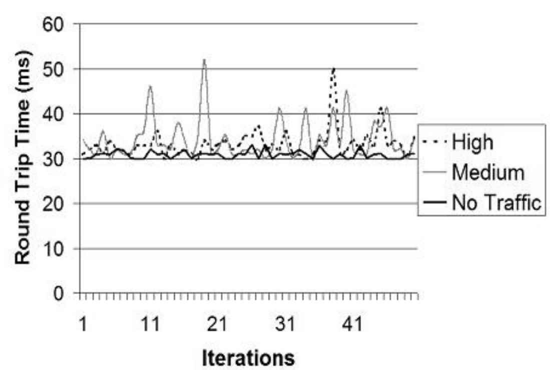

Figure 7. Round trip delay with varying traffic for WiFi at 5ft

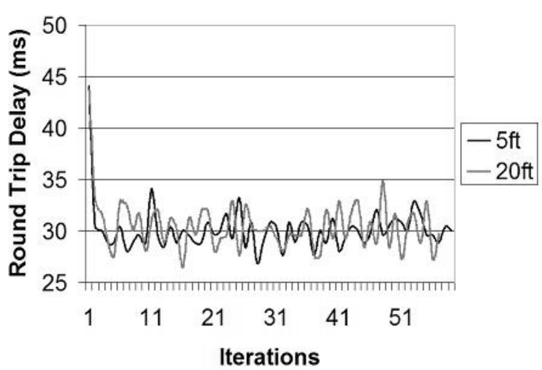

Figure 8. Round trip delay with varying distance for Bluetooth

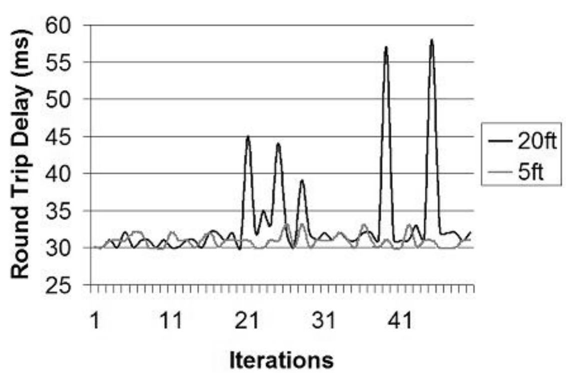

Figure 9. Round trip delay with varying distance for WiFi

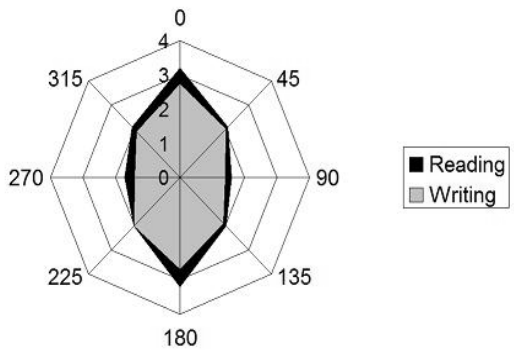

Figure 10. RFID Reading Range in inches with changing orientation in degrees