Reconfigurable Wireless Interface for Networking Sensors

[1]D.Saravanan [2]B.Kumaragurubaran

1. Assistant Professor, Department of Computer Science & Engineering,Pavendar Bharathidasan College of Engg. & Tech., Trichy 24
2. Lecturer, Department of Automobile Technology, Anna University,Trichy-24.

ABSTRACT

Remote Monitor & Control systems are increasingly being used in security, transportation, manufacturing, supply chain, healthcare, biomedical, chemical engineering, etc. In this paper, attempt is to develop a solution of wireless monitoring and control for such industrial scenarios. The solution is built on two components – a generic wireless interface for remote data collection/ actuation units and control architecture at the central control unit (CCU) for smart data processing. The data collection/actuation unit (sensors / actuators) is intelligent by virtue of smart reconfigurable- microcontroller based wireless interface, which is reconfigurable using Over-the-Air (OTA) paradigm. The RF link is also reconfigurable to accommodate a variety of RF modules (Bluetooth, 802.11 or RFID) providing plug-n-play capability. These capabilities make the interface flexible and generic. The control architecture supports services such as naming, localization etc., and is based on JavaBeans, which allows a component level description of the system to be maintained, providing flexibility for implementing complex systems.

1. INTRODUCTION

The current generation automation systems control & monitoring systems, security Systems, etc., all have the capability to share information over the network and are being increasingly employed to aid real-time decision support. The inter-device communication in such systems can be leveraged to maximize the efficiency and convenience in a variety of situations. Intelligent wireless sensors based controls have gained significant attention due to their flexibility, compactness and ease of use in remote unattended locations and conditions. These wireless sensor modules can be designed to combine sensing, provide in-situ computation, and contact-less communication into single, compact device, providing ease in deployment, operation and maintenance. Already large-scale wireless sensor networks having different capabilities are being used to monitor real-time application needs. Different types of sensors (thermal, photo, magneto, pressure, accelerometers, gyros, etc.) having different capabilities, interfaces and supporting different protocols are used for different applications. For remote data collection, RF communication links with different characteristics, such as frequencies, data carrying capacity, bandwidth, Susceptibility to interference, power needs, etc., have been employed to transmit the data. The appropriate design of the wireless sensing device depends on the end application needs such as data bandwidth, range, interference; etc. In the proposed work the attempt is to provide a single comprehensive architecture to support the diverse control automation needs of a variety of industrial applications. The data collection/actuation units will be made intelligent by equipping them with smart microcontroller based wireless interface. Utilizing the plug-n-play modularity of the system architecture, appropriate sensor interfaces and RF communication interfaces can be chosen according to the application requirements. Further, once the interfaces are chosen, the (developed) application interface could be used to implement the specifics like description, placement, interaction of sensors and actuators, etc. For example; the interaction could be a "closed loop" control of a motor where the sensor is an encoder and actuator a motor.

Typical Application Scenario

A typical application scenario for our system can be aircraft sub-systems' monitoring.

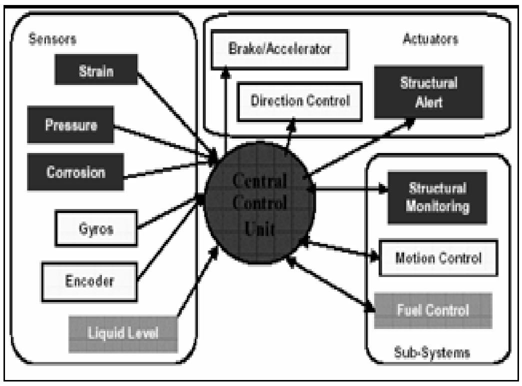

Fig.1. Application Scenario-Aircraft Health Monitoring the arrow direction denotes the direction of signal flow

As depicted in Fig. 1 monitoring the operational status and condition of a number of aircraft sub-systems such as structural monitoring, fuel level, motion control, etc., involves data retrieval and processing from a high-density of sensors, and provide real time decision support. Each such subsystem may have multiple sensors installed, which continually update the status of the aircraft. The CCU is responsible for continuously aggregating real-time information from sensors and disseminates it to each of the respective subsystem for appropriate

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response (to actuators). Benefits of wireless communication such as significant space reduction, lower maintenance costs (as armoured cables are done away with) and flexibility of deployment can be suitably leveraged. Further, utilizing the proposed reconfigurable and plug-n-play functionality in this research, the sensing system can be upgraded or updated with lesser effort.

2. SYSTEM OVERVIEW

In this section, we present a brief overview of the system architecture. The system consists of a network of sensors, actuators and aggregators communicating with the central control unit using standard RF-links. The basic scenario is shown in Fig. 2.Here D represents the devices, which can be sensors or actuators and A is the aggregator. The scenario we consider is an infrastructure based deployment. In a typical industrial scenario like aircraft systems monitoring or automotive control, the sensors are typically stationary and have fixed wireless communication links, unlike mobile ad-hoc scenario. Fixed wireless communication links are more reliable than mobile links, which have inherent problems such as loss of connection, varying data rates, etc. Fixed links help in providing certain performance guarantees in terms of data-rate, mean delay, etc., which are essential for deployment in industrial scenarios. We thus believe an infrastructure based deployment (i.e. fixed wireless deployment) is more suitable in such scenarios. We term sensor as any kind of transducer which is capable of exchanging information in the form of electrical signals and similarly actuator is any kind of device which will accept data in the form of electrical signals and perform a measured action. Sensors and actuators will be referred generically as devices henceforth. The main function of the aggregator is to collect the data and signals from/to the devices and using aback haul link (Wi-Fi) to transmit it back to the CCU.

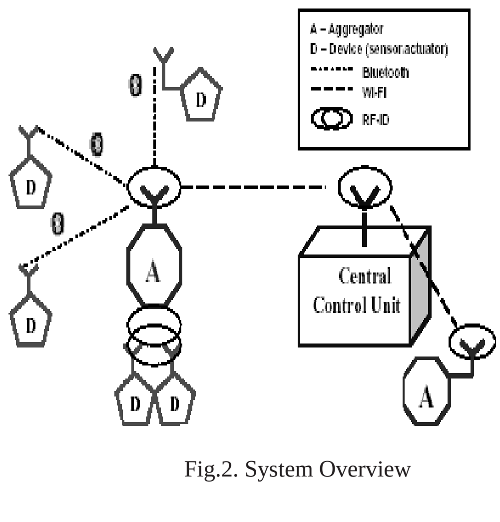


Fig.2. System Overview

The features of the proposed system include:
1. Reconfigurability: Central Control Unit can set the run-time parameters of the device and/or update/upgrade the firmware of the system over the air (OTA).
2. Plug-n-play: Depending on the application needs/requirements, different infrastructure and their configurations can be deployed quickly.
3. Self-identification: Necessary for high volume data collection systems as multiple Sensors/actuators may be read at one time.
4. Self-calibration: the intelligent adaptive sensors can accurately measure data and Self-calibrate without significant user intervention.
5. Wireless connectivity: provide bi-directional communication over a wireless Connection.
6. Lower installation and maintenance cost as no wiring/cables, etc., is required and therefore enabling greater acceptance and speedy deployment.

3. AGGREGATOR – FUNCTION AND DESCRIPTION

The Aggregator has been introduced in the architecture to deal with the case of highly dense network of distributed sensors and where it may not be possible for all sensors to directly communicate with the central control unit. The problems encountered in a direct sensor-control unit network can be summarized as:
1. Paucity of communication channels – The number of RF communication channels available in a given space are limited; thus limiting the number of sensors that can be present in the system. The aggregator with spatial channel re-uses functionality will help improve the number of sensors that can be present in the system. Further, this will also bring down the power requirements (smaller transmission range) at each device and hereby increasing the battery life of the device.
2. Diverse sensors and their requirements – Different sensors have diverse capabilities and requirements. For example, a corrosion sensor may not need a stringent monitor/control as a motor rotary system. Also different sensors and different application needs warrant wireless communications with a variety of bandwidth and range requirements. The aggregator model efficiently addresses these issues by supporting multiple wireless interfaces and aggregating the payload. An aggregator collects data and enables signal flow from the devices and sends it to the CCU and forwards the data/signals from the CCU to the respective recipient devices. The important functions of the aggregator will now be described.

Connection Establishment and Maintenance

The aggregator maintains connections with the devices within its purview and central control unit. Both connections are of master-slave type. In the device-aggregator connection, an aggregator is the master while in the aggregator-CCU connection the CCU is the master. In this type of connections, the master initiates connections and is responsible for maintaining them. For each type of device, the aggregator maintains the list of devices (i.e. device IDs – Section 5) connected to it for the backhaul connection. Aggregator-CCU, WI-Fi is used, the devices can use different RF technologies to communicate with aggregator, which supports multiple wireless interfaces.

Data Forwarding

The aggregator receives data from both the devices & CCU and forwards it to its intended recipients. Data from devices are marked with their specific device IDs at the aggregator and sent to CCU. Data from CCU is marked with device IDs and the aggregator extracts this information and forwards the data to the respective-device.

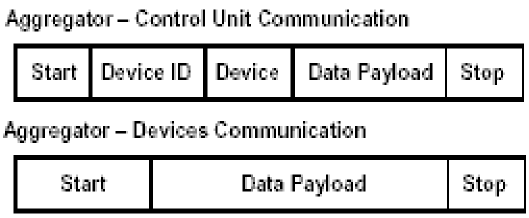


Fig.3. Payload over Wireless Link

A typical payload is shown in Fig. 3. The data payload, i.e. the particular order in which bits will be transmitted, is device specific and can be tailored to application needs. For example; the data payload could be a trigger or acknowledgement as specified in IEEE 1451.2 standard or it could be a simple data measurement byte. The format of data payload is fixed during initialization of the device (Section 6.1) and can be modified while the device is in Command mode.

Exception Handling

In the event of wireless connection drop between the aggregator and any of the devices, the aggregator reports to the CCU about the loss of connection. This helps differentiate between device inactivity and connection loss. The CCU then takes appropriate steps to compensate for the loss of device. This for example includes: entering a” safe-state”, instructing other aggregators to start looking for the device, raising an exception, etc. In the event of connection severance with CCU, the aggregator instructs all the devices to enter the “safe-state” and wait for the CCU to respond.

4. DEVICE ARCHITECTURE

Architecture of the wireless intelligent data collection device is shown in Fig. 4. The device is composed of three components: a Sensor/Actuator, Microcontroller interface and RF interface. Microcontroller acts like an intelligent interface between the sensor or the data collection unit and the RF module. It handles tasks related to data collection, data processing and wireless transmissions. The RF trans-receiver communicates with the aggregator or CCU over the RF-link.

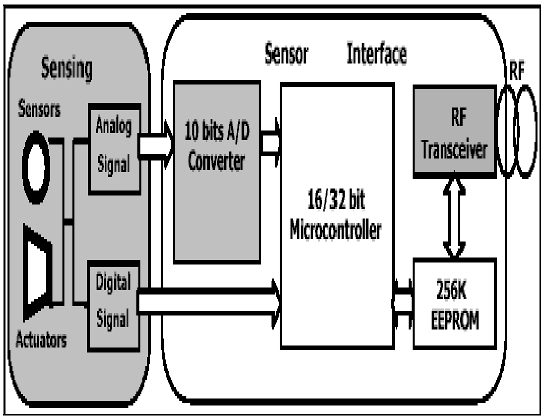


Fig.4. Hardware design of intelligent sensor

Software Architecture

The device is implemented as an asynchronous finite state machine as shown in the Fig. 5. The device while in operation will be in any one of the two modes: Command Mode and Data Mode. This design facilitates flexible configuration i.e. forming networks, setting up device specific parameters, etc., while the device is in command mode. Further, once the device is configured, the device data (i.e. sensed data or actuator instructions) can be communicated without overhead in the data mode utilizing the wireless link efficiently. We now describe each of the modes in detail.

Command Mode

The device enters the command mode by default and the first task is the configuration of the wireless interface, after which the device awaits for an authenticated connection. Thus two states are identified in this mode – the "connected" state and "unconnected "state. Upon connection the device still remains in command mode and configures itself as a slave and waits for instructions from master. In case the connection is dropped anytime the device resets itself and waits for a fresh connection. The control unit typically queries the device type information and sets the format of payload (Sect. 4.2 & 6.1) to be used in command & data mode. It then instructs to start the device specific configuration procedure. Typically in case of an analog device, the A/D or D/A converters are initialized. Further, the control unit may instruct the device to switch to data mode.

Data Mode

Once in Data mode the device will transmit/receive the device data using the RF-link. The device can be switched back to command mode using an escape sequence through the wireless interface. Otherwise the device will remain in data mode and transmit/receive data in the prescribed format. In the data mode, the device has to perform the following two tasks

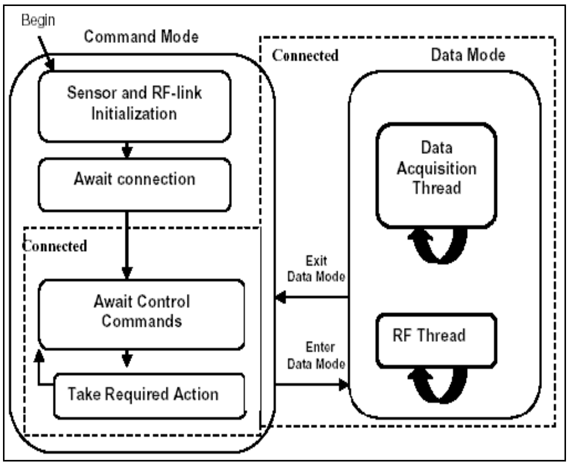


Fig.5. Software Architecture of the Design

1) Data collection in case of sensor or issuing instructions in case of actuator, 2) Interfacing and communicating with RF-link. As real-time processing of these tasks is required, separate threads are run for each task on the device.

Connection Drop & Exception Handling

The device periodically checks the status of the wireless link. In case the connection is dropped and cannot be reinstated; the device executes an "emergency routine" where the device is set to a "safe-state", which is particularly necessary in case of actuators. For example, a safe-state for a motor would be a complete stop. After executing the emergency routine the device just waits for the connection from the aggregator/CCU. The device thus can be only in "connected" state in this mode.

Memory Organization and Over-the-Air Reconfiguration

The data stored in the microcontroller/EEPROM is divided into five types and each Stored in different portion of memory. The memory allocation is shown in Fig. 6. This kind of memory organization helps in supporting reconfigurability, upgrade & update of firmware over-the-air (OTA) and fast real-time data processing in the device. Self-identification information contains the unique device ID and type information. The main program is the basic "monitor" Program which initializes the system i.e. device hardware (sensor and wireless) interfaces. The main program cannot be altered and is permanent. Services like naming, service discovery, functionality of reconfigurability and other such core services are supported in the main program.

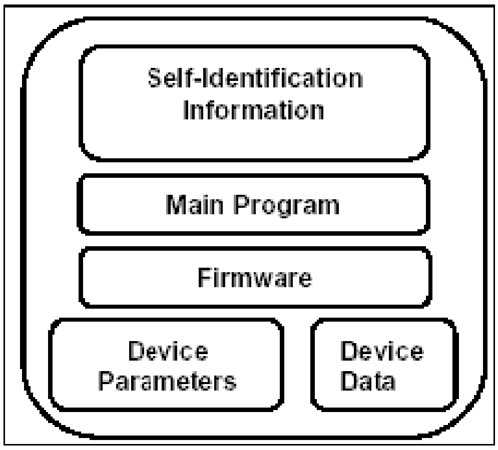


Fig.6. Memory Organisation

The firmware program takes care of data-handling, parsing, taking actions and setting run-time parameters. The firmware can be modified by the main program. Device Parameters contain the device-specific information like bit accuracy, sampling rate, aggregator identification etc and functions (names) supported by the device like sampling rate modification, toggle switch support etc. These parameters are characterized by the attribute-value pair. For function names, the value corresponds to the function version. The device parameter characterization is essential for supporting querying services over the device. Reconfiguration Over-The-Air (OTA) is initiated by the CCU and is carried out through a set of messages exchange between the CCU and device as shown in Fig. 7.

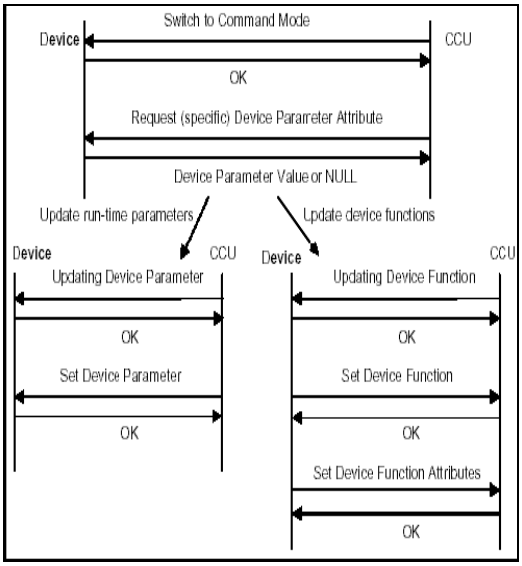


Fig.7. Message Exchange Flowchart for Device reconfiguration (OTA)

5. CENTRAL CONTROL UNITS SOFTWARE ARCHITECTURE

This section provides a brief overview of the software architecture of the CCU. The developed system is targeted to be used with complex systems such as aircraft subsystem monitoring where a number of devices have to be identified, probed and instructed after performing some complicated logical computation such as closed loop control, wing balancing, etc. In order to implement complex systems, we had identified that the following features need to be supported by the CCU:

1. Flexibility of implementation – No restrictions on how device should be placed (geographically and logically) and connected to the system
2. Flexibility of control – Allow inclusion of complex control algorithms over devices & the sub-system formed by these devices
3. Friendly user and control interface – A framework by which the system can be described with ease; i.e. using a declarative language like XML. The software architecture is what drives the central control unit. Thus in order for the system to support the aforementioned features, the software architecture of the control unit has to address the following issues:

1. Device detection, representation and characterization in the system
2. Inter-device interaction & information sharing; formation of sub-systems by these devices and aggregation of subsystems to form the complete system

Formation of Subsystems

A subsystem can be defined as a collection of logically connected devices; for example a simple motor control subsystem will have a motor (actuator) and an encoder (sensor). The logical connection specifies how data present in the device can be exchanged as information, for e.g., the control logic like closed-loop control of a motor control system. Further only those devices, which have some information to share, can be connected. Here we will like to differentiate between "data" and "information". Information is what devices can extract from data to self-adjust and modify their behaviour. For example for a motor, rotary position from an encoder demonstrated. In the current version of the system different type of sensors, viz., rotary and linear have been interfaced. Class -1 Bluetooth

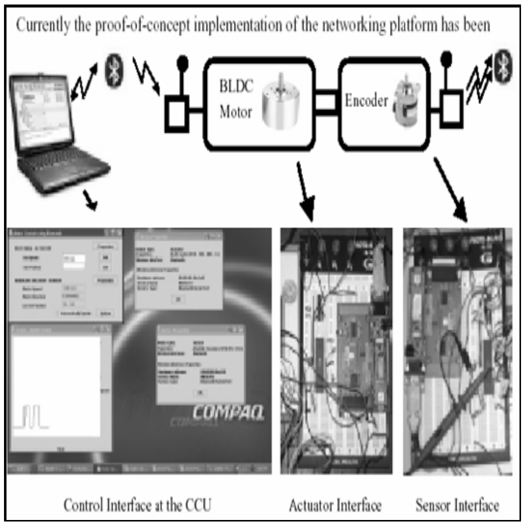


Fig.8. Snapshots Of The Current Implementations

has been used for the RF communication link. Work on supporting other RF technologies like UWB and RFID is currently being done. In the current implementation, as the aggregator is just a logical component, the aggregator resides on the CCU itself. Here the aim was to support both "open-loop" and "closed-loop" control on a motor as actuator. An encoder was used to sense

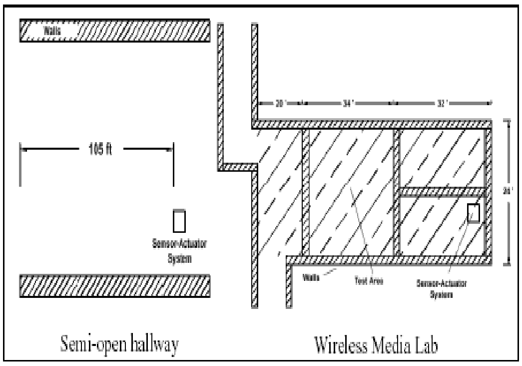


Fig. 9. System Test scenarios

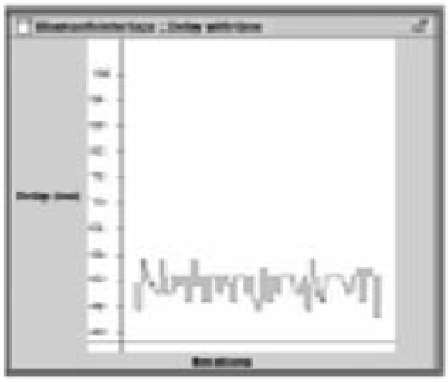
the position of motor. Fig. 8 shows the block diagram and snapshots of the current implementation.

6. RESULTS

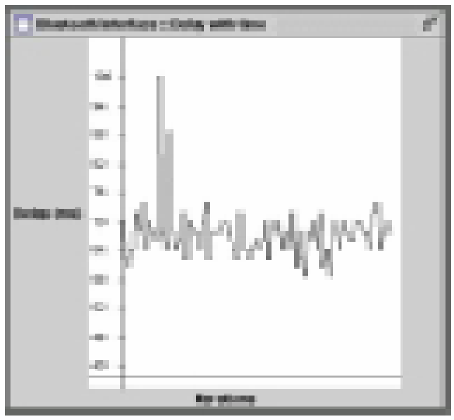
Preliminary tests of the system were carried out in certain scenarios and the results are presented below: The system was tested in two scenarios as shown in Fig. 9. Here the walls are shown as hatched rectangles and the rectangular box is the sensor-actuator system. The laptop (control unit) was able to control the sensor-actuator system from 105ft without degradation in the performance. In the second scenario, the hatched area shows where system performance didn't degrade. The system performed well even in presence of obstacles like walls (2).

System Performance Tests

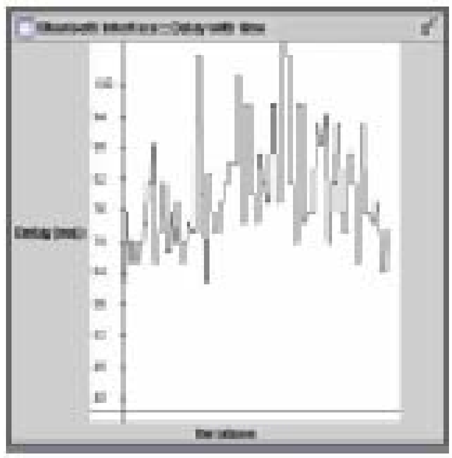
Since these systems will be used for real-time monitoring and control, performance studies were carried out. Delay and bandwidth have a significant effect on the fidelity and responsiveness of the system. To characterize the parameters, simulations were performed in an "echo-scenario", i.e. whenever the CCU sends a packet to the device; the device simply echoes back the packet. Measuring the delay from start of transmission from CCU to end of reception at CCU will give the round-trip delay of the link and bandwidth can be measured by the rate at which the data is received. Simulations were carried out for different inter-device distances and the results are shown in Fig.10 and 11. As can be seen from simulation results the round-trip-delay increases with distance. Further, the delay becomes jittery as the distance is increases. This is attributed to the increased interference and fading at longer distances. Similarly bandwidth decreases with distance and becomes jittery due to the same reason.



Testing distance 1m



Testing distance 10m



Testing distance 25m

Fig. 10 Delay Performance with Distance

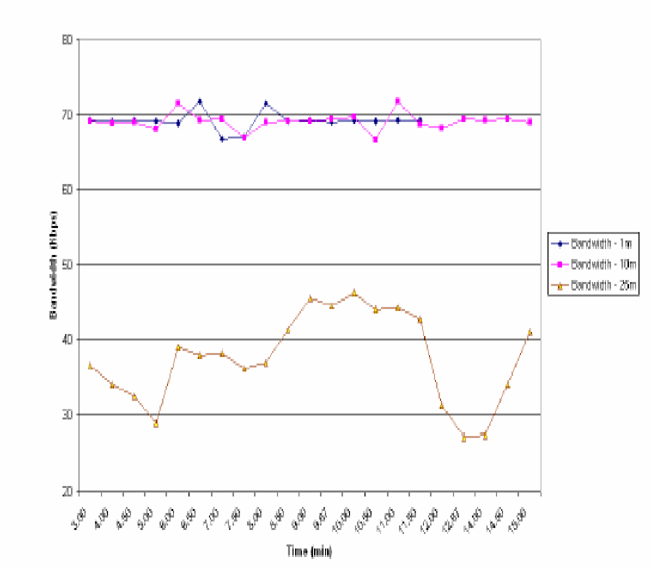


Fig. 11 Bandwidth Performance with Distance

7. CONCLUSION

In this research, an end-to-end solution for wireless monitoring & control in industrial Scenarios have been proposed. It was shown how traditional sensors could be transformed into intelligent wireless sensors, capable of making real-time decisions using the developed generic wireless interface. A proof-of-concept working model of the solution is also demonstrated with successful integration of a variety of sensors/actuators by using the developed application interface. To illustrate, a suitable application scenario was also discussed for such a remote data collection system.

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Corresponding Author

D.Saravanan,
Assistant Professor, Department of Computer Science & Engineering, Pavendar Bharathidasan College of Engineering & Technology, Mathur, Trichy – 24.
E-Mail : dsarav23@rediffmail.com
Mobile No. +91 98651 81743