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A Wireless Toolkit for Monitoring Applications

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ABSTRACT OF
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Monitoring the behavior of physical structures and processes gives valuable information about their condition and performance. This information can be used to improve safety, reliability and performance of the monitored physical structure. Complex systems of today require efficient and intelligent monitoring strategies which will help forming cause-effect relations between certain variables and problems. Wireless sensing is a promising technology for monitoring applications due to its advantages, e.g., in installation times and costs. Many systems were successfully implemented over the last decade. However these systems are often hard to use and designed for a specific purpose. Moreover, high sampling rate data collection with these systems can take long times due to limited bandwidth of the wireless networks.

In this thesis, a wireless monitoring toolkit is developed and it can be defined as a portable, easy-to-use, simple-to-setup and fast monitoring system to be used for simultaneous multi-parameter monitoring of physical structures and processes. The toolkit consists of user interfaces, a novel data acquisition system which optimizes wireless communication speed in the network, a real-time monitoring application, a communication test application, a high sampling rate application, and wireless sensors hardware equipped with multiple sensors and IEEE 802.15.4 radios. Real-time monitoring application has a flexible, reliable and efficient structure due to its dynamic and multi-task operation. These two features distinguish this application from other wireless monitoring applications.

Tests on a wooden bridge, a laboratory scale trolley crane, and an industrial bridge crane show that the developed system works seamlessly in industrial environments as well as in laboratory environments. Data collected in these case studies provide valuable information about the condition and performance of the monitored structures and systems, as shown by the data analysis performed.

The thesis includes a review of state of the art wireless monitoring systems and determines framework of a general purpose wireless monitoring system to be used for condition monitoring and performance optimization purposes.

Keywords: wireless monitoring, performance optimization, condition monitoring, structural health monitoring, crane monitoring, wireless sensors, controller tuning, wireless sensor networks.

Preface

Presented research is done in the Intelligent Structural Health Monitoring System (ISMO) project which is funded by the Multidisciplinary Institute of Digitalization and Energy (MIDE) of Helsinki University of Technology.

I started working as a research assistant in the Control Engineering Group at the Helsinki University of Technology in June 2008. I have been working on wireless monitoring which covers many engineering branches such as computer science, electronics engineering, mechanical engineering, control engineering and telecommunications. Thesis work on this multidisciplinary field allowed me to apply my previous knowledge in practice. The work has always been fulfilling and kept my attention alive. At the end, I am grateful to choose this field and still excited about the opportunities it has to offer.

I would like to thank my instructor Lasse Eriksson for encouraging me to work on new approaches at every phase of the work. During my work, I always felt the freedom to experiment and yet the confidence of being supervised by a remarkable scientist. I would also like to thank my supervisor Heikki Koivo.

Work presented in this thesis is by no means a one man's work, but it is an outcome of a successful teamwork. It has been a remarkable experience for me to work with such an elite research group. Among others, I would like to thank Maurizio Bocca and Juho Salminen for their support and contributions to the thesis work. I have to thank Konecranes, a Finland based international lifting equipment and service company, who let us use one of their test cranes to evaluate the performance of wireless sensor nodes in an industrial environment.

I would like to thank two very wise and humble persons: my parents Necla and Huseyin Cosar. They helped me realize myself in uncountable ways. I would like to thank my brothers Caglar and Bilgehan, and my lovely sister Banu for being there whenever I needed them, and my mentors Nesrin Demirel, Kayihan Keskinok, Baris Sentuna, and Nebi Vural for inspiring me throughout my life.

October 2009, Emre Ilke Cosar

Nomenclature

a_r	Radial accelerations
a_t	Tangential accelerations
A	Peak acceleration [m/s^2]
A_r	r^{th} coefficient of the DFT
$ADC1$	ADC channel one
$ADC2$	ADC channel two
$Axis$	Number of accelerometer axis
b	Number of bits used for mapping
BpS	Bytes per Sample
D	Peak-to-peak displacement [mil]
D_{org}	Original data (4-bit)
f	Frequency [rpm]
f_r	Frequency resolution
f_s	Sampling frequency
g	Constant of gravity
H	Humidity
j	$\sqrt{-1}$
l	Length of string
n	Number of samples
N	Number of samples in time series
NI	Node Interval
$Noise$	Measurement noise [bit]
$N_{voltage}$	Peak to peak input noise voltage [V]
r	Length of the pendulum string
R	Voltage reading provided by NI USB-9215A
Res	Measurement resolution [bit]
SpP	Samples per Packet
T	Temperature
T_o	Period of oscillation
T_s	Sampling Interval

T_t	Time between two consecutive synchronization packets
V	Peak velocity in [m/s]
$V_{p\text{-}p}$	Peak to peak voltage range
V_{DAC}	Voltage range of DAC module
x_i	i^{th} value of the sampled signal
X_k	The k^{th} sample of the time series
X_{rms}	RMS value
α	Angular acceleration [rad/s^2]
θ	Angular displacement of the swinging pendulum [rad]
ω	Angular velocity of the pendulum mass [rad/s]

Abbreviations

6LowPAN	IPv6-based Low power Wireless Area Network
ADC	Analog to Digital Converter
AI	Analog Input
AODV	Ad hoc On Demand Distance Vector
AP	Access Point
API	Application Program Interface
ASK	Amplitude Shift Keying
BPSK	Binary Phase Shift Keying
BSS	The base station subsystem
CBM	Condition Based Maintenance
CCK	Complementary Code Keying
COFDM	Coded Orthogonal Frequency Division Multiplexing
COM	Common
CSMA-CA	Carrier Sense Multiple Access With Collision Avoidance
DAC	Digital to Analog Converter
DFT	Discrete Fourier Transform
DIO	Digital I/O
DSSS	Direct-Sequence Spread Spectrum
DS-UWB	Direct Sequence Ultra Wide Band
ESS	Electronic Switching System
ETD	Embedded Temperature Detector
FFD	Full Function Device
FFT	Fast Fourier Transform
FHSS	Frequency-Hopping Spread Spectrum
GCC	GNU Compiler Collection
GFSK	Gaussian Frequency-Shift Keying
GNU	GNU’s Not Unix
GUI	Graphical User Interface
Hp	Horsepower
HVAC	Heating Ventilation Air Conditioning
I/O	Input/output

IEEE	Institute of Electrical and Electronics Engineers
IP	Internet Protocol
IPv6	Internet Protocol version 6
ISA	International Society of Automation
ISMO	Intelligent Structural Health Monitoring System
ISO	International Organization for Standards
ITT	International Telephone & Telegraph
LR-WPAN	Low Rate Wireless Personal Area Networks
LSb	Least Significant four Bits
LSB	Least Significant Byte
Mbps	Mega Bits Per Second
MB-OFDM	Multi Band Orthogonal Frequency-Division Multiplexing
MCU	Micro Controller Unit
MIDE	Multidisciplinary Institute of Digitalization and Energy
M-QAM	M-Ary Quadrature Amplitude Modulation
MSb	Most Significant four Bits
MSB	Most Significant Byte
ODR	Output data rate
OFDM	Orthogonal Frequency-Division Multiplexing
OS	Operating System
O-QPSK	Offset Quadrature Phase-Shift Keying
PAN	Personal Area Network
PCB	Printed Circuit Board
PCMS	Process Control Monitoring Systems
PdM	Predictive Maintenance
PID	Proportional-Integral-Derivative
QPSK	Quadrature Phase-Shift Keying
RF	Radio Frequency
RFD	Reduced Function Device
RH	Relative humidity
RPM	Revolutions Per Minute
RSSI	Received Signal Strength Indicator
RTD	Resistance Temperature Detectors

SHM	Structural Health Monitoring
SPI	Serial Peripheral Interface
TX	Transmission
UWB	Ultra Wide Band
WLAN	Wireless Local Area Network
WPAN	Wireless Personal Area Network
WSN	Wireless Sensor Network
Yr	Year

Contents

1 Introduction

1.1 Background and Motivation

More than $1 trillion is estimated to be spent each year to replace perfectly good equipment. The main reason for this is the lack of reliable and cost-effective methods that can predict the equipment's remaining lifetime (McLean and Wolfe, 2002).

Physical structures such as bridges, machines, motors, airplanes or buildings have typical modes of vibration, acoustic emissions and response to stimuli. Monitoring these behaviors provide valuable information on wear, fatigue or other mechanical changes (Culler *et al.*, 2004). This information can be used to improve safety, reliability and performance of the monitored physical structure. However, as systems and structures become more complex day by day, forming a cause-effect relationship between certain variables and problems becomes harder. For example, there are usually between five hundred to five thousand regulatory controllers in a continuous process industry facility and only about one third of these industrial controllers provide an acceptable level of performance (Desborough *et al.*, 2001).

Condition monitoring and performance optimization are two approaches that are used to develop optimal systems. These two fields are interconnected; for example, a malfunctioning valve in a control-loop will affect the performance of the whole plant. The performance can be improved if intelligent condition monitoring and maintenance strategies are employed (Hägglund, 1995). Similarly an overhead crane with optimum control will cause fewer vibrations on the load and eventually less deterioration in the structure. This means reduced need for maintenance and longer lifetime of the crane (Okubo *et al.*, 1997). Intelligent performance optimization strategies such as root cause analysis (Andersen *et al.*, 2006) and condition monitoring methods such as multi-parameter monitoring (Tavner, 2008) are likely to play an important role in future monitoring operations. Wireless sensing technology can play an important role in future condition monitoring and performance optimization strategies.

Reduced size and power consumption of wireless sensors combined with their certain advantages in installation times and costs compared to traditional wired sensing techniques led them to be the promising technology for many monitoring and control applications. However, they have certain limitations in terms of power, bandwidth, memory size, security and reliability. Allocation of the resources in an efficient way and development of reliable systems remains a challenge. Even so, several wireless monitoring systems have been presented in recent years in a variety of fields such as in structural health monitoring (Lynch *et al.*, 2006), building automation (Osterlind *et al.*, 2007), pipeline monitoring (Stoianov *et al.*, 2007), food and agriculture industries (Wang *et al.*, 2006), environmental monitoring (Yick *et al.*, 2008), condition monitoring of electrical machines (Tuononen, 2009), etc.

Often the developed wireless monitoring systems are complex to use and designed for a specific purpose which limits their application into other fields. Furthermore limited bandwidth of wireless networks can cause long data collection times when a high sampling rate is used. Studies address some key issues to be taken into account when designing monitoring systems such as usability, ease of set up, speed, etc. (Desborough *et al.* 2001). A wireless monitoring toolkit, which considers aforementioned issues, can fill the gap between technology and user’s needs.

1.2 Scope and Objectives

The scope of this thesis is to develop and test a general purpose wireless monitoring toolkit to be used for condition monitoring and performance optimization purposes. Every monitoring application has its own needs and priorities in terms of sampling frequency, number of nodes, sensors used, reliability, etc. Developing specific hardware or software for these applications can be time and energy consuming. A generic wireless monitoring toolkit which meets the needs of several monitoring applications can greatly speed up the research and development in the field.

The main objective of this thesis is to determine and implement a framework of a general purpose wireless monitoring toolkit which is easy to use, fast and reliable. Toolkit should be easy to use so that, for example, a serviceman can setup the monitoring system, and collect the measurement data easily without dealing with low level programming issues. Wireless monitoring toolkit should allocate the resources and the bandwidth of the network to optimize the speed of data collection in order to avoid long data collection times. Finally the toolkit should be able to provide reliable information from multiple measurement locations and by using several sensors.

1.3 Contributions

Contributions of the author in the thesis are listed as follows:

- A literature review has been done to gain a better understanding of monitoring applications. Desirable characteristics of a general purpose wireless monitoring toolkit have been determined.
- A wireless monitoring toolkit has been developed and tested. The toolkit consists of wireless sensors hardware equipped with multiple sensors, user interfaces, a novel data acquisition system which optimizes wireless communication speed in the network, a real-time monitoring application, a communication test application and a high sampling rate application. Real-time monitoring application has two important features that distinguish it from other wireless monitoring applications: dynamic and multi-task operation. These features give this application a flexible, reliable and efficient structure.
- Wireless monitoring toolkit has been tested for structural health monitoring (SHM) on a model bridge built to scale along with a wired measurement system. This study proved the usability of the wireless sensors in SHM applications and provided important insights for future development directions that will improve the reliability of wireless sensors.
- Wireless monitoring toolkit has been tested on a laboratory scale trolley crane for simultaneous multi-parameter monitoring of the system properties, i.e., load position and crane vibrations. It has been shown that it is possible to measure system properties with wireless sensors without disturbing the normal operation of the system, which is an essential feature of process monitoring.
- Tests on the trolley crane system indicated that the wireless sensors equipped with accelerometers can be used to evaluate the control system performance. Measurements also showed the close relation between angular displacement of the load and the accelerations experienced by the load.
- Wireless monitoring toolkit has been used to investigate wireless communication characteristics of the sensor nodes in an industrial environment.

Vibrations induced due to movement of an industrial crane were measured and evaluated.

- Cosar, E.I., Bocca, M., and Eriksson, L.M., 2009, “High Speed Portable Wireless Data Acquisition System for High Data Rate Applications”, in Proceedings of the 2009 ASME/IEEE International Conference on Mechatronic and Embedded Systems and Applications (MESA 2009), San Diego.
- Bocca, M., Cosar, E.I., Salminen, J., and Eriksson, L.M., 2009, “A Reconfigurable Wireless Sensor Network for Structural Health Monitoring”, Proceedings of the 4th International Conference on Structural Health Monitoring of Intelligent Infrastructure (SHMII-4 2009), Zurich, Switzerland.

The work described in this thesis is an outcome of a research project. Following paragraph presents people who have contributed to different aspects of the work.

Hardware components described in the thesis were mainly put together by Juho Salminen. Accelerometer sensor board was designed by Jose Vallet. Driver of accelerometer sensors was developed by Jose Vallet, Maurizio Bocca and Emre Ilke Cosar. Sensor boards were manufactured by Juho Salminen. Driver for temperature and humidity sensors on wireless sensor nodes was developed by Maurizio Bocca. Communication test application was developed by Maurizio Bocca and Lasse Eriksson. Data collected in bridge monitoring case study was analyzed by Maurizio Bocca. Real-time monitoring application was developed by Emre Ilke Cosar under supervision of Lasse Eriksson. High sampling rate application was developed by Emre Ilke Cosar, Maurizio Bocca and Lasse Eriksson. High Speed Portable Wireless Data Acquisition System for High Data Rate Applications was developed by Emre Ilke Cosar and Lasse Eriksson. Rest of the development, literature review and analyses were done by Emre Ilke Cosar.

1.4 Structure

Structure of this thesis is presented as follows. Chapter 2 is a review of wireless sensor networks in monitoring applications. Key design considerations for wireless monitoring systems are given at the end of this chapter. Chapter 3 describes the hardware and software components developed for the wireless monitoring toolkit. Chapter 4 introduces three case studies done with the wireless monitoring toolkit and presents the results of these studies. In the conclusions chapter, developed applications and key findings of the thesis are summarized.

2 Wireless Sensor Networks in Monitoring Applications

Widespread availability of intelligent, small and cheap sensors enabled human to understand, monitor and control the environment more than ever. Sensors that are combined with advanced wireless communication technologies, form wireless sensor networks (WSNs). Despite their certain limitations in terms of power, bandwidth, memory size, security and reliability, WSNs have gained a huge ground in many applications. Main reason for this is their advantages in installation times and costs compared to traditional wired sensing technologies. Moreover their reduced size and power consumption have considerably increased their applicability (Yick *et al.*, 2008). Figure 1 shows the classification of WSNs according to their application areas. Each of these applications have different development perspectives, hence they face different challenges and constraints.

Following the classification in Figure 1, this thesis focuses on public/industrial monitoring applications, with main emphasis on condition monitoring and performance optimization. Even so, accumulated experience and gained knowledge can easily be applied to other fields as well.

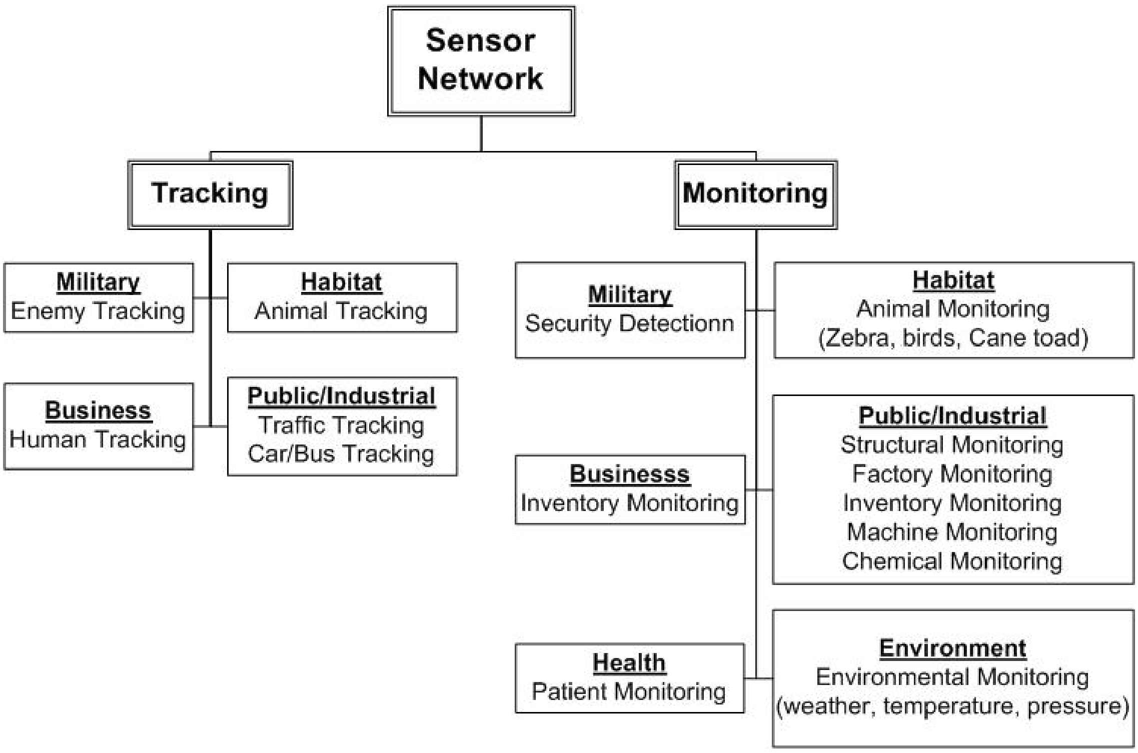


Figure 1. Overview of WSN applications (Yick *et al.*, 2008).

In this chapter, currently available wireless sensor network technologies will be investigated. Then condition monitoring trends and importance of performance optimization will be discussed. Presentation of public/industrial monitoring strategies will be followed by introducing typical monitoring applications. After that, a review of current state of the art in wireless monitoring applications will be presented by introducing reference applications. Finally, design considerations for monitoring systems will be discussed.

2.1 Wireless Sensor Networks

A node consists of hardware and software components, e.g., radio, sensor, application, etc. It is responsible of measurements and communications in a wireless sensor network. See Section 3.2 for a detailed description.

Fixed wireless communication technologies, excluding cellular networks, can be divided into three main groups: Wireless Local Area Networking (WLAN), Wireless Personal Area Networking (WPAN) and Wireless Metropolitan Area Networking. Perspective and limitations of these wireless networking technologies are different. Among these technologies, WLAN and WPAN are designed for indoor use. Figure 2 shows the data rates and indoor ranges of present WLAN and WPAN technologies.

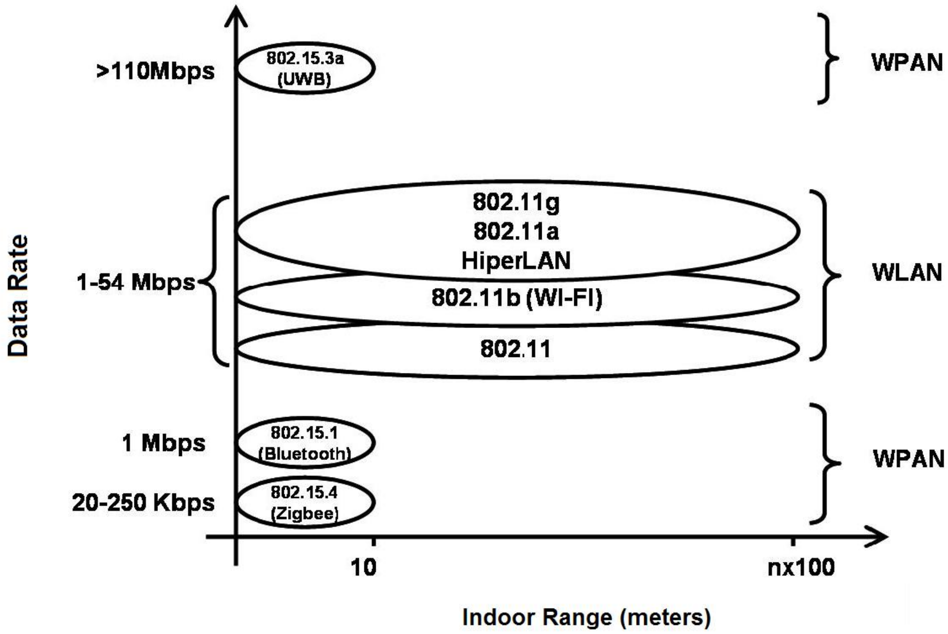


Figure 2. Comparison of indoor ranges and data rates of wireless network technologies (Zheng and Lee, 2004).

Wireless local area networks (WLAN) have been developed to replace local area network cable. WLAN, standardized within Institute of Electrical and Electronics Engineers (IEEE) 802.11 (IEEE 802.11, 2009), provides a high bandwidth with the cost of complex hardware and high power consumption. WPANs have been developed to connect personal communication devices within a shorter range. IEEE 802.15 working group (IEEE 802.15, 2009) is working on standardization of WPANs. A comparison of WLAN and WPAN radio technologies are given in Table 1.

Table 1. Comparison of WLAN and WPAN protocols (Lee *et al.*, 2007).

	WPAN			**WLAN**
	Bluetooth (802.15.1)	**UWB (802.15.3a)**	**Zigbee (802.15.4)**	**WLAN (802.11b)**
Frequency Band	2.4 GHz	3.1- 10.6 GHz	868/915 MHz, 2.4 GHz	2.4 GHz, 5.8 GHz
Nominal Range	10 m	10 m	10 – 100 m	100 m
Max. Signal Rate	1 Mbps	110 Mbps	250 kbps	54 Mbps
Nominal TX power	0-10 dBm	-41.3 dBm/MHz	(-25) - 0 dBm	15 - 20 dBm
Number of RF channels	79	1-15	1/10, 16	14 (2.4 GHz)
Modulation type	GFSK	BPSK, QPSK	BPSK(+ASK), O-QPSK	BPSK, QPSK, COFDM, CCK, M-QAM
Spreading	FHSS	DS-UWB, MB-OFDM	DSSS	DSSS, CCK, OFDM
Basic cell	Piconet	Piconet	Star	BSS
Extension of the basic cell	Scatternet	Peer-to-peer	Cluster tree, Mesh	ESS
Max. number of cell nodes	8	8	>65000	2007

IEEE 802.15.1, which is almost identical to Bluetooth standard, is designed for hand phones and other mobile devices. Leopold *et al*. (2003) have studied the applicability of Bluetooth to wireless sensor networks.

IEEE 802.15.3 is a physical and MAC layer standard for high data rate WPANs. It is designed for real-time multi-media streaming of video and music. Devices that employ this standard include wireless speakers, portable video electronics, wireless gaming tools, cordless phones, printers and televisions (Yick *et al.*, 2008).

Several wireless sensor network standards, which define the necessary functions and protocols for networking of the sensor nodes, have been developed with low power consumption goal. Some of these standards include IEEE 802.15.4, ZigBee, WirelessHART, ISA 100.11, IETF 6LoWPAN, and Wibree (Yick *et al.*, 2008).

IEEE 802.15.4 is the proposed standard for low rate wireless personal area networks (LR-WPAN's). This standard aims low cost of deployment, low complexity and low power consumption. The IEEE 802.15.4 standard, published in spring 2003, defines the characteristics of physical and MAC layers. The physical layer in IEEE 802.15.4 supports three frequency bands: 2450 MHz, 915 MHz band and 868 MHz, all using the Direct Sequence Spread Spectrum (DSSS) access mode (Baronti *et al.*, 2007). Some of the key features of these bands are listed in Table 2.

The MAC layer in IEEE 802.15.4 is responsible for validating frames, frame delivery, network interface, network synchronization, device association, and security services.

Table 2. IEEE 802.15.4 radio features (Baronti *et al.*, 2007).

	2450 MHz	**915 MHz**	**868 MHz**
Gross data rate	250 kbps	40 kbps	20 kbps
No. of Channel	16	10	1
Modulation	O-QPSK	BPSK	BPSK
Chip pseudo-noise sequence	32	15	15
Bit per symbol	4	1	1
Symbol period	16 μs	24 μs	49 μs

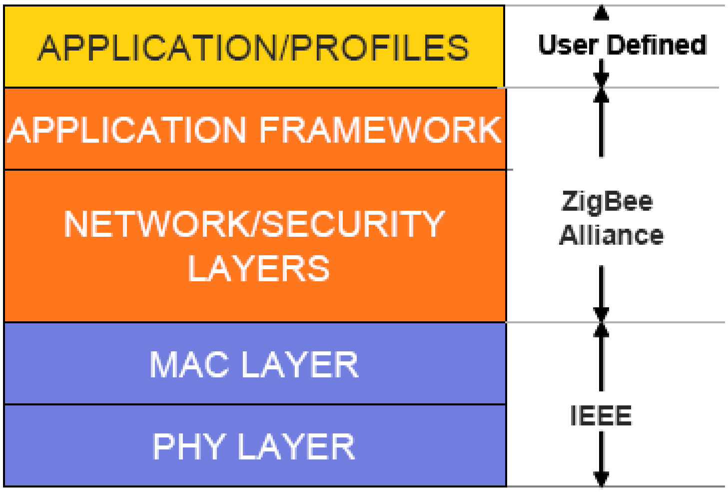


Figure 3. IEEE 802.15.4 protocol stack (Craig, 2009).

The MAC layer controls access to the radio channel using carrier sense multiple access with collision avoidance (CSMA-CA) mechanism. Residential, industrial, and environmental monitoring applications widely use IEEE 802.15.4 (Yick *et al.*, 2008).

ZigBee is a higher layer communication protocol built on IEEE 802.15.4 standards for LR-PANs (Figure 3). ZigBee Alliance, including more than 70 members, established ZigBee protocol to add network, security and application software to the IEEE 802.15.4 standard (ZigBee Alliance, 2009). ZigBee is optimized for automation sensor networks, where there is no need for high bandwidth, but low power usage, low cost, low latency and high quality-of-service are required (Eriksson *et al.*, 2008 b). ZigBee devices support mesh networks enabling hundreds to thousands of devices working together.

WirelessHART is a wireless network communication protocol for process measurement and control applications built on IEEE 802.15.4 for low power 2.4 GHz operation. Mesh networking, channel hopping and time-synchronized messaging are some of the key features of WirelessHART.

6LowPAN is an Internet Protocol version 6 (IPv6) based low power wireless personal area network. It is based on IEEE 802.15.4 standard and it enables low power devices to communicate directly with internet protocol (IP) devices.

ISA 100.11a is another standard working on 2.4 GHz band and it is designed for low data rate wireless monitoring and process automation. It provides simple, flexible, and scalable security functionality (Yick *et al.*, 2008).

Companies that provide commercially available wireless sensor network devices include; Crossbov, Moteiv, Dust Networks, Millenialnet, Sensinode and Sensicast. Available products usually offer easy to use platforms to be utilized according to the requirements of intended applications.

2.2 Condition Monitoring and Performance Optimization

2.2.1 Condition Monitoring

Condition monitoring programs aim to assess and trend the condition of monitored equipment in order to minimize risks and economic impact of an unexpected failure or shutdown (Rao, 1996). When it is done efficiently, condition monitoring strategies can significantly reduce the cost of maintenance.

Table 3 shows four types of maintenance strategies, basic philosophies of these maintenance strategies and related costs calculated per horsepower per year. Horsepower is a widely used unit in industry to state the power required to drive machinery. One horsepower is equal to 745.7 Watts (Mobley *et al.*, 2008).

It is seen from Table 3 that as the intelligence of maintenance strategy is increased, costs decrease. Intelligent maintenance operations employ predictive and reliability centered strategies that require extensive monitoring of target systems.

As complexity of the systems increase, it becomes harder to determine a cause-effect relationship between certain variables and problems. Root cause analysis is the structured investigation of the true cause of a problem and identification of necessary actions to eliminate it (Andersen *et al.*, 2006). Condition monitoring systems play an important role in gaining system knowledge which enables detection of real root causes of problems.

2.2.2 Performance Optimization

Performance optimization, or performance tuning, aims to improve system performance. In a continuous process industry facility, such as an oil refinery, chemical plant, or paper mill, there could easily be from five hundred to five thousand regulatory controllers, most of which are proportional-integral-derivative (PID) controllers. Only

Table 3. Types of maintenance strategies (Modified from O&M Best Practices, 2002, ch. 5, pp. 6-8).

Types of Maintenance Strategies	Basic philosophy	Cost (/hp/yr)
Reactive Maintenance (Breakdown or Run-to-Failure Maintenance)	• Allow machinery to run to failure. • Repair or replace damaged equipment when obvious problems occur.	$18
Preventive Maintenance (Time-Based Maintenance)	• Schedule maintenance activities at predetermined time intervals. • Repair or replace damaged equipment before obvious problems occur.	$13
Predictive Maintenance (Condition-Based Maintenance)	• Schedule maintenance activities when mechanical or operational conditions warrant. • Repair or replace damaged equipment before obvious problems occur.	$9
Reliability Centered Maintenance (Pro-Active or Prevention Maintenance)	• Utilizes predictive/preventive maintenance techniques with root cause failure analysis to detect and pinpoint the precise problems, combined with advanced installation and repair techniques, including potential equipment redesign or modification to avoid or eliminate problems from occurring.	$6

about one third of industrial controllers used in these facilities provide an acceptable level of performance (Desborough *et al.*, 2001).

Performance evaluation of industrial plants and subprocesses is essential for high product quality and economical operation. Over the years advanced methods have been developed to assess performance of devices and control loops. However there are a few generic solutions for plant wide monitoring due to the complexity of even a small real-world plant (Hölttä, 2009).

Monitoring the system to gather data is the first step in performance assessment. Studies address some key issues to be taken into account when designing industrial process control monitoring systems (PCMS) (Desborough *et al.*, 2001):

- A simple to use, maintain, and setup PCMS that allows quick and easy access to information is desired by practicing control engineers.
- It is difficult and time consuming to collect and analyze real-time, high frequency time series data.
- Performance monitoring with legacy control systems is usually not possible since these old systems do not have enough computing power. Moreover they lack the capacity to transfer data to more powerful platforms due to their limited bandwidths.
- Dynamic process models are not available for most of the controllers and they are very expensive to obtain.

In this respect, simple to use, easy to set-up, fast, and real-time process monitoring systems can contribute to performance optimization of the processes.

2.3 Public/Industrial Monitoring Strategies

In this section, non-intrusive monitoring concept is introduced. Then a comparison of wireless and wired monitoring, and continuous and periodic monitoring strategies will be given.

2.3.1 Non-Intrusive Monitoring

Non-intrusive monitoring aims to monitor the condition of a machine or process without disturbing its operation. Industrial machines are planned to be continuously running during their lifecycles and every minute they are stopped reduces their profitability. In the case of industrial processes, additional hardware connected to the process increase the risk of technical problems which may eventually cause a shutdown (Hölttä, 2009). Thus, non-intrusive strategies are the most economical type of monitoring.

2.3.2 Wireless vs. Wired Monitoring

It has been shown that the cost of installing and wiring a sensor exceeds the cost of sensor itself by more than ten times (Sanderford, 2002). Costs related to wires and deployments of these wires in an industrial/public environment are not in question when wireless sensors are used. Increased mobility of wireless sensors makes the monitoring system more flexible compared to their wired counterpart. Furthermore it is not always feasible to place wires in industrial environments such as in medium or high voltage environments and on rotating parts of the machines (Nordman, 2004).

Despite their certain advantages, WSNs have their own resource constraints and design considerations. Resource constraints include limited amount of energy, short communications range, low bandwidth, and limited processing and storage capacity of nodes. Design considerations for a WSN depend on the application and the monitored environment (Yick *et al.*, 2008).

2.3.3 Continuous vs. Periodic Monitoring

It is possible to divide public/industrial monitoring applications into two groups: continuous (on-line) and periodic monitoring. Periodic monitoring applications use measurements taken on a periodical basis and analysis of these measurements, whereas a continuous monitoring system takes measurements from the monitored structure or machine continuously and generates warnings and alarms if necessary. Periodic monitoring usually refers to manual data collection. With this technique, workers physically connect PDAs or other portable data acquisition devices to the monitored equipment for maintenance or calibration purposes (Lapedus, 2003). On-line systems are more reliable and allow frequent data collection. However they are not always feasible due to the initial cost of purchase and deployment. On-line monitoring systems are suitable for equipment and systems that have a potential cost impact greater than $ 250, 000 and they do not provide a sufficient return for the majority of the equipment in a typical industrial deployment (Krishnamurthy *et al.*, 2005).

Table 4 shows cost analysis of three predictive maintenance (PdM) approaches for a typical factory deployment: Manual data collection with hand held instruments, a traditional wired on-line monitoring system, and an online monitoring system where device is powered with wires but wireless transmission is used to transfer data (Krishnamurthy *et al.*, 2005).

Design constraints valid for most public/industrial wireless monitoring systems are reliability, re-configurability and energy efficiency. Reliability can be further divided into two classes: communication reliability and measurement reliability.

Table 4. Cost breakdown of three PdM approaches (Krishnamurthy *et al.*, 2005).

	Manual Collection	**Online System**	**Wireless Data / Wired Power**
#Wired APs (Access Points)	0	450	35
#Wireless APs	0	0	875
#Analyzers	8	1	1
Hardware Costs			
Sensors (installed)	$1,260,000	$1,260,000	$1,260,000
Wired APs	$0	$2,250,000	$17,500
Wireless APs	$0	$0	$262,500
Analyzers	$144,000	$18,000	$18,000
Installation Costs			
Wired APs	$0	$3,375,000	$262,500
Wireless APs	$0	$0	$1,726,974
Labor (Collection Costs)	$168,000	$3,360	$3,360
Total Costs	$1,572,000	$6,906,360	$3,550,834
Total Costs w/o Sensors	$312,000	$5,646,360	$2,290,834

Communication reliability can be defined as the ratio of correctly received packets to the total transmitted packets. Difference between measured data and the real data is defined as measurement reliability. Re-configurability of a WSN is its capacity to adopt into new environmental and operational conditions. Energy efficiency is another key design consideration in WSNs since most of the systems are battery powered. Replacing these batteries introduces new costs to the monitoring system (Wan *et al.*, 2008).

As explained earlier, continuous monitoring strategy is feasible for the systems that have a high cost impact hence above defined constraints hold for wireless continuous monitoring systems and there is a huge amount of research done on WSN to meet these design requirements. However in the case of a periodic monitoring system design considerations are slightly different. In such a system, the idea is a serviceman would install these sensors in a periodic manner and energy efficiency would not be a critical issue. Furthermore, communication reliability is not a key design consideration, since in the case of broken links, the system can be reconfigured by changing communication parameters or the places of the nodes. On the other hand, data reliability and re-configurability are still of utmost importance for a wireless periodic monitoring system.

2.4 Typical Monitoring Applications

In this section the most common monitoring techniques and their application areas are introduced.

2.4.1 Vibration Monitoring

Vibration is a widely used indicator of condition. A loose screw on an electromechanical machine or a crack on a bridge will change the vibration characteristics. An accelerometer, a velocimeter or a proximeter can be used to monitor these vibration characteristics. Root mean square (RMS) techniques and spectrum analysis are commonly used practices in industry (Tavner, 2008).

Following subsections present two common vibration monitoring methods: overall transverse vibration monitoring and spectrum analysis. These vibration monitoring techniques are presented in context of rotating machines. Other vibration monitoring applications also employ similar methods, however, findings on other fields are usually not standardized.

2.4.1.1 Overall Transverse Vibration Monitoring

Overall transverse vibration monitoring is the simplest but least effective technique used for rotating machinery. Measurements are done by measuring RMS value of the vibration acceleration or velocity on the non-rotating side of the machine over a bandwidth of 0.01-1 kHz or 0.01-10 kHz (Tavner, 2008). RMS value is calculated by

$$x_{rms} = \sqrt{\frac{1}{n}\sum_{i=1}^{n} x_i^2} \quad , \tag{1}$$

where *n* is the number of samples, x_i is the i^{th} value of the sampled signal and x_{rms} is the resulting RMS value.

A serviceman can determine the machine state with an accelerometer, a velocimeter or a proximeter. Velocimeters and proximeters are more suitable for low frequencies, whereas accelerometers perform better when monitoring high frequencies (Tavner, 2008). Conversion formulas that are used to calculate vibration severity are presented in (2) - (7).

$$D = 19.1 * 10^{3} * (V / f)\,, \tag{2}$$

$$D = 70.4 * 10^{6} * (A / f^{2})\,, \tag{3}$$

$$V = 52.36 * 10^{-6} * D * f\,, \tag{4}$$

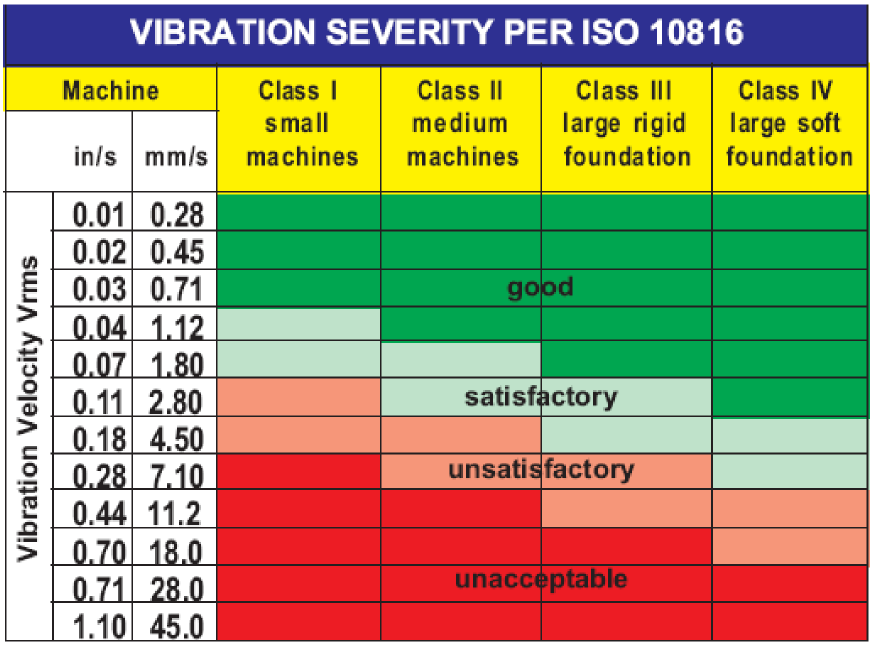
$$V = 3.68 * 10^{3} * (A / f)\,, \tag{5}$$

$$A = 14.2 * 10^{-9} * D * f^{2}\,, \tag{6}$$

$$A = 0.27 * 10^{-3} * V * f\,, \tag{7}$$

D is the peak-to-peak displacement in mm, *V* is the peak velocity in m/s, *A* is the peak acceleration in m/s^2, and *f* is the frequency in rpm. Over the years, several guidelines were developed to assess relative running condition of rotating machines based on RMS vibrations. These standards do not give diagnostic information, but indicate the machinery health at a given vibration level. Up to date standard is the ISO 10816-1:1995, which defines general conditions and procedures for the measurement and analysis on the non-rotating parts of machines operating in the 10 to 200 Hz (600 to 12,000 rpm) frequency range. Table 5 shows the ISO 10816 vibration severity chart for four classes of machines.

Table 5. ISO 10816 vibration severity chart (Monarch Instrument, 2002).



VIBRATION SEVERITY PER ISO 10816

Vibration Velocity Vrms in/s	mm/s	Class I small machines	Class II medium machines	Class III large rigid foundation	Class IV large soft foundation
0.01	0.28	good	good	good	good
0.02	0.45	good	good	good	good
0.03	0.71	good	good	good	good
0.04	1.12	satisfactory	good	good	good
0.07	1.80	satisfactory	satisfactory	good	good
0.11	2.80	unsatisfactory	satisfactory	satisfactory	good
0.18	4.50	unsatisfactory	unsatisfactory	satisfactory	satisfactory
0.28	7.10	unacceptable	unsatisfactory	unsatisfactory	satisfactory
0.44	11.2	unacceptable	unacceptable	unsatisfactory	unsatisfactory
0.70	18.0	unacceptable	unacceptable	unacceptable	unsatisfactory
0.71	28.0	unacceptable	unacceptable	unacceptable	unacceptable
1.10	45.0	unacceptable	unacceptable	unacceptable	unacceptable

2.4.1.2 Spectrum Analysis

Goal of spectrum analysis in monitoring applications is to relate various frequencies seen in spectra (plot of amplitude versus frequency) to the various physical phenomena (Goldman, 1999). Measured overall vibration signal contains multiple smaller vibrations due to the condition of the monitored structure or machine, i.e., misalignment of rotating machines, crack on a bridge, etc. The overall vibration signal can be analyzed to reveal individual contributing components (Brown, 2006).

When a continuous waveform is to be analyzed digitally, data has to be sampled (usually at equally spaced intervals of time) in order to produce a time series of discrete samples to be fed into a digital computer. Such a time series completely represents the continuous waveform if this waveform is frequency band-limited and the samples are taken at a rate that is at least twice the highest frequency (i.e., Nyquist frequency) present in the waveform. Spectrum of such a time series can be defined by Discrete Fourier Transform (DFT). DFT is calculated by

$$A_r = \sum_{k=0}^{N-1} X_k \exp(-2\pi jrk/N) , \qquad r = 0,\cdots,N-1 \tag{8}$$

where A_r is the r^{th} coefficient of the DFT and X_k denotes the k^{th} sample of the time series which consists of N samples and j represents $\sqrt{-1}$. The k^{th} Fast Fourier Transform (FFT)

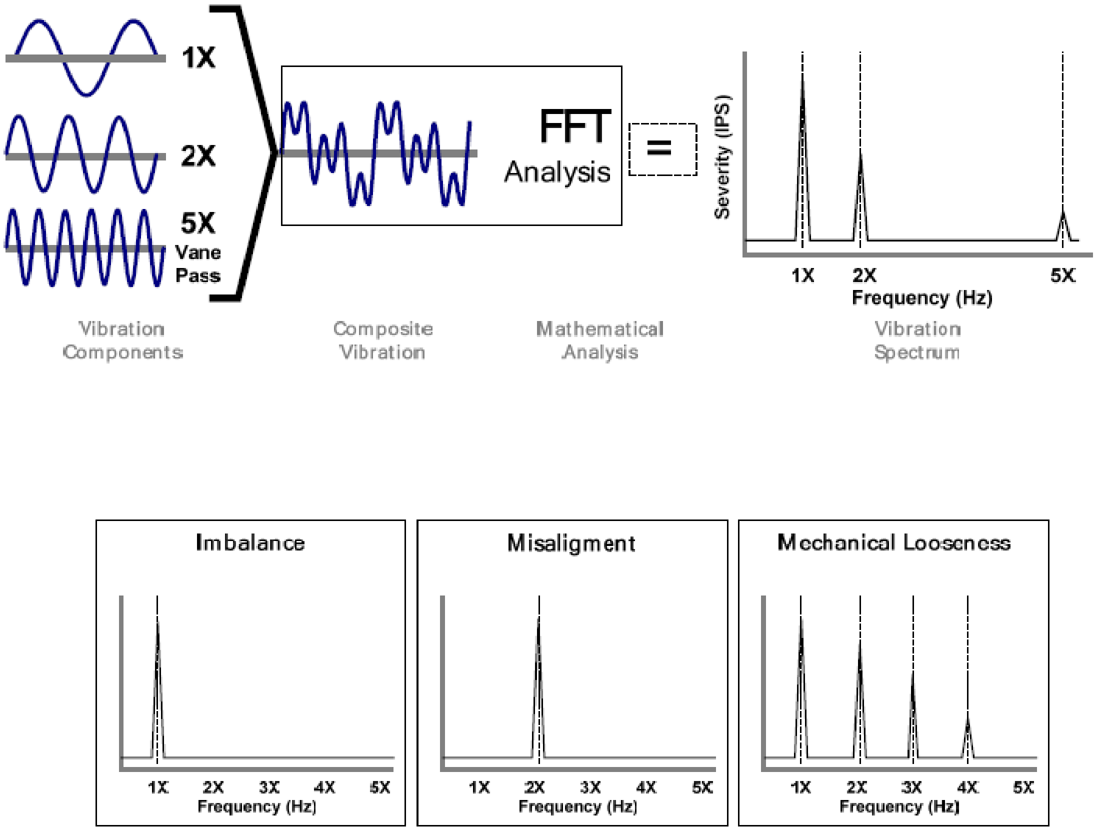


Figure 4. Spectrum analysis of a vibration signal taken from a rotating machine (Brown, 2006).

algorithm is a rapid and efficient method to compute DFT of a time series data (Cochran *et al.*, 1967). Figure 4 shows spectrum analysis of a vibration signal taken from a rotating machine.

2.4.1.3 Vibration Monitoring Applications

Vibration Monitoring for Rotating Machines

Rotating machinery constitutes the core of the industry. During the last decades a great amount of research has been conducted and several electrical, mechanical and other condition monitoring techniques have been developed to improve reliability of these devices.

Spectral transverse vibration monitoring is a widely used modern technique when monitoring rotating machines (Tavner, 2008). In this technique, spectra are reduced to a simple sequence of numbers at discrete frequencies. These numbers can then be used with criteria such as ISO 10816 to assess health condition of the machine. Figure 5 shows the basis of this technique. In the figure, a baseline is set according to maximum expected vibrations and an operational envelope is set above this.

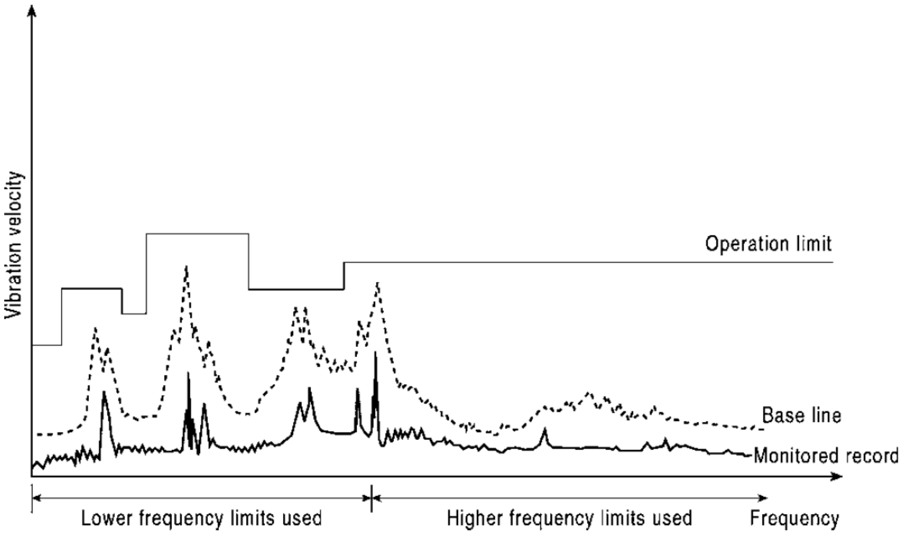


Figure 5. Operational envelope around a vibration spectral response (Tavner, 2008).

Other condition monitoring techniques, for rotating electrical machines, utilizing vibration signature include chock pulse method, torsional vibration monitoring and specific spectral transverse vibration monitoring (Tavner, 2008).

Vibration monitoring is used to discover and diagnose a wide variety of problems related to rotating machinery such as unbalance, eccentric rotors, misalignment, resonance problems, mechanical looseness/weakness, rotor rub, sleeve-bearing problems, rolling element bearing problems, flow-induced vibration problems, gear problems, electrical problems, and belt drive problems (O&M Best Practices, 2002).

Table 6 shows examples of how vibration monitoring can be used to detect problems related to rotating machinery.

Vibration Monitoring in Structural Health Monitoring

Civil structures deteriorate over time due to harsh environmental conditions, hurricanes, earthquakes, corrosion and fatigue. Real-time and periodic structural health monitoring (SHM) has a great potential to reduce the effects of these catastrophic events (Lynch *et al.*, 2006). Over the last decade, many vibration based structural damage detection methods have been developed (Doebling *et al.*, 1998; Sohn *et al.*, 2001).

Table 6. Vibration monitoring of rotating machines (Modified from MAARS, 2009).

Machine	Condition	Indication	Sensor
80 Kilowatt Standby Generator(3600 RPM)	Resonance @ 1.5X RPM	Excessive 1X and 1.5X RPM vibration amplitude (3600 RPM/60Hz, 5400 RPM/90 Hz)	Accelerometer
Large Propylene Process Refrigeration Compressor(5700 RPM)	Rotor bow from inter-stage seal rub	Failure to Achieve Operating Speed, Trip When Passing Critical Speed, Excessive 1X Amplitudes on all Probes (5700RPM/95Hz)	Proximity probes
Vertical Pump Motor (540 RPM)	Looseness induced Resonance at 1X RPM	Excessive Vibration (Shaking) at 1X RPM (540RPM/9Hz), resonance verified with transient capture, coast-down and impact tests	Accelerometer
Vertical “Canned” Safety Injection Pump (1781 RPM)	Piping and Motor Base Resonance, Turbulence, Whirl	Excessive sporadic amplitude at 46% of RPM (819 RPM/13.7 Hz), Impact tests	Accelerometer

Crane Vibration Monitoring

Bridge, overhead and deck cranes use a trolley to move their loads. For these types of cranes, there are two options to establish a higher speed and hence a faster operation: to increase maximum speed of the trolley and to decrease time spent for acceleration and deceleration. These methods increase trolley acceleration at the expense of introduced vibrations. These vibrations eventually cause various problems such as structural fatigue, operator discomfort, etc. The vibration information taken from a crane can be used to tune the controllers (Okubo *et al.*, 1997).

Besides the applications mentioned in this section, vibration monitoring has been studied for various other purposes such as pipeline monitoring (Stoianov *et al.*, 2007) and road surface monitoring (Eriksson *et al.,* 2008 a).

2.4.2 Temperature Monitoring

Temperature monitoring with simple sensors, narrow bandwidths (<1 Hz), and low data rate signals, has shown to be an effective monitoring technique for rotating electrical machines. Overloaded machines or malfunctioning coolant circuits can be detected by monitoring temperatures at one or more locations (Tavner, 2008).

Applications of temperature monitoring combined with humidity measurements, are used to enhance the productivity of greenhouses, to investigate effects of environmental conditions on the buildings, for fault detection and diagnostics in HVAC (Heating Ventilation Air Conditioning) systems, and to monitor food condition (see Section 2.5).

2.4.3 Ultrasonic Monitoring

Sound waves that have a frequency level above 20 kHz are defined as ultrasounds. Ultrasounds travel in a straight path and do not penetrate solid surfaces. Many fluid systems and most rotating equipment will emit sound patterns in ultrasonic frequency spectrum. Equipment condition can be monitored by observing these ultrasonic wave emissions. Fluid leaks, vacuum leaks and steam trap failures can be identified by ultrasonic monitoring. Furthermore it is possible to detect electrical and mechanical abnormalities by monitoring ultrasonic wave emissions (O&M Best Practices, 2002).

2.4.4 Other Monitoring Techniques

Pressure, oil, speed, flow, level, and pH monitoring techniques are other widely used monitoring techniques in many industrial plants. Besides these techniques, discharge, electrical current, flux, and power monitoring are used to assess condition of electrical machines (Tavner, 2008). Many of these monitoring techniques are discussed and their applicability and suitability for wireless condition monitoring is evaluated in (Tuononen, 2009).

2.4.5 Multi-parameter monitoring

Multi-parameter monitoring can be described as combining a number of indicators together into a single monitoring system to improve detection. For example, temperature, chemical degradation or vibration signals can be used alongside with electrical signals to assess health condition of electrical machines. This approach gives operators a better confidence. Multi-parameter methods are believed to play a major role in machine condition monitoring in the future (Tavner, 2008).

2.5 Review of Wireless Monitoring Applications

Various transducers have successfully been integrated into wireless nodes and several academic and commercial applications have been developed. In this section some of these reference applications will be introduced.

2.5.1 Academic Studies and Applications

PipeNET of Cambridge University, aims to monitor water transmission pipelines to detect and localize leaks using wireless sensor networks. The system is also used to monitor water quality and level in water transmission and distribution systems. PipeNET system employs pressure, flow, acoustic/vibration, level and pH sensors. Figure 6 shows high level description of three pipeline monitoring scenarios (Stoianov *et al.*, 2007). PipeNET is a good example of a wireless monitoring system, since it combines several transducers, wireless monitoring strategies and application areas into one monitoring system.

Krishnamurthy *et al.* (2005) studied applicability of industrial wireless sensor networks for predictive maintenance purposes. Nodes equipped with accelerometer sensors and ZigBee radios were tested in a semiconductor fabrication plant and in an oil tanker.

Applicability of wireless monitoring systems in building automation (Osterlind *et al.*, 2007) and HVAC systems (Oksa *et al.*, 2008; Kintner-Meyer *et al.*, 2004) has been studied.

Intensive research is being conducted on WSN applications for SHM and several prototypes were proposed in recent years. These prototypes utilize nodes equipped with

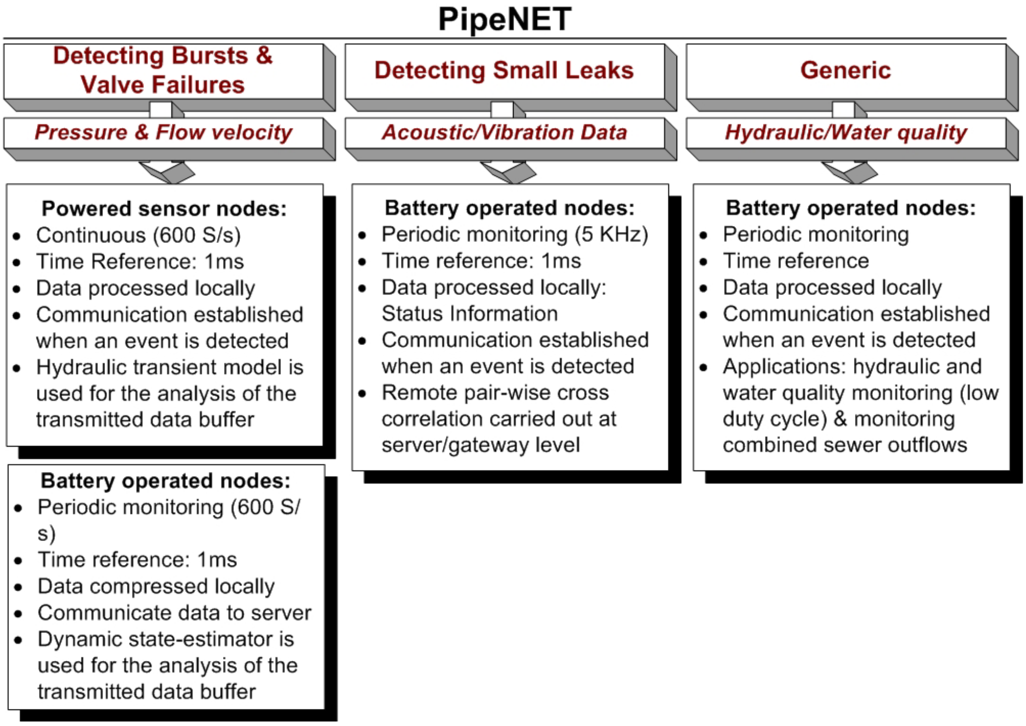


Figure 6. Monitoring system for water transmission pipelines (Stoianov *et al.*, 2007).

accelerometer sensors and ZigBee radios (Pakzad *et al.*, 2008; Xu *et al.*, 2004; Bocca *et al.*, 2009).

A wireless sensor network has been implemented and deployed in a petroleum facility. Effects of latency and environmental noise on a WSN were investigated (Johnstone *et al.*, 2007).

Several other wireless monitoring applications have been developed for food and agriculture industries (Wang *et al.*, 2006), volcanic monitoring, health monitoring, and environmental monitoring (Yick *et al.*, 2008).

2.5.2 Commercial Applications

In this section a number of commercial wireless monitoring systems are described. Emerson Process Management provides smart wireless field network solutions for process and asset monitoring that employ temperature, pressure, vibration, pH, corrosion, flow, and level transducers and WirelessHART communication protocol (Emerson, 2009). Honeywell, another key player in sensors and sensing applications industry, uses their own OneWireless universal mesh network, which supports multiple industrial protocols and applications simultaneously, to monitor plants (Honeywell, 2009). Accutech Instrumentation Solutions provides wireless instrumentation products (wireless acoustic, temperature, pressure or discrete input sensors) for the industry. Accutech radios work on 902 MHz – 928 MHz band and support open communication standards such as ISA and HART (Accutech, 2009). ProSmart of International Telephone & Telegraph (ITT) is a wireless monitoring system for rotating equipment health monitoring and pumping system control. ProSmart nodes, with 2.4 GHz radios, employ vibration, tachometer, temperature, and inductive speed sensors and other terminal blocks (ProSmart, 2009). WiSensys system of Wireless Value provides wireless solutions for food, industrial, building automation and agricultural monitoring (WiSensys, 2009). Tollgrade Communications Inc. produces wireless sensors to monitor key circuit parameters, such as voltage, current and power, for fault detection and maintenance purposes (Honath, 2008). Other companies that provide commercial wireless monitoring systems include Microstrain, Millenial Net, Flowserve, SKF, Siemens, Sensicast and ABB.

2.6 Key Design Considerations for Wireless Monitoring Systems

This section gives an overview of key design considerations when designing wireless monitoring systems. Note that communication reliability and power consumption are not going to be mentioned in this section. These are two very important issues to be considered when designing wireless systems for continuous monitoring. However, this thesis focuses on developing a general purpose wireless monitoring toolkit which is going to be used mainly for periodic monitoring, where requirements on battery lifetime and energy use optimization are not playing a significant role.

2.6.1 Sampling Frequency

Sampling frequency of a sensor in a monitoring application is set by the highest frequency of interest. Highest frequency of interest is highly application dependent and it is impossible to state that one sampling frequency that will suit all applications. For example, as it can be seen in Section 2.4.1, when monitoring vibrations of the rotating machines, frequencies of interest are usually below 200 Hz. Rotating electrical machines, however, in some cases require monitoring a much broader bandwidth (50 kHz) (Tavner, 2008). On the other hand, for very stiff structures, such as concrete bridges, a bandwidth of 0.1 to 20 Hz is of importance (Kruger *et al.*, 2004).

Once the highest frequency of interest is determined, theoretical lower limit for sampling frequency can be found according to Nyquist–Shannon sampling theorem, i.e., by multiplying the highest frequency of interest by two. However, in practice, when filters and noise reduction algorithms are taken into account, higher sampling frequencies are required. Most commercial frequency analyzers sample at a rate of 2.56 times highest frequency to compensate these effects (Goldman, 1999). In this respect, maximum achievable sampling rate is an important criterion when designing wireless sensor nodes.

2.6.2 Sensitivity of the Sensors

Sensitivity of a sensor is the ratio of the magnitude of its response to the magnitude of the quantity measured (Vig *et al.*, 2000). For example, if the mercury in a thermometer moves 1 cm when temperature changes by 1 °C, the sensitivity is said to be 1 cm/°C. It is important to use high sensitivity sensors when measuring very small variables.

2.6.3 Sensor Resolution

Resolution is an important specification for reliable measurements. Resolution of a sensor is the smallest change it can detect in the quantity that it is measuring. This smallest change is often limited by the electrical noise present. Resolution is only useful when it is evaluated within the context of bandwidth. Low-pass filters can be used to eliminate high frequency noise, however, they reduce the bandwidth of the sensor at the same time. Similarly, when a lower measurement bandwidth is used, a higher resolution is obtained. Thus the resolution information in sensor datasheets can be misleading and it should not be assumed that sensors' bandwidth and resolution specifications can be achieved simultaneously (Lion Precision, 2009).

2.6.4 Frequency Resolution and Windowing

Frequency resolution defines the minimum frequency difference between two sinusoids that allows resolving two distinct peaks in the spectrum. It is calculated by

$$f_r = \frac{f_s}{N}, \tag{9}$$

where f_s denotes sampling frequency, f_r denotes frequency resolution and N denotes number of samples taken.

Windowing technique is used to increase spectral resolution by minimizing edge effects that result in spectral leakage in the FFT spectrum. FFT algorithm assumes that the finite data set consists of one period of a periodic signal, which means that two endpoints of the time waveform are interpreted to be connected. However, this can introduce sharp transition changes into the measured data and different spectral characteristics than that of original continuous signal. Windowing is a technique used to shape the time portion of the measurement data, to minimize edge effects that result in spectral leakage in the FFT spectrum. There are various types of windowing functions and their performance varies according to the applications they are used for (National Instruments, 2009). Table 7 shows some window recommendations for different types of signals.

2.6.5 Measurement Length

Once the required frequency resolution and sampling frequency are known, number of data points, hence the measurement length, can be calculated according to (9). If a higher sampling frequency than that of needed is chosen, the amount of data to meet the same frequency resolution will increase. This will decrease the performance of a wireless node which has limited memory, computational power and energy.

2.6.6 Synchronization

Wireless sensor nodes have the capability of monitoring physical phenomena at multiple locations and possibly by measuring more than one type of parameter. Synchronization of the measurement nodes should be established in order to have a reliable cause-effect relationship among the various monitored parameters. “Time related, abrupt, spurious (false) variation in the duration of any specified related interval” is defined as varying time delay, or jitter by IEEE. These variations depend on the clock accuracy, scheduling algorithm (CPU), computer hardware structure and network protocol (Eriksson *et al.*, 2008 b). Jitter should be handled carefully to obtain reliable and synchronous measurements from the measurement nodes in a wireless sensor network.

Table 7. Recommendations for different window types (National Instruments, 2009).

Type of Signal	Window
Transients whose duration is shorter than the length of the window	Rectangular
Transients whose duration is longer than the length of the window	Exponential, Hanning
General-purpose applications	Hanning
Spectral analysis (frequency-response measurements)	Hanning (for random excitation), Rectangular (for pseudorandom excitation)
Separation of two tones with frequencies very close to each other but with widely differing amplitudes	Kaiser-Bessel
Separation of two tones with frequencies very close to each other but with almost equal amplitudes	Rectangular
Accurate single-tone amplitude measurements	Flat top
Sine wave or combination of sine waves	Hanning
Sine wave and amplitude accuracy is important	Flat top
Narrowband random signal (vibration data)	Hanning
Broadband random (white noise)	Uniform
Closely spaced sine waves	Uniform, Hamming
Excitation signals (hammer blow)	Force
Response signals	Exponential
Unknown content	Hanning

2.6.7 Radio, Routing and Networking Issues

Among the physical radio specifications explained in Section 2.1 (IEEE 802.15.1, 802.15.3a, 802.15.4, 802.11b), IEEE 802.15.4 is ideal for monitoring, control, automation, sensing and tracking applications for the home, medical and industrial environments. Being based on IEEE 802.15.4, ZigBee is considered to be the most promising standard for wireless sensors due to its low power consumption, data rates and simple networking capability (Wang *et al.*, 2006). However, limited bandwidth (250 kbps) of IEEE 802.15.4 radios can result in long operation times when they are used for high data rate applications (Cosar *et al.*, 2009). Bluetooth can be an option when monitored system requires a high sampling rate, however, its low scalability (8 devices per network) compared to that of ZigBee's (up to 65,000 devices per network) limits its usage. In the context of monitoring applications, only case Bluetooth would be more advantageous over ZigBee would be when a system requires high data rate communication in a small area with less than eight sensor nodes for a short period of time. Otherwise, being an open standard and mature in development, ZigBee is a good candidate for most of the wireless monitoring systems.

ZigBee defines three device types: ZigBee coordinator, ZigBee router and ZigBee end device. These devices form one of the three types of network topologies: star, tree and mesh (peer-to-peer). These topologies are shown in Figure 7.

In star topology, ZigBee end devices only communicate with ZigBee coordinator. In mesh topology any device can communicate with any other device in their range. Mesh networks can form ad-hoc, self organizing and self healing communication schemes. Hierarchical/Tree routing and integrated routing method combined with Ad hoc On Demand Distance Vector (AODV) are used in mesh networks. Multipath routing capacity improves reliability of mesh networks. Cluster tree networks are utilized by full functioning devices (FFD) and reduced function devices (RFD). FFD device is a coordinator which provides synchronization services to other devices and coordinators. Hierarchical /tree routing mechanism is used in cluster tree networks (Sun *et al.*, 2007).

Radio, routing and network topology requirements of a wireless monitoring system can vary depending on the application. Simplest scenario employs a single hop star topology. Note that time required to transfer the data increases as the number of hops

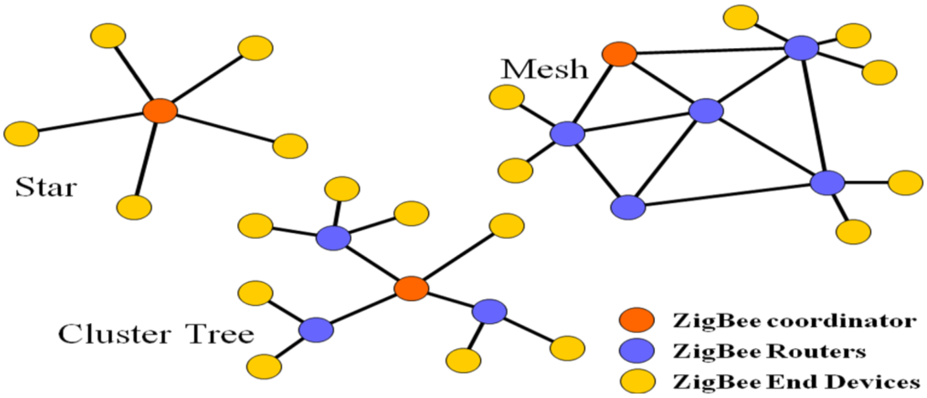


Figure 7. ZigBee network topologies (Kinney, 2003).

increases. Furthermore, synchronizing multiple nodes becomes harder when multi-hop topologies are used. However, when the monitored area is large, communication range of the radio can be a limitation, and in such a case multi-hop networks would be needed.

2.6.8 Data Storage and Transmission

Wireless sensor networks have limited communication bandwidths. When high sampling rates are used, it is not possible to transmit the measurement data immediately after sampling (the sample-and-transmit method). In such cases, samples have to be stored in memory of the sensor node and transmitted after the sampling operation has finished (the sample-store-transmit method) (Mechitov *et al.*, 2004). If the internal memory of wireless node’s microcontroller unit (MCU) is not sufficient to store all the samples, external memories are needed, such as an external flash memory. However, using an external memory can introduce additional delays in sampling which will cause lost samples (Bocca *et al.*, 2009).

Data collected by wireless sensor nodes have to be transferred unless locally processed in the node. This data transmission can take ten times the measurement length due to the limited bandwidth of wireless sensor networks in traditional WSN applications (Cosar *et al.*, 2009). A practical wireless monitoring system should provide the collected data in a reasonable length of time.

2.6.9 Simplicity and Configurability

Monitored structures or processes can require a variety of measurement settings. A general purpose wireless monitoring application should meet the requirements of different monitoring applications. Configuration of the system should be easy so that a serviceman should be capable of setting the system without considering the application level issues (Desborough *et al.*, 2001).

2.7 Summary

In this chapter, current condition monitoring and performance optimization trends were presented. It has been shown that there is an increasing need for intelligent monitoring applications and wireless sensor networks are likely to play an important role in future monitoring operations.

Monitoring systems are widely used in industry. Reference academic and commercial wireless monitoring applications reviewed here show how wireless sensors can contribute to monitoring systems.

This study showed that an easy-to-use, easy-to-setup, flexible, non-intrusive multi-parameter wireless monitoring system, which can provide reliable measurements in a short time, has a great potential for condition monitoring and performance optimization purposes. Design considerations for such a system were discussed in the last section of this chapter.

3 Wireless Monitoring Toolkit

3.1 General Description

Wireless monitoring toolkit can be defined as a multipurpose, portable, easy-to-use, simple-to-setup, simple-to-reconfigure and fast-to-collect-data monitoring system. It is designed for simultaneous multi-parameter monitoring of physical structures and processes.

Toolkit includes three applications, one data acquisition system, hardware components (sensors, casing, antennas, etc.), sensor drivers, and user interfaces.

Sensor nodes consist of temperature and humidity sensors, an accelerometer sensor printed circuit board (PCB), an off-the-shelf wireless node, antenna, battery, an on and off switch, and strong magnets enabling easy installation. All these components are put into a compact case. Wireless node includes an IEEE 802.15.4 compatible radio, MCU, memory and external I/O pins.

During the toolkit development, a novel data acquisition system was implemented. This system optimizes data transfer from wireless sensor nodes to PCs. Optimization of this data transfer was seen to considerably decrease data collection times.

Applications developed within the scope of the toolkit are listed below:

- A communication test application was developed to evaluate wireless network characteristics.
- A high sampling rate application was developed. This application aims fast collection of measurement data without losing any packets. Developed data acquisition system is integrated into this application.
- A real-time monitoring application was developed to collect measurement data in real-time for low sampling rate (< 200 Hz) applications. Synchronization of the wireless nodes was improved by using the multi-tasking capability of the operating system.

Usability of these applications was improved by user interfaces that hide lower level programming issues from the operator.

Initial goal of the thesis was to integrate all the developed modules into one node and interface. However Micro.2420 nodes have a limited amount of memory, hence when the size of the program exceeds the memory size of the MCU, it is not possible to compile a code.

Currently communication test and high sampling rate applications are embedded in one code and user interface. However, the real-time monitoring application is located in another code and has its own user interface. Future study will focus on optimizing these codes and putting them together in one code.

3.2 Sensor Node

3.2.1 Micro.2420 Wireless Sensor Network Platform

Sensinode Micro.2420 nodes were chosen as the wireless sensor network platform. The Micro.2420 nodes are based on a TI MSP430 MCU core having 10 kB RAM and 256 kB flash memory. The clock of the MCU and the bus run at 8 MHz. The MCU provides a multi channel 12 bit analog to digital converter (ADC) with voltage range 0-3.3 V and two 12 bit digital to analog converters (DACs) (0-2.5 V). An external 0.5 MB serial flash memory is connected to the MCU. The radio module is an IEEE 802.15.4 compatible, Chipcon CC2420 transceiver, operating on the 2.4 GHz band, having 250 kbps bandwidth. The platform runs the FreeRTOS real-time kernel. The Micro.2420 nodes have a 12 pin external connector on which 8 GPIO, 2 ground pins and one power pin are located. A 50-pin Micro.bus connects Sensinode Micro series modules into a stack and it has SPI, programming, power, UART, clock, reset, interrupt, 1-wire and parallel I/O lines on it. Dimensions of Micro.2420 are 40 x 50 mm. Wireless node can be powered by two AAA batteries (Sensinode, 2006). Figure 8 shows a Micro.2420 wireless sensor node and its components.

Micro.2420 runs NanoStack™ 1.0.3, a flexible 6LoWPAN protocol stack with a full IEEE 802.15.4 implementation (Nanostack, 2009).

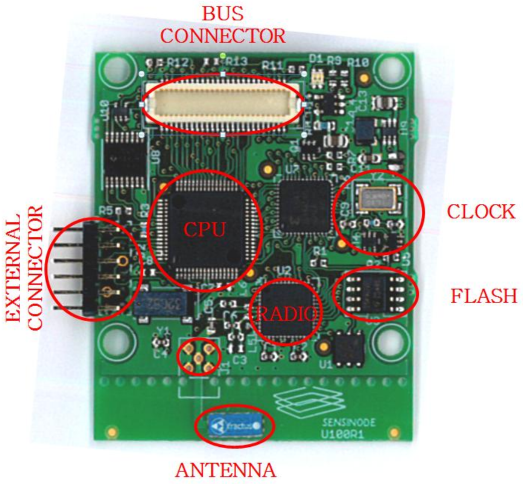


Figure 8. Micro.2420 wireless node.

3.2.2 Sensors

Wireless sensor nodes are equipped with 3-axis digital accelerometers (LIS3LV02DQ by STMicroelectronics, 7x7x1.5 mm) that have 1 mg resolution at 40 Hz bandwidth. Output data rate (ODR) can be set to 40, 160, 640 or 2560 Hz. Sensor bandwidth is defined to be one fourth of the output data rate, thus the maximum measurement bandwidth is 640 Hz. Sensor has a user selectable full scale of ±2g or ±6g. Data is transferred through a Serial Peripheral Interface (SPI) interface. A dedicated PCB board is created to connect the sensor to Micro.2420 though a 50 pin bus connector.

A low power temperature and humidity sensor (SHT71 by Sensirion) is connected to the Micro.2420 through 12 pin external connector. Typical resolution of SHT71 is 0.01 ºC for temperature and 0.05 % Rh (Relative Humidity) for humidity. Communication is established using a digital 2-wire interface.

3.2.3 Integration of Components

Components of the sensor node are combined into one single node box. This node box includes an accelerometer board stacked on Micro.2420 node, temperature and humidity sensor connected to Micro.2420, an external antenna to enhance wireless communication capability of Micro.2420, and four external I/O pins including a ground, 3.3 V and two Input/output (I/O) pins. Accelerometer Board is tightly screwed to the bottom of the box to increase accuracy of measurements. Two strong magnets are used to attach the nodes to the monitored structure. Damping is minimized by doing so. Node case also includes two AAA batteries and an on/off switch. Figure 9 shows a picture of wireless sensor node after all the components combined into one node box.

3.2.4 Programming, Control and I/O

Sensinode U600 Micro.USB modules are used to interface Sensinode Micro series nodes with a PC, providing a serial connection over USB for debugging, controlling and programming purposes. Micro.USB programming board includes a FTDI FT232R UART-to-USB chip. Thus chip is compatible with USB full speed (12 Mbit/s), and provides a serial port between Sensinode nodes (directly to the microcontroller) and PC.

Application codes are written in C programming language. GNU (GNU's Not Unix) Compiler Collection (GCC) is used to create binary files. Compiled files are uploaded by msp430-bsl programmer for Micro platform devices.

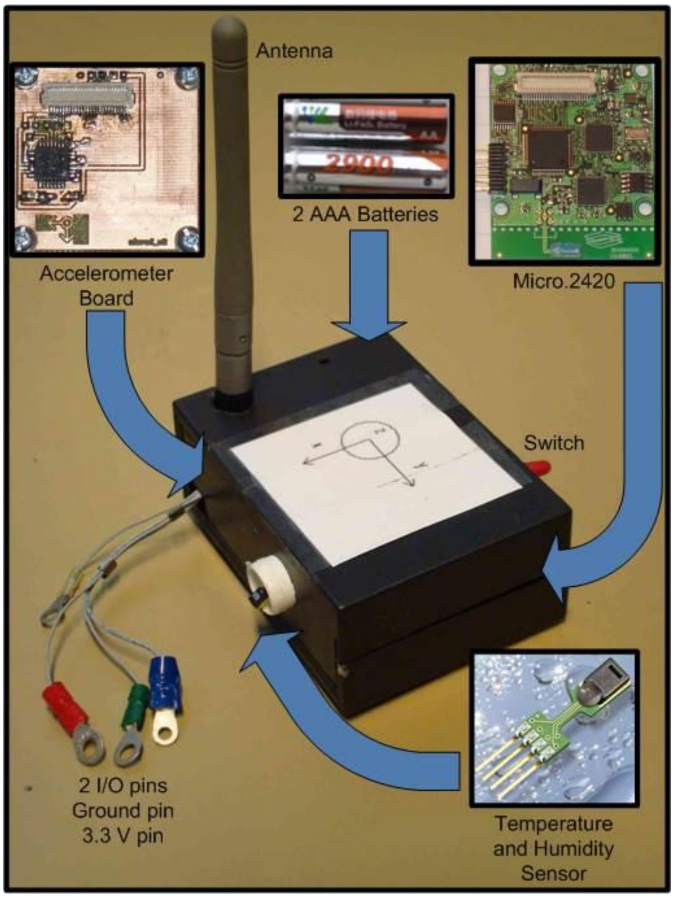


Figure 9. Wireless sensor node.

MATLAB 7.5.0 (R2007b) serial port interface is used to manage the I/O between Micro.USB and PC. When data are sent from the node to serial port of the PC, callback functions handle and parse the data. Using MATLAB software enhances the flexibility of the system in the sense that the nodes can be controlled and data can be processed in near real-time by a script or user.

3.2.5 Network Topology and Communication

Single hop star topology is used for communication. This approach represents a simple case, however, generated knowledge and experience can easily be used for more complex scenarios in future.

Communication tasks are handled by NanoStack. Features are accessed via Socket API (Application Program Interface). Communication sockets can be bind to specific addresses. NanoStack ports are identical to those of TCP/IP stack and they range from 5 to 65536 in uncompressed mode and from 61616-61631 in restricted mode. Address structure supported by NanoStack includes address type, address and port information.

Developed applications use port numbers for identification. This means that every node has its own port number. Messages are sent to or received from a node through these ports.

Packets received by the wireless nodes can be handled in one of the two ways: scanning the socket, or in a callback manner. When the former is chosen, incoming packets are stored in the receive buffer of the radio and pulled only when node reads the communication socket. When callback reception is selected, a callback function handles the data whenever a packet is received (Sensinode, 2007). Using a callback function provides more precision when a timing critical packet is to be received.

3.2.6 Measurement Node and Sink Node

Two node types are used in wireless monitoring toolkit: a measurement node (see Figure 9) and a sink node. Sink node is simply a Micro.2420 module connected to a PC through a U600 Micro.USB programming board. It has two main tasks:

1. Managing I/O with PC, i.e., taking user defined setting, sending incoming measurement data to PC, debugging errors, etc.

2. Communication with measurement nodes, i.e., sending setting packets, operation initiation, synchronization, receiving data, acknowledgement, etc.

A measurement node is the node equipped with the hardware presented in Section 3.2.3. Two main tasks of measurement nodes are:

1. Communication with sink node

2. Sampling

3.3 Real-time Monitoring Application

A real-time monitoring system has been developed for low sampling rate (< 200 Hz) applications. When the monitored frequencies are not high, wireless nodes can sample and transmit without storing the measurement data to an external memory. This approach reduces the time spent for measurements.

A MATLAB based graphical user interface (GUI) has been developed to increase usability of the system. Synchronization of the wireless nodes is established by using multi-tasking capability of the operating system. Conventional processors execute tasks one by one, however, an operating system is said to be multitasking when it rapidly switches between tasks (FreeRTOS, 2009). Figure 10 illustrates the task execution in a multitasking operating system.

Operation starts after the user sets the configuration parameters and press start button of the GUI. MATLAB program generates a settings packet according to the user preferences. This packet includes operational parameters such as timing of the operation, active nodes, active sensors in active nodes, etc. The packet is first transferred to the sink node using MATLAB’s serial port interface. Sink node transfers this packet to the measurement nodes and waits for an acknowledgement. When the measurement nodes receive this message, they check whether they are going to be active in this operation or not. If they are going to be active, they take the settings

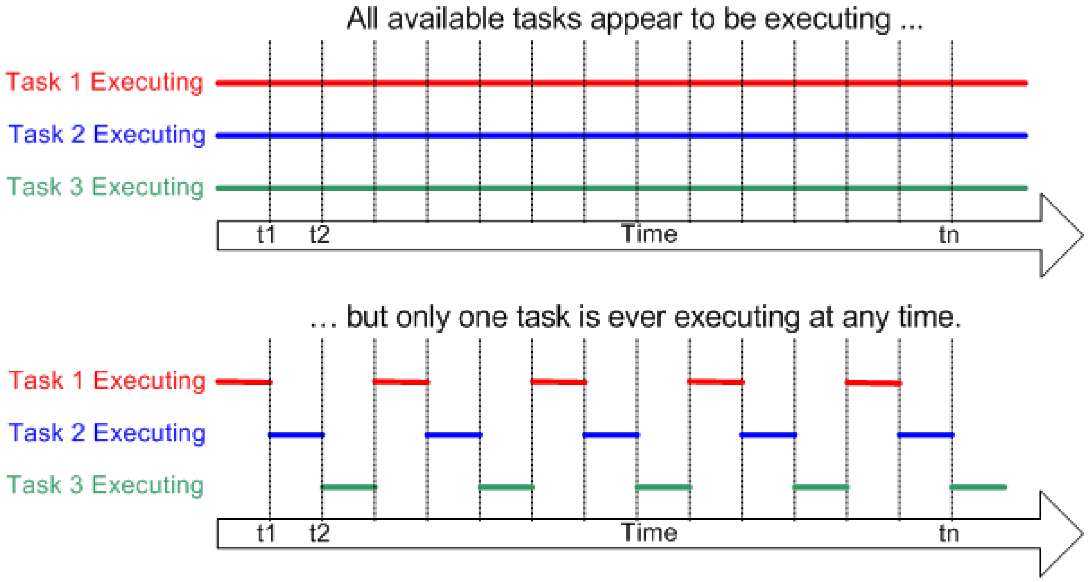


Figure 10. Task execution in a multitasking operating system (FreeRTOS, 2009).

and adjust themselves according to the settings. They send a confirmation message indicating that they took the settings, and are ready for sampling operation. Then sampling and data collection starts. Operation ends when the user presses “stop” button of the GUI. Details of the operation will be presented in the following sections.

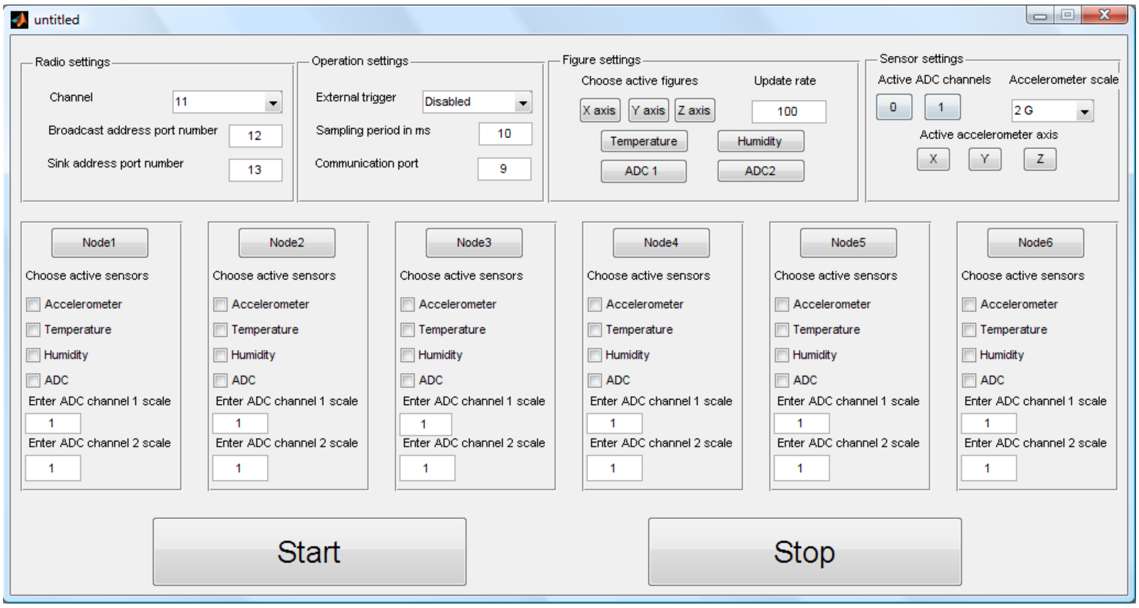
3.3.1 User Interface and Configuration

MATLAB user interface is designed and implemented so that a user can easily setup the monitoring system parameters according to the needs. Main idea is to hide complex application details from the user by providing an easy-to-use interface. MATLAB GUI can be seen in Figure 11. Note that for the developed prototype toolkit, 6 nodes are enough and that is why the GUI is designed for 6 nodes. However, the toolkit and the GUI can easily be expanded to support more nodes.

The settings of the GUI are listed below.

1. Radio Settings:

Suitable communication parameters can vary according to the environment. This menu is designed considering the “communication test” application which will be explained later. With communication test application the user can choose the optimum radio



Radio settings
Channel: 11
Broadcast address port number: 12
Sink address port number: 13

Operation settings
External trigger: Disabled
Sampling period in ms: 10
Communication port: 9

Figure settings
Choose active figures
Update rate: 100

Sensor settings
Active ADC channels
Accelerometer scale: 2 G
Active accelerometer axis

Node1
Choose active sensors
☐ Accelerometer
☐ Temperature
☐ Humidity
☐ ADC
Enter ADC channel 1 scale: 1
Enter ADC channel 2 scale: 1

Node2
Choose active sensors
☐ Accelerometer
☐ Temperature
☐ Humidity
☐ ADC
Enter ADC channel 1 scale: 1
Enter ADC channel 2 scale: 1

Node3
Choose active sensors
☐ Accelerometer
☐ Temperature
☐ Humidity
☐ ADC
Enter ADC channel 1 scale: 1
Enter ADC channel 2 scale: 1

Node4
Choose active sensors
☐ Accelerometer
☐ Temperature
☐ Humidity
☐ ADC
Enter ADC channel 1 scale: 1
Enter ADC channel 2 scale: 1

Node5
Choose active sensors
☐ Accelerometer
☐ Temperature
☐ Humidity
☐ ADC
Enter ADC channel 1 scale: 1
Enter ADC channel 2 scale: 1

Node6
Choose active sensors
☐ Accelerometer
☐ Temperature
☐ Humidity
☐ ADC
Enter ADC channel 1 scale: 1
Enter ADC channel 2 scale: 1

Figure 11. MATLAB GUI.

channel and this channel can be set as the communication channel through the GUI. Furthermore sink address port and broadcast address port settings can be changed to avoid mixing packets with other active wireless networks using the same channel.

2. Operation Settings:

Communication port, external triggering and sampling period can be set through this menu. Communication port is the dedicated serial port number of the PC for the communication with the sink node. External triggering is useful when measurements are needed to be triggered by an event. There are three options for this menu bar: disabled, high-to-low, and low-to-high. This setting adjusts an external I/O port of the sink node so that it will sense a high-to-low or low-to-high transition. Sampling period is the time between two consecutive measurements.

3. Sensor Settings:

With this menu, user can choose active ADC channels (*ADC1* or *ADC2*), active axis of the accelerometer (X, Y, or Z), and the scale of the accelerometer (± 2 g or ± 6 g).

4. Figure Settings:

User can choose which graphs will be active during the measurement, i.e., temperature, humidity, accelerometer (X, Y, or Z), ADC (*ADC1* or *ADC2*). Update rate defines number of samples to be taken before graphs are updated.

5. Node Settings:

Currently, the GUI is implemented for six measurement nodes. User can choose active nodes in the measurement and active sensors in these nodes (accelerometer, temperature, humidity or ADC). Scale of ADC can be set in this menu. This property is added considering the analog signals that can be connected to the ADC terminals. Graphs are presented and data are saved with this scaling.

6. Start Stop Buttons:

These buttons are used to start and stop the operation. When stop button is pressed, user is asked whether he wants to save the current measurements.

3.3.2 Settings Packet

Data transmission during the operation is based on 80 byte packets, 72 of which are reserved for data. A packet is transmitted from measurement nodes to the sink node only when there is enough data available, not after every sample taken. By this way, unnecessary wireless transmission is prevented. In this respect, settings packet does not just transfer user preferences to the measurement nodes. Instead it also transfers operational parameters of the network.

Following equations give the most critical calculations done when forming the settings packet.

$$BpS = (Axis*2) + [2*(T+H+ADC1+ADC2)]\ , \tag{10}$$

BpS stands for bytes per sample and it indicates the amount of data bytes during one sampling interval. $Axis$ is the number of accelerometer axis, i.e., 1 for X axis, 3 for X, Y, and Z. Abbreviations T, H, $ADC1$, $ADC2$ indicate respectively temperature and humidity sensors, and ADC channels one and two. These parameters are set to one if the sensor in concern is active. BpS is calculated for each node, since node setting can be asymmetrical. Number of samples per packet, SpP is calculated as below

$$SpP = \text{floor}\left(\frac{72}{\max(BpS)}\right) \,, \tag{11}$$

Time in between two consecutive synchronization packets, T_t, is calculated by

$$T_t = SpP.T_s \,, \tag{12}$$

where T_s stands for sampling interval. Finally each node is assigned a portion of T_t for data transmission according to

$$NI = \frac{T_t}{number\_of\_nodes} \,, \tag{13}$$

where NI stands for node interval. Timing of the operation and use of the calculated parameters are illustrated in Figure 12.

3.3.3 Application Tasks

Table 8 shows the tasks defined for the measurement and sink nodes and the task priorities.

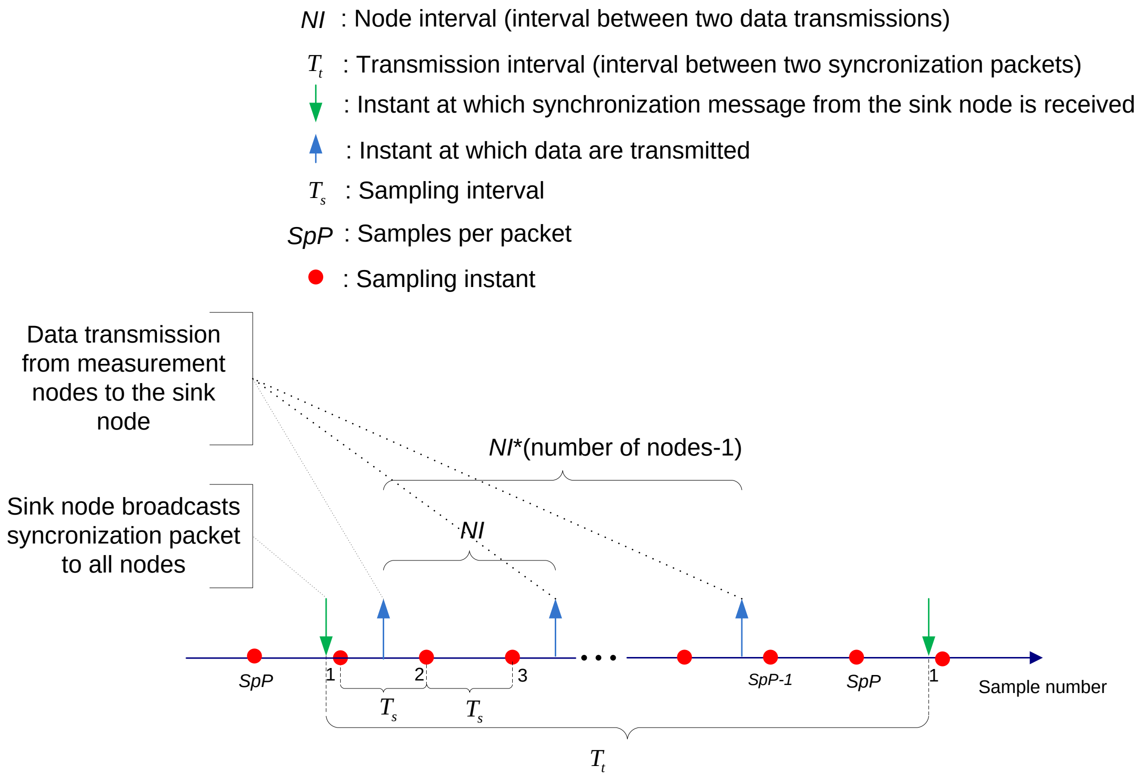


Figure 12. Timing of the operation.

Table 8. Application tasks and their priorities.

	Measurement Node	Sink Node	Priority
Task 1	Take settings from sink node	Take settings from PC and transfer those to measurement nodes	High
Task 2	Sampling	Transmit synchronization message	High
Task 3	Transmit measurement data	Receive measurement data and pass it to PC	Low

Time critical tasks such as sampling and transmission of synchronization packet are given the highest priorities. Transmitting and receiving measurement data are not critical for the precision of the measurements, hence their priorities are lower.

Sink Node Task 1: Settings

This task is responsible of taking the settings packet from the PC, broadcasting it to the sink nodes and waiting for the acknowledgement. During this task, other tasks are pending. This task is killed once the nodes are set.

Measurement Node Task 1: Settings

Measurement node scans the channel until the settings packet is received from the sink. Then the node checks whether it will be active during the measurement. Active nodes adjust their sensor and ADC settings. Then they send an acknowledgement packet to the sink. Task kills itself after the settings are done. Note that other tasks are pending during this task.

Sink Node Task 2: Synchronization

Sink node transmits synchronization packets periodically with intervals defined by T_t. Synchronization packets are designed to arrange timing of the measurements and to ensure synchronous sampling of all the nodes despite their individual clock drifts. This is why this task is given the highest priority. Synchronization packet includes a two byte counter, which is used to detect packet order and lost packets.

Measurement Node Task 2: Sampling

This task is responsible of sampling. Samples from the active sensors are taken and stored in a measurement buffer, which then will be transferred to a transmission buffer. This is the task that has highest priority for the measurement node.

Sink Node Task 3: Data Storing

Incoming packets are stored in the sink node's receive buffer and packets are handled whenever the node can spare its resources for this task. This means that the sink node does not handle the data right after it is received, but waits until there is no other critical task ongoing. Handled data is transferred to the PC through the serial port. The program is configured so that the sink node has enough time for this task and no data loss occurs due to the execution of other tasks.

Measurement Node Task 3: Data Transmission

This task is responsible of transferring the measurement data taken during the previous cycle. Every node is assigned a time period within a cycle to transmit its measurements. Exact time of this transmission is not exactly known a priori, since the node transmits whenever it has the resources. Transmitting the data is not time critical, that is why this task has lower priority.

3.3.4 Remarks of the Operation

Note that for measurement nodes, reception is not defined in a task. A callback function is used to handle the synchronization packets. This callback function resets the measurement timer of the node to reduce the effects of clock drift and other delays. Measurements of the previous cycle are transferred to a transmission buffer to be sent during the next cycle. Counter in the synchronization packet is stored in the measurement buffer to indicate the order of the packet. This counter information is present in the transmitted data packets, and sink node forwards this number to the PC along with the data itself. MATLAB callback function compares this number with number of previous packet received. If the difference is larger than one, it introduces a gap to the data stored in PC. MATLAB callback function parses the data according to the node number and sensors. MATLAB plots the selected figure in real-time.

Note also that two types of buffers are used in measurement nodes: measurement buffer and transmission buffer. This is due to nature of the multi-task operation. A data packet is not transferred at a predetermined instant. Instead the MCU schedules an interval for transmission when it is available. Meanwhile the sampling operation continues. So if the same buffer was used for both new measurements and transmission, new samples would be written on the data taken in the previous cycle.

3.3.5 Summary

Real-time monitoring application is carefully planned to meet the objectives of wireless monitoring toolkit. This application has two very important features which distinguish it from other wireless monitoring applications. These two features are dynamic and multi-task operation.

Dynamic operation means that the timing of the operation is not predetermined and operational parameters are adjusted each time according to user preferences. This enables the user to choose any number of nodes, any sampling frequency and any number of sensors. Operation would be optimally adjusted each time according to the given preferences as long as the platform limitations are not exceeded. This property of the application makes it suitable for a broad range of monitoring applications.

Multi-tasking operation provides efficient allocation of resources and increased measurement precision. With this approach, time-critical tasks, such as sampling and synchronization, are given higher priorities whereas other tasks, such as transmission and handling of measurement data, are given lower priorities.

The user can choose the best performing channel based on the RSSI measurements. Furthermore, effect of node location on RSSI can be determined with this application.

3.4 Communication Test Application

This application is developed to assess communication link quality of measurement environment. Received signal strength indicator (RSSI) measurements are used as quality indices. RSSI is based on measuring the power present in a received radio signal.

In this application the user defines radio channels and nodes to be tested, number of packets in each test, number of bytes in each packet and transmission power. Then MATLAB transfers these settings to the sink node. Sink node transmits the settings to measurement nodes. Nodes set their radio channels and transmission powers accordingly. Then they transmit test packets. Sink node compares RSSI values of received packets to a set of standard values and calculates RSSI histogram based on this data and sends it back to PC. Results are plotted once the tests are completed. Section 4.3.1 presents how this application can be used to evaluate wireless communication characteristics of the sensor nodes in an industrial environment.

3.5 High Speed Portable Wireless Data Acquisition System

One of the objectives of this thesis was to develop a wireless monitoring system which can collect high sampling rate data in a reasonable amount of time. In a typical wireless structural health monitoring application, we have observed an operation time of approximately 30 minutes for a measurement setup with 6 nodes, 30 seconds of sampling, 6 bytes of data per sample at 1 kHz sample rate (a total of 1.08 MB of data). This means several hours of data collection for larger deployments. Importance of data aggregation on scalability (Mechitov *et al.*, 2004) and long data aggregation periods of WSNs in SHM applications (Pakzad *et al.*, 2008) have been previously reported and several studies have concentrated on the efficient utilization of communication bandwidth in WSNs (Paek *et al.*, 2005, Kimura *et al.*, 2005).

High data rate applications are an emerging branch of wireless sensor networks (WSNs) including applications, such as structural health monitoring (Lynch *et al.*, 2006), condition monitoring (Wright *et al.*, 2008), wireless surveillance (Akyildiz *et al.*, 2006), and patient health monitoring (Paksuniemi *et al.*, 2005). Communication between a sink node and a PC can constitute a bottleneck for high data rate applications of wireless sensor networks (WSNs). The cause of this bottleneck will be discussed in this section. Then four different data acquisition approaches will be evaluated. Finally, a detailed description of a novel data acquisition system will be given.

A sink node in a wireless sensor measurement application is responsible for collecting and transferring measurement data to a device that has higher processing power, in most cases a PC. USB ports provide a suitable environment for digital communication of modern PCs with external devices, with data rates ranging from 1.5 Mbps to 480 Mbps. Programming or development boards, such as Sensinode U600 Micro.USB, used for interfacing wireless sensor nodes and PCs, have USB modules on them. On the other hand, MCUs of wireless sensor nodes do not support USB communication, since it is not critical for a wireless measurement node to communicate with the PC all the time. Instead, they have embedded UART modules for external communications. UART is a widely used serial interface component between a modem and a PC due to its simplicity and low cost (Osborn, 2009). UART module of a MCU is responsible of converting parallel data from memory to a coherent serial stream of bits at the transmitter and doing the reverse at the receiver. Baud rate defines the speed at which a single bit is transmitted and received. Theoretically, the UART could use a very high baud rate in communication, e.g. in the case of TI MSP430 MCU, maximum baud rate is defined to be one third of the UART clock source frequency (2.67 Mbps for 8 MHz clock). However, electrical noise and software limitations like interrupt latency, data moves, and protocol handling limit the maximum practical speed. UART speed also depends on the data rates supported by the terminal program and operating system (OS).

Figure 13 shows data transfer in a typical WSN focusing on the sink node to PC communication link. The speed of wireless sink node to PC communication, in most cases the speed of UART, has an important role in optimizing the speed of wireless communication in a WSN from the user perspective. If the sink node is not capable of processing and forwarding the data in its radio buffer faster than data arrives, the buffer will eventually be full, which will cause lost data packets during wireless transmission. Thus the period in between two consecutive wireless transmissions should be long enough, so that the sink node will have time to handle the data. This means that faster data logging systems can reduce the time sink nodes spend on data processing, which will lead to faster wireless transmissions and shorter operation times.

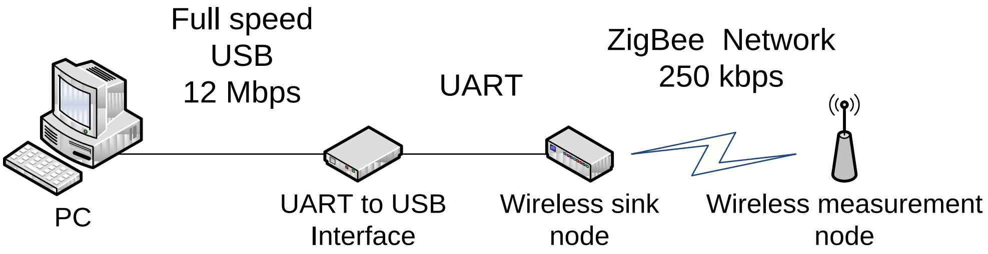


Figure 13. Data transfer in a WSN.

To evaluate effect of data acquisition system on the speed of wireless sensor network, performances of four different data acquisition methods are investigated (Figure 14): 1) UART communication through 50 pins connector, 2) parallel port with a DB-25 connection using RS-232 protocol, 3) USB-connected digital I/O board with 8 digital inputs, and 4) USB-connected DAQ board with 4 ADCs. Last three methods utilize GPIO pins of Micro.2420 instead of UART communication. Micro.2420 nodes and Dell Latitude D630 laptop with Intel Core2Duo T9300 @ 2.50GHz processor running Windows XP are used for the tests. MATLAB 7.5.0 (R2007b) software is used to manage the I/O.

3.5.1 UART Communication through 50 Pins Connector

Sensinode U600 Micro.USB modules are designed to interface Sensinode Micro series nodes with a PC, providing a serial connection over USB for debugging, controlling and programming purposes. An FTDI FT232R UART-to-USB chip, compatible with USB full speed (12 Mbit/s), providing a serial port between Sensinode nodes (directly to the microcontroller) and PC, is used in Micro.USB.

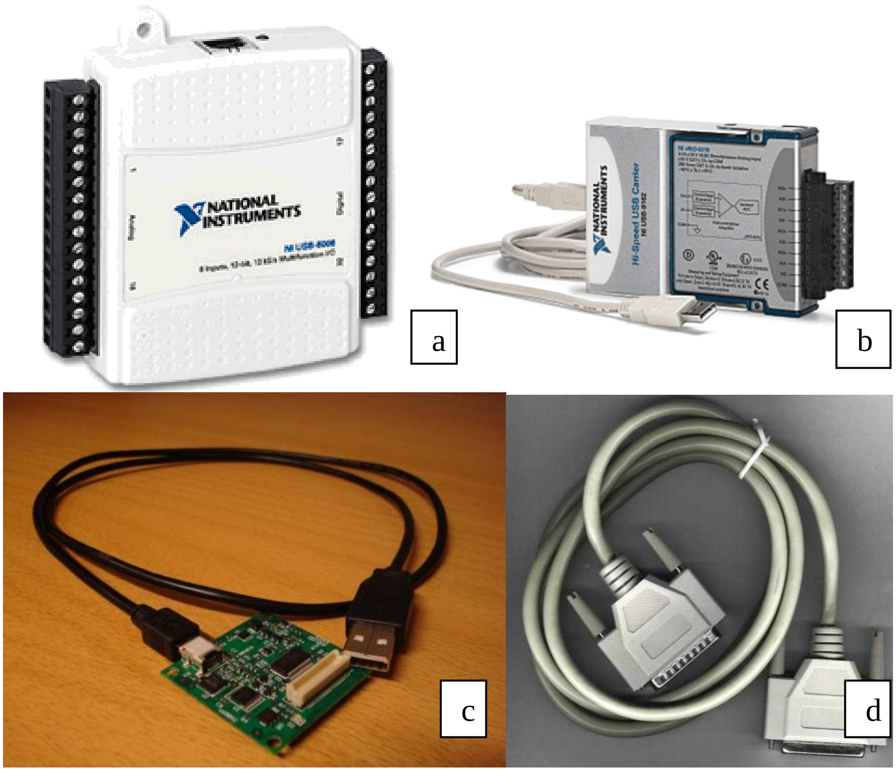


Figure 14. Four different hardware used in tests: a. NI USB-6501 USB-connected I/O board, b. NI USB-9215A USB-connected DAQ board with 4 ADCs, c. Sensinode Micro.USB programming board with UART communication through 50 pin connector, d. Parallel port with a DB-25 connection that uses RS-232 protocol.

Practical outcomes of different baud rates were investigated with Micro.USB board connected to a Micro.2420 and PC. Tests were done with a predetermined 1 MB random data and the results are presented in Table 9. In this case data is read from the internal memory of MCU, repeating all over again once finished reading the memory. This scenario is chosen to test the speed, however, in practice values would be taken from a sensor. One start bit and one stop bit are added to transmitted values according to the UART communication method. When these start and stop bits are removed, net bit rate can be found. In the table, three baud rates and their corresponding net bit rates are presented. "Net bit rate - Node" column lists the net bit rates found by measuring the time spent for the node to output all the data. Values in "Net bit rate - PC" column are found in a similar manner by measuring the time it takes for PC to capture the data and present it to the user. The differences in the latter two columns result from pulling the data from the input buffer of PC by the OS.

It is seen from the table that even though baud rate can be increased toward 2000 kbps, the practical net bit rate has an upper bound (< 400 kbps). Since the baud rate defines the rate at which one bit is transferred, the actual speed of the communication is lower due to other data handling operations of the microprocessor.

It should be noted that the bit rate of UART highly depends on the functions used in the node. The results presented in Table 9 are obtained with the lowest level functions available after a thorough investigation of different options. FreeRTOS is a multitask operating system that uses semaphores to guarantee the synchronization between tasks/thread. If higher level functions, which take the semaphores into account, are used, the practical net bit rate is observed to be around 55 kbps for 115.2 kbps or any of the higher baud rates.

Table 9. Comparison of UART baud rates and their practical net bit rates.

Baud rate (kbps)	**Net bit rate (kbps)**	**Net bit rate – Node (kbps)**	**Net bit rate – PC (kbps)**
115.2	92.16	87.545	87.105
921.6	737.28	394.65	385.93
2000	1600	395.12	386.19

3.5.2 Parallel Port with a DB-25 Connection Using RS-232 Protocol

Parallel port of a PC, also known as the printer port, is an inexpensive tool for interfacing. The printer port provides eight data lines, five status lines and four control lines. Printer port is OS dependent, since it is a software timed platform. A DB-25 connector with RS-232 communication was tested in node to PC data transfer. RS-232 is a digital communication protocol for serial communications that standardizes voltage levels and functions of the signals and physical interface pins. Two methods were tested with parallel port to transfer data from the wireless node to computer. During the tests, MATLAB was the only active program. Data was read and stored into a register, 75 kB of data were transferred and the average data rate was computed. The communication could be implemented with or without a handshake mechanism. In one way communication case (without handshake), the computer simply reads the bits from the port continuously and stores them into a buffer. To enable separating which bits belong together and indicating the presence of new data, synchronization bits are needed. In our implementation, two lines are reserved for this purpose. In the handshake case, one line is reserved for the node to inform PC that new data is available, and another line for the PC to inform the node that data has been read. Since Micro.2420 node has 8 external I/O pins available, in both cases only 6 lines could be used for data.

One Way Data Logging:

The 8 data lines of the parallel port are set as input and the data in the node is output through the node external I/O pins as bits (6 for data, 2 for control). The total time elapsed for reading the original data of 75 kB was 15.81 s, thus a data rate of 37.95 kbps was achieved with this method. Note that practical data rate would be slightly lower due to the required after-processing.

Communication with a Simple Handshake:

In the simple handshake case, PC needs to read from and write to the parallel port. A simple handshaking algorithm was tested by setting 6 data lines and one status line for input and one control line for output. At each cycle input lines are read and output line is toggled between 1 and 0. With these settings, reading the 75 kB of data takes 62.27 s, and hence by this method a communication speed of 9.635 kbps can be reached. Note that when there is a writing operation from the PC side, established speed reduces considerably compared to one way data logging.

It is seen that achievable bandwidth with parallel port is less than with UART, thus further investigation has not been done on these methods.

3.5.3 USB-Connected Digital I/O Board with 8 Inputs

Another way to take advantage of the node external I/O in data transfer is to use a low-cost USB-connected digital data acquisition board, which can be used to read the data bits. We tested NI USB-6501 low-cost digital I/O (DIO) device for USB with 24 digital I/O channels, one 32 bit counter and full-speed USB bus interface. The board is software timed and there is no explicit information about its sampling frequency in the datasheets. Without software delays or data verification we obtained a minimum sampling interval of 1 ms, which means that the DIO board can reach 6 kbps raw data rate as two bits are reserved for status. The board manufacturer (National Instruments) has also confirmed that it is not possible to obtain sampling intervals faster than 1 ms with software timed digital I/O devices.

3.5.4 USB-Connected DAQ Board with 4 ADCs

This method employs a NI USB-9215A portable USB data acquisition device. The USB-9215A has four analog input channels which provide simultaneous sampling. Maximum sampling rate is 100,000 samples/s/channel with 16 bit resolution, and voltage range is from -10 V to 10 V. Dimensions of NI USB-9215A are 14x8.6x2.5 cm. MATLAB program is used to control the data acquisition. In the proposed method, two DAC outputs and two digital output pins of Micro.2420 node are connected to the terminals of USB-9215A. Micro.2420 is also connected to PC through Micro.USB programming board to manage the configuration of data acquisition. Both Micro.2420 and USB-9215A can be accessed and controlled from a MATLAB program. The basic idea of the method is to map the data bits into analog voltages, a certain voltage corresponding to a particular series of bits. Both two analog outputs of the node can be used and, in addition, two digital lines are used as counter pins. The method establishes a one way communication, after which the raw data is processed and the original data is reconstructed offline in MATLAB. Details of this method will be explained in the following section. With this method, we established a data transfer rate of 264.7 kbps, which is higher than that of the wireless sensor network (250 kbps). This data rate uses a 4-bit mapping of data, which results in error-free communication. If some error is tolerated, the speed can go up to 640 kbps with an 8-bit mapping.

3.5.5 DAQ-Based System Design

DAQ-based system setup can be seen in Figure 15. A Micro.2420 node is stacked on top of a Micro.USB programming board. Micro.USB is connected to the PC. NI USB-9215A is connected to the external I/O pins of Micro.2420, and the PC.

The basic idea of the analog DAQ-based interface is that the node outputs analog voltages through two DACs. These voltages are read by the DAQ board that is attached to the PC. Additionally, two digital outputs of the node are used for synchronization purposes. The output range of the DACs is split into $2^4 = 16$ different levels each representing a certain bit pattern. On the PC side, the voltages are read through the DAQ board and converted back to bit patterns. Thus the data is actually transported in

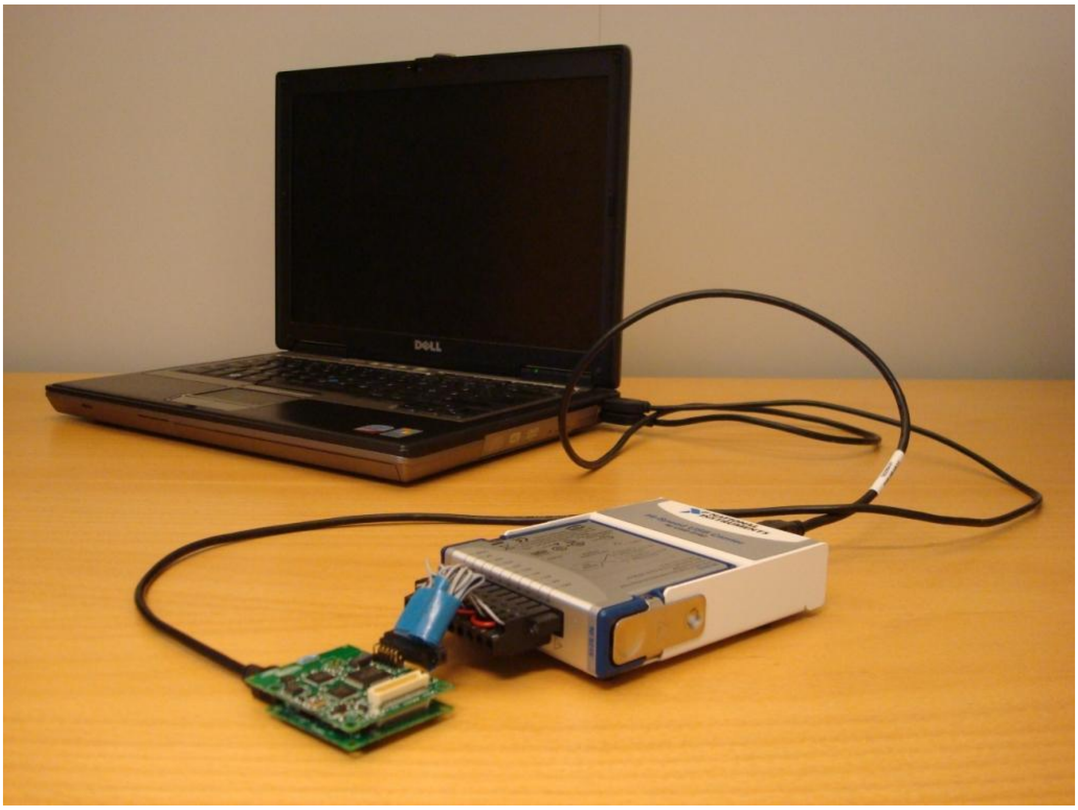


Figure 15. System setup with Micro.2420 node on top of Micro.USB programming board connected to the PC, and USB-9215A connected to the external terminals of Micro.2420 and the PC.

digital form by which we prevent measurement noise to disrupt the numbers in the transfer as far as the voltage levels are correctly interpreted.

NI USB-9215A Configuration:

NI USB-9215A has four pairs of analog terminals, one NC (no connection) and one COM (common) terminal. COM and the negative terminals of analog channels are connected together. As it can be seen from Table 10, four positive input terminals of NI USB-9215A are connected to two digital output pins and two analog output pins of Micro.2420. NI USB-9215A is connected to the PC with a USB cable. NI USB-9215A does not support hardware triggering and thus sampling is set to be triggered by the software with the rising edge of the input terminal AI0+ (sync 1). Sampling rate is set to 100 kSamples/s and the sampled data is stored into a file on the PC.

Micro.2420 Configuration:

Two pins of the Micro.2420 are set as analog outputs (DAC) with 12 bit resolution and two other pins are set for digital output. Two digital output pins of Micro.2420 are grouped together so that they update simultaneously. Micro.2420 is plugged on Micro.USB board through 50 pin connector, which establishes the communication needed for setting up the data transfer.

External connector of Micro.2420 is connected to NI USB-9215A as depicted in Table 10. Abbreviations LSb and MSb in the table stand for least and most significant four bits.

Data Logging:

Table 10. NI USB-9215A and Micro.2420 connection diagram.

NI USB-9215A terminal	Micro.2420 External connector
AI0+ (sync 1)	Digital output
AI1+ (sync 2)	Digital output
AI2+ (LSb)	Analog output
AI3+ (MSb)	Analog output

A MATLAB program is used to control the whole data logging operation. The program initializes Micro.2420 through Micro.USB and NI USB-9215A. All digital outputs of Micro.2420 are set to zero before the operation begins. NI USB-9215A starts logging data when it detects first increasing edge of AI0+ terminal voltage. In the case of 4-bit mapping, Micro.2420 separates every 16 bit data (2 bytes = 1 sample) first into two bytes and then into two four bit segments (Figure 5). Finally, it outputs the corresponding analog output voltages via DAC module of the MCU. The DAC's peak to peak voltage of 2.5 V has been split into 16 levels, so the step size of the output voltage is 0.1563V. After the analog voltage is output, MCU waits until the data is settled down in the output register. After the correct data is put, a digital pin that is connected to AI0+ terminal of NI USB-9215A is set to one. Then the node waits for 10.5 μs for data to be sampled by NI USB-9215A. Then the digital pin, which was previously set to one, is set back to 0. Operation is the same for the following byte except the second digital pin is set to one instead of the first one. The flow of the operation can be seen in Figure 16.

Reconstruction of the Original Data:

Logged data is saved into a file of type ".daq", as a series of voltage readings. Table 11 shows seven samples taken by NI USB-9215A during the operation. These samples can also be tracked from Figure 16. During the waiting time (the time the node waits after outputting the DAC values), either one of digital output pins is set to high. Only the

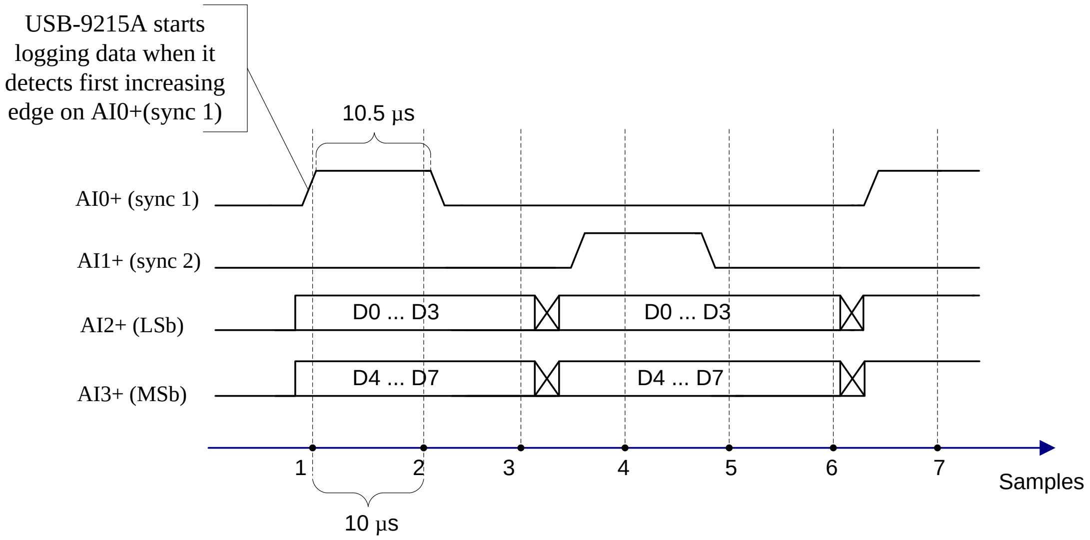


Figure 16. Flow of the operation for DAQ-based system.

Table 11. Samples taken by NI USB-9215A during operation (samples considered in data reconstruction are in boldface).

Sample number	AI0+ (sync 1)	AI1+ (sync 2)	AI2+ (LSb)	AI3+ (MSb)
1	3.065	0.001	0.002	2.014
2	**3.243**	**0.001**	**0.003**	**2.016**
3	0.000	0.001	0.003	2.017
4	**0.001**	**3.219**	**0.156**	**1.084**
5	0.001	0.001	0.156	1.086
6	0.001	0.001	0.156	1.086
7	**3.206**	**0.001**	**1.088**	**1.086**

samples taken during this waiting time are considered to be valid and the rest is ignored in order to avoid samples taken during the transition states of analog outputs. Multiple samples taken for one byte of data are grouped together and averaged. Then the sampled voltage values are converted to bits according to the following equation:

$$D_{org} = floor\left(\frac{R\times 2^{b}}{V_{DAC}}+0.4\right), \tag{14}$$

D_{org} is the original (4-bit) data, R is the voltage reading provided by NI USB-9215A, b is the number of bits used for mapping (4) and V_{DAC} is the voltage range of DAC module, which is 2.5 V. Floor represents the operation of rounding the values obtained towards minus infinity. Each byte is reconstructed by combining the two segments of the 4-bit data. Samples number 2 (least significant byte, LSB) and 4 (most significant byte, MSB) in Table 3 result in a two byte data of 29136 when they are reconstructed according to the equation given above, and organized afterwards. Figure 17 shows the status of data at different phases of the operation.

With 10 seconds of data logging, 8 MBs of raw data are obtained, which is then reduced to 331 kB at the end of reconstruction period. Processing 8 MB of raw data takes 2.17 s in our MATLAB implementation, including all file I/O operations. Note that this period

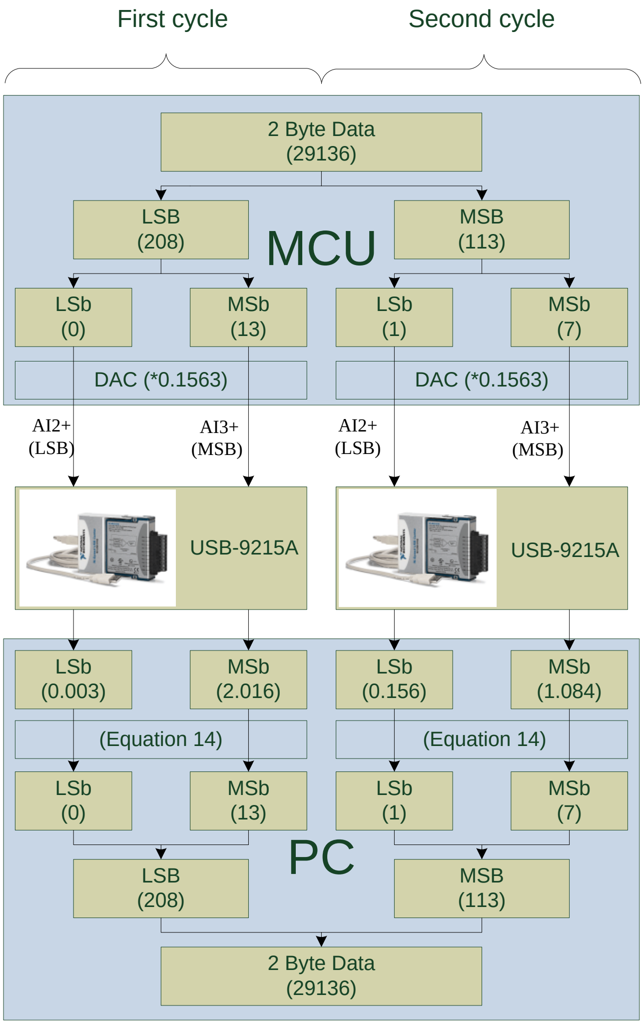


Figure 17. Data transformation through the operation.

is OS and software dependent. With the processing time included, overall transmission speed is found to be 217.6 kbps, but this also depends on the amount of data to be transferred.

Development

Since the operation employs a one way communication, a counter mechanism is critical to differentiate consecutive samples. Two digital pins of Micro.2420 are used to indicate the order and the validity of the data. Even though two pins can be used as a 2-bit counter, in the current algorithm only one pin is updated at a time, since longer update intervals were experienced when two pins were updated simultaneously, which would eventually reduce the speed of the communication and increase the error rate.

Two methods of analog data validation at MCU level were tested: controlling a flag of DAC module which indicates the status of the output data and comparing the output data register with the data to be written. Faster data transfer rates were observed with output register comparison method.

The operation needs three output registers of MCU (port 6 for digital output register that consists of eight digital outputs, DAC1 and DAC2 analog output registers) to be updated. It is critical to be able to ignore the data taken during the transition period of the analog voltages, thus a safety mechanism is employed by outputting 0's to the counter pins, when there is possibility of a transition. One of the digital outputs is updated at a time only when it is certain that there is the correct analog voltage output in the DACs. In theory, Micro.2420 can output 12 bits of data at a time and these data can be reconstructed perfectly, since NI USB-9215A takes 16-bit samples. However, DAC and ADC modules are imperfect and have output and input noises, which make it impossible to reconstruct the original data, if a 12-bit mapping is used. Input noise of NI USB-9215A is defined to be 7 LSB, which corresponds to 39.1 mV when calculated with the following formula.

$$N_{voltage} = \frac{V_{p-p}}{2^{(Res-Noise)}} \quad , \tag{15}$$

$N_{voltage}$ is the peak to peak input noise voltage, $V_{p\text{-}p}$ is the peak to peak voltage range, *Res* and *Noise* are measurement resolution and noise in terms of bits. 39.1 mV corresponds to the step size of 6-bit mapping in 2.5 V peak to peak voltage range of the node. However, when the output noise of the DAC module of Micro.2420 is considered, the optimum number of bits to map the data without any errors into 2.5 V is found to be smaller than six. The system was tested with 4, 5, 6 and 8-bit mapping methods and the results were compared. During these tests, NI USB-9215A logged the data for 10 seconds, while the Micro.2420 consecutively output a predefined pseudo-random set of data. Transferred and reconstructed data and the original data were compared offline. Percentage error rates and data transfer rates with four different mapping methods can be seen in Table 12. High resolution mapping results in higher speeds; however, error rates increase accordingly. Zero error rates are achieved only with four bit mapping.

Increasing the waiting time allows NI USB-9215A to take more samples for each byte and it provides longer time for settling, hence reducing the risk of an error, since the

Table 12. Percentage error rates and data transfer rates of four different mapping methods.

Mapping method	% Error	Data transfer rate (kbps)
8-bit	36.26	640.00
6-bit	5.13	480.64
5-bit	0.04	402.74
4-bit	0.00	264.70

averaging technique is used when reconstructing the data. Even though the error percentage is lower for longer waiting times, it is observed to never be zero with the mapping orders other than four.

3.5.6 Comparisons

In this section, the above discussed data acquisition methods are summarized and compared. Table 13 summarizes the theoretical bit rates and practical data transfer rates of the tested data acquisition methods and compares them with the IEEE 802.15.4 network data rate.

Table 13. Comparison of theoretical data rates and practical data transfer rates of IEEE 802.15.4 network and tested data acquisition methods.

Method	Theoretical data rate (kbps)	Practical data transfer rate (kbps)
UART communication (921600 baud rate)	921.6	385.93
Parallel port-one way data logging	OS-dependent	37.95
Parallel port-communication with a simple handshake	OS-dependent	9.64
USB connected Digital I/O board	OS-dependent	6.00
USB connected Analog DAQ board	6400.00	264.70
IEEE 802.15.4 network	250.00	Application dependent

The practical data rate numbers consider only the speed of transferring data from the MCU internal memory to PC. In practice, though, data are usually not in the (small) internal memory, but they are either read from the external flash or they arrive wirelessly from another node. Thus, in Table 14, we also present a comparison of UART and DAQ-based system, when data are transmitted simultaneously over the IEEE 802.15.4 network and transferred from the sink to PC, which represents a realistic use case scenario of a wireless data logging system. In the table, the waiting time after transmission is the time the transmitter node waits after a transmission, before the next one. These waiting times in the table are optimized for the corresponding communication method and speed, and with faster transmissions a high amount of packets would be lost. The effect of data logging method on the performance of the networked data logging system can be seen from the table.

It should be noted that in Table 14 the data rate provided by the DAQ-based system is with zero error (4-bit mapping). The speed of the DAQ-based system could be further improved with a faster data acquisition device that has lower input noise and hence would tolerate more efficient data mapping methods (see Table 12).

A significant increase in network throughput was observed with the proposed method compared to the traditional UART communication method with 115.2 kbps. However when UART baud rate is increased, performances of two approaches were seen to be close to each other.

Table 14. Comparison of data rates including wireless transmission.

	Waiting time after transmission (ms)	Network throughput (kbps)
UART / baud rate		
115.2	11	48.67
230.4	9	57.40
460.8	4	69.57
921.6	4	69.75
DAQ-based system	4	70.14

3.6 High Sampling Rate Application

This section presents the high sampling rate application. Reliability of this system is improved by implementing a retransmission algorithm for lost packets. Developed data acquisition system is integrated into this application.

WSN, in this case, is organized in a star topology. In this topology, all measurement nodes transmit measurement data to sink node. Operation is controlled by a MATLAB program. User can define the operation parameters, such as number of nodes to be used in the operation, accelerometer scale, sampling frequency, sampling period and the axes to be sampled. MATLAB transmits these settings to the sink node via Micro.USB programming board. Sink node sets the wireless nodes according to the user preferences. A temperature and humidity reading is taken at the beginning of each operation. Then wireless measurement nodes start sampling. A sample-store-transmit algorithm is used for the operation. External 500 kB serial flash memory of Micro.2420 platform is used to store the sampled data. Flash memory of Micro.2420 is separated into 8 segments of 256 pages, where each page can store 256 bytes of data. Memory can be written in page-wise manner. Writing a page takes 3.45 ms during which MCU is blocked and no measurements can be done. This means there will be gaps in data if the sampling period is shorter than 3.45 ms.

After measurement nodes finish sampling, sink node asks measurement nodes to transmit their data one node at a time. Data are transmitted in the form of 80 byte packets. First byte of each packet carries package type information and following two bytes carry the sequential number of the packet. This sequential number is used to detect unsuccessful transmissions.

MATLAB program assigns a *.daq* file for every node in operation. This *.daq* file is used to store the data logged by USB-9215A. With the first data packet received, sink node starts outputting data to its external pins. USB-9215A starts logging data with the first packet received and continues logging until the end of transmission. Logging is stopped by MATLAB after the last data packet is received. Once all data packets are transmitted, MCU of the sink node checks if there are any missing data. In case of lost packets, it asks the measurement node to retransmit the lost packets providing the sequential numbers of the lost packets. MATLAB program assigns a separate *.daq* file

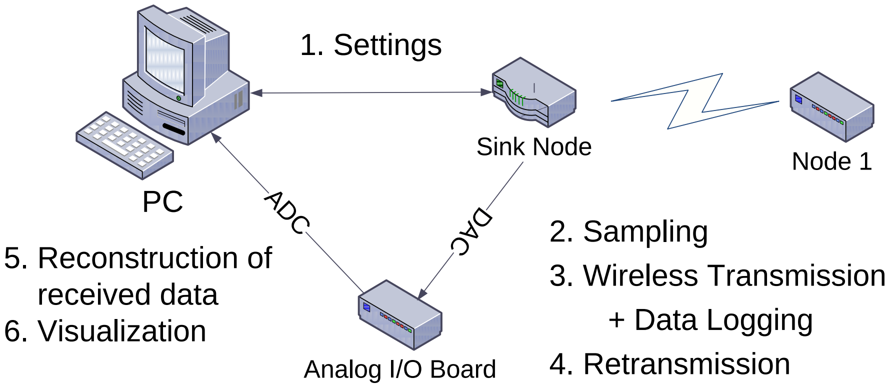


Figure 18. Operation flow of the high sampling rate application.

for retransmission and USB-9215 starts logging into this file after the reception of first retransmitted packet.

Retransmission continues until all the packets are received. Once the retransmission is over, MATLAB stops USB-9215A. The order of the received retransmission packets is stored in a register in order to correctly recover the data offline. This operation is repeated for every measurement node in use.

If a data packet is not received after 10 re-transmissions, program continues with the following packet or ends the operation as the case may be. Lost packets due to wireless communication can be recovered, however, during the experiments there occurred some lost packets due to the operation of writing to the flash. In such a case measurement node cannot take the data from flash memory and hence cannot transmit the data.

After the nodes have completed the transmissions, received data are reconstructed offline and retransmitted packets are placed accordingly. Figure 18 shows operation flow of the high sampling rate application.

4 Case Studies

Three wireless sensor applications were presented in the previous chapter. This chapter presents three case studies done by using the developed applications for wireless sensor nodes. These case studies are:

- Bridge monitoring
- Trolley crane monitoring
- Crane monitoring in an industrial environment

Bridge monitoring case study aims to evaluate suitability of wireless sensor nodes for structural health monitoring. For this purpose, wireless sensor nodes equipped with accelerometers were used to collect vibration data from a laboratory scale wooden bridge.

In trolley crane monitoring application, wireless sensor nodes were used to collect vibration data from a laboratory scale trolley crane. These data were used to compare performances of different controller settings and to evaluate the significance of acceleration data for control of cranes. Furthermore, position data was collected non-intrusively from the system.

Aim of the last case study, crane monitoring in an industrial environment, was to observe the performance of wireless communication in an industrial environment. Additionally, vibration data was collected from the crane when it is in motion. The data was used to observe the changes in time and frequency domains related to the motion of the crane.

4.1 Bridge Monitoring

Structural health monitoring applications require many detailed sets of data to be collected to assess the health condition and to estimate lifetime of structures. Intelligent Structural Health Monitoring System (ISMO) project of TKK aims to develop wireless sensing and networking technologies to be used for structural health monitoring. The high sampling rate application has been used in ISMO project. Aim of this case study was to investigate the applicability of wireless sensors equipped with accelerometers, in real world structures, such as bridges. In this case study vibration data were collected by using wired and wireless accelerometer sensors and these data are compared against each other.

A wooden bridge built to scale with dimensions 420 cm x 65 cm x 33.5 cm was used for the tests. An electromechanical shaker is used to shake the bridge at pre-defined frequencies and amplitudes. Wired high sensitivity digital 1-axis accelerometers (8712A5M1 by Kistler) were placed on the bridge simultaneously with the wireless nodes. Wired accelerometer sensors, shaker and the wooden bridge can be seen in Figure 19.

First set of tests was done by using the shaker, one wireless node and one wired node. Aim of these tests was to compare the performances of wired and wireless sensors individually. This study showed that data collected by wired and wireless sensors match and gave information on noise levels of collected data. After validation of their performance, wireless sensors were used on the bridge along with wired measurement system. Six wireless sensor nodes were placed on the bridge to collect the vibration data while the shaker was introducing vibrations. Illustration of the test setup can be seen in Figure 20.

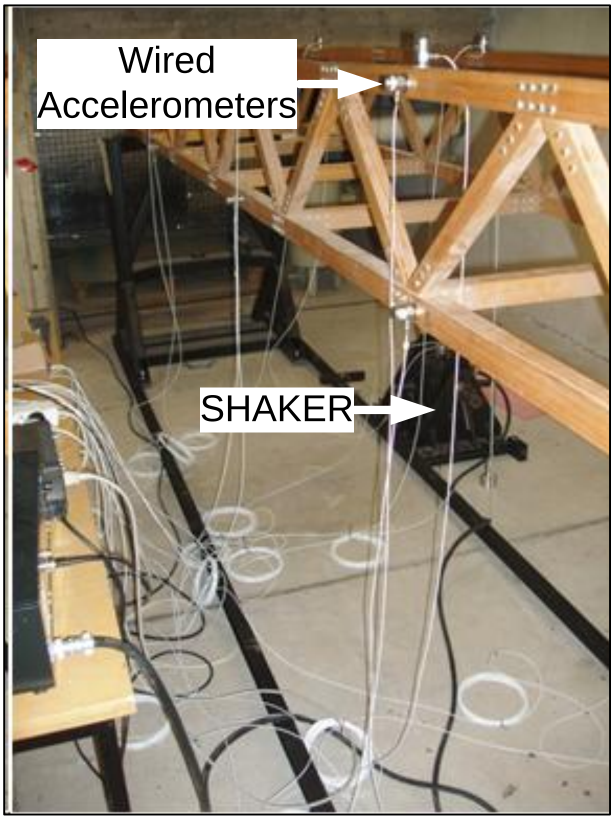


Figure 19. Wooden bridge and wired accelerometer sensors.

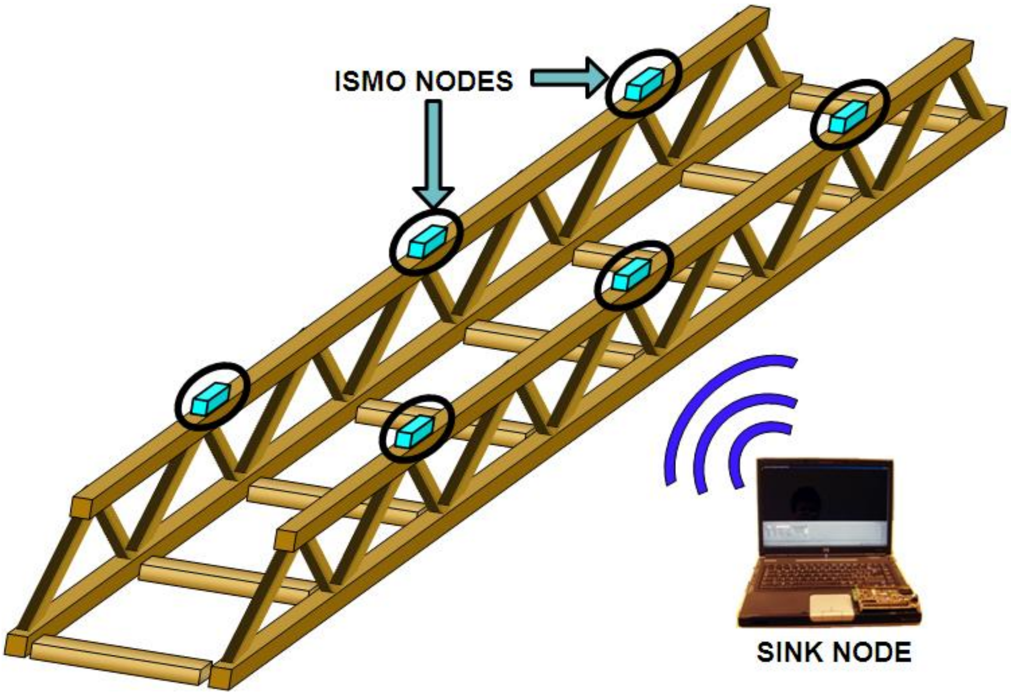


Figure 20. Test setup with wireless sensors placed on the wooden bridge (Bocca *et al.*, 2009).

When high sampling rate application is used at sampling frequencies higher than 250 Hz, a gap is introduced to the data due to the writing operation into the external flash memory (see Section 3.6). Figure 21 shows a comparison of frequency spectrums of the data collected from wired and wireless sensors when the bridge was excited at 30 Hz. There are two plots in Figure 21 for wireless sensors: one showing the spectrum of raw data, and the other one showing the spectrum of compensated data. Sampling frequency in FFT is adjusted to compensate the error introduced by the writing of the samples in the flash memory of the nodes (Bocca *et al.*, 2009).

Results show that the data collected by wired and wireless sensors have some differences in the frequency spectrum. Some of these differences are because of imperfect casing of the nodes. These cases cause damping and affect the vibrations that accelerometers experience. The difference in frequency values is because of imprecise sampling of wireless sensors. The main reason for this is the clock drifts in microprocessors which change the true sampling frequency compared to the desired sampling frequency. More noise is observed in the data collected by wireless sensors. Furthermore, lack of synchronization of measurement nodes with a central node can affect cross-correlation analysis when different nodes' data are considered. At the time of writing, ISMO project is ongoing and further study will focus on eliminating these causes by optimizing the cases, the synchronization, and the clock drift.

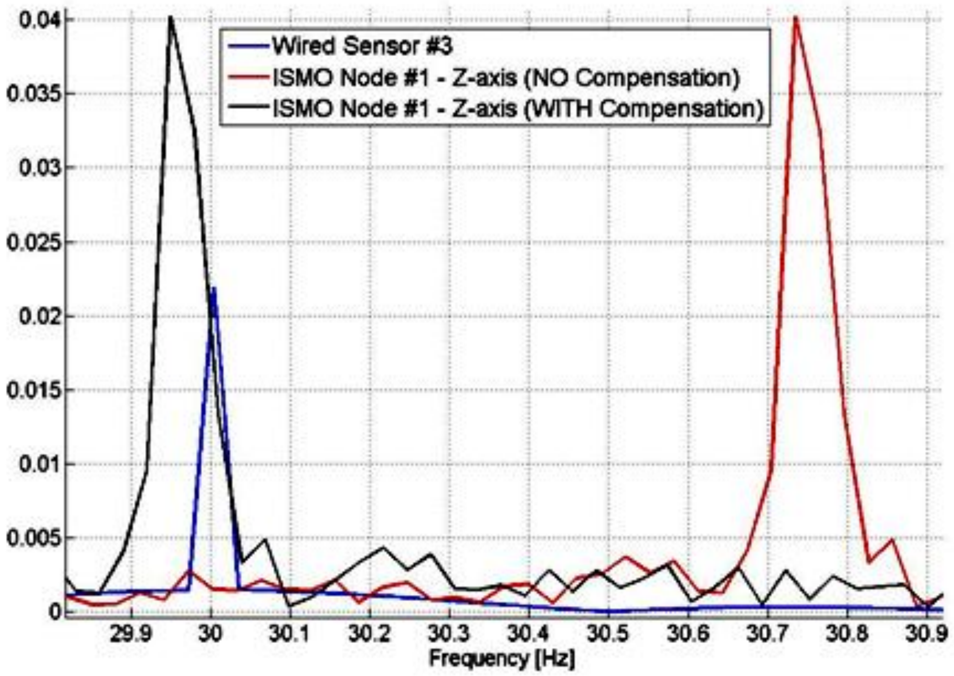


Figure 21. Comparison of wired and wireless sensors' data (Bocca *et al.*, 2009).

4.1.1 Results of Bridge Monitoring Case Study

High sampling rate application has been tested in the bridge monitoring case study. This study proved the usability of the developed wireless sensors equipped with accelerometers in structural health monitoring applications. It was seen that match of wired and wireless sensors is good. Measurements done with wireless sensors include more noise than those done with wired sensors. The wireless sensors provide accurate data which allows identification of structure vibrations. Better time-synchronization of the nodes and optimization of the casing can improve quality of the data. This study provided important insights for future development directions that will improve reliability of wireless sensors.

4.2 Trolley Crane Monitoring

This case study was done on a laboratory scale trolley crane system which has been developed for educational and research purposes at the Helsinki University of Technology. Aim of this case study was to track the trajectory of the load, to monitor the behavior of the trolley crane vibrations (on the load, structure, and motors) with different controller settings, and to investigate the relationship between load angle and vibrations on the load. Another aspect of this study is to monitor the trolley crane without interfering into the control system. This means that the monitoring system does not disturb the operation of the system.

Trolley crane systems are widely used in industry when heavy loads are to be transported, such as in container ships. These systems aim to transfer payloads as fast as possible without damaging the load. As the trolley of the crane moves, load swings due to the introduced acceleration. These load swings can cause structural fatigue in long term and decrease the lifetime of the machine. Moreover, they can cause operator discomfort when the operator is situated on the crane. Controller performance of these systems can be improved by monitoring the operation. Furthermore by monitoring the behavior of the crane, operator's performance can also be evaluated and efficiency of the operation can be increased (Tervo *et al.*, 2009).

4.2.1 Overview of the Trolley Crane System

Trolley crane system used here is equipped with two actuators: a trolley motor which controls the horizontal position of the trolley, and a hoist motor which controls the vertical position of the load by controlling a rope connected to the load. Dimensions of the system are 2.5 x 0.8 x 0.6 m. System model and three degrees of freedom of the system (d, l and Φ) can be seen in Figure 22.

Previous studies conducted on the system are: modeling and the development of control algorithms for the load position, anti-swing control and human adaptive control (Tervo *et al.*, 2009).

An ultrasound based monitoring system is used to track the load angle Φ. Ultrasound receivers, located on the back rail of the system, are used to determine the distance between the receivers and an ultrasound emitter located on the load (Figure 23). Load

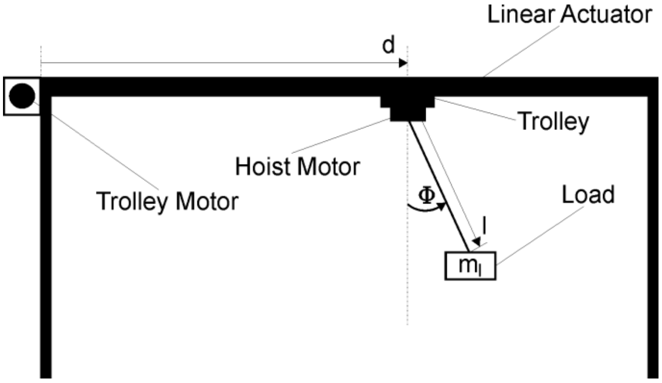


Figure 22. Trolley crane system (Eriksson *et al.*, 2006).

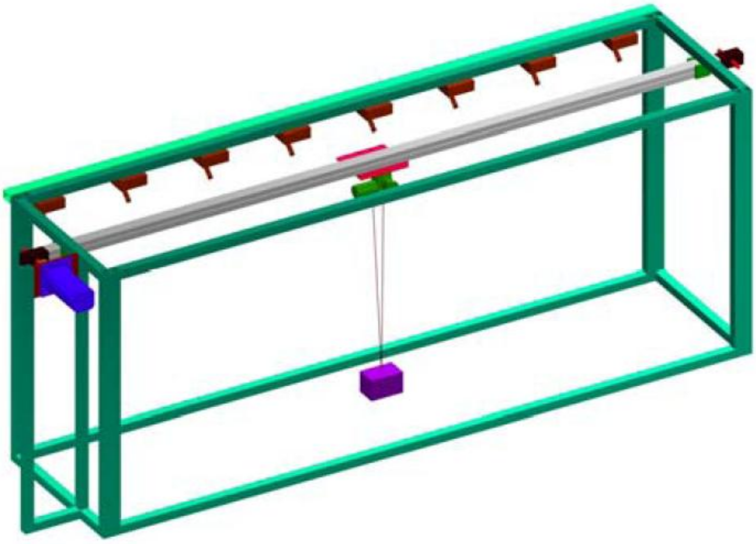


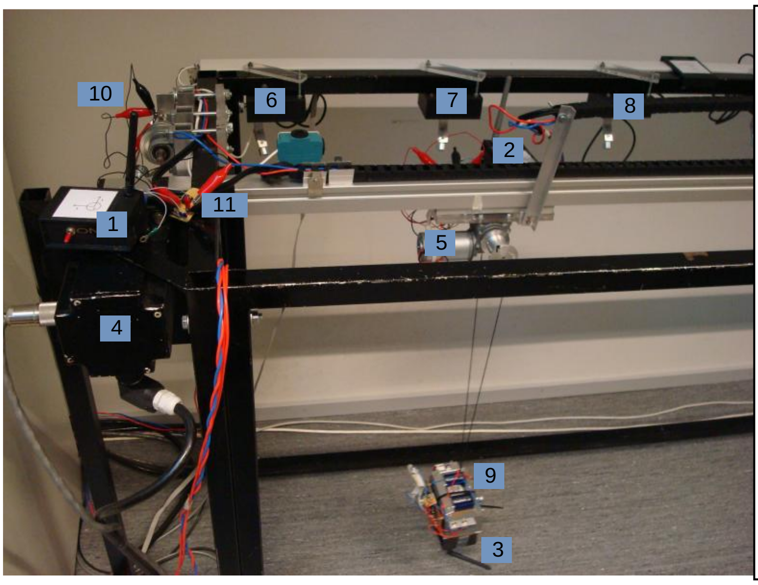
Figure 23. Trolley crane equipped with ultrasound measurement system (Eriksson *et al.*, 2008 b).

angle is calculated by using these distance measurements, trolley position and rope length (Eriksson *et al.*, 2008 b).

4.2.2 Test Setup

Three of the wireless nodes described in Section 3.2 were used in the tests. Figure 24 shows the test setup.

Trolley crane system employs two potentiometers to measure the rope length and trolley position. These potentiometers are connected to the shafts of the motors. As the trolley moves or as the rope length changes, resistance of the potentiometers and hence the



1. Wireless Sensor Node
2. Wireless Sensor Node
3. Wireless Sensor Node
4. Trolley Motor
5. Hoist Motor
6. Ultrasound receiver
7. Ultrasound receiver
8. Ultrasound receiver
9. Ultrasound transmitter
10. Crocodile connectors
11. Buffer and Scale circuitry

Figure 24.Test setup.

voltage on them changes. In this way, position information is mapped into 5 V analog voltage span. Control system monitors these voltages to determine the position of the load.

Three wireless sensor nodes were placed on the system and they were used to collect acceleration data. Two wireless sensor nodes (1 and 2 in Figure 24) were used also to collect the position information. Analog I/O pins of the nodes are used to acquire this information. However since the wireless sensor platform works with 3.3 V and the potentiometers with 5 V supply voltage, a voltage scale and buffer circuitry was needed to interface the wireless nodes and the system.

In the interface circuitry, a MC 33202 low voltage, rail-to-rail operational amplifier is used as a buffer. Two resistors connected to the output of the buffer are used to scale the input voltage coming from potentiometers. Figure 25 shows the electrical schematic of the buffer and scale circuit. Potentiometers' output pins were connected to the input of the circuit (Crocodile connectors were used to connect the potentiometer legs to the buffer and scale circuitry).

By using the wireless monitoring toolkit, system data were collected without interfering the system itself, namely by non-intrusive monitoring method (see Section 2.3.1). In this case it was possible to reach the system data, however, in larger plants, with multiple controllers and data buses, it is not always possible to reach the system data (see Section 2.2.2).

4.2.3 Communication Tests

Communication tests were done to find out the most appropriate radio channel to be

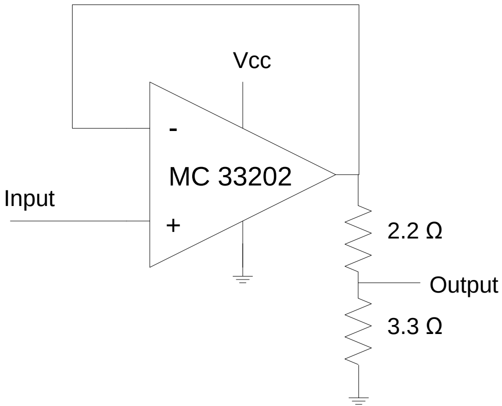


Figure 25. Buffer and scale circuitry.

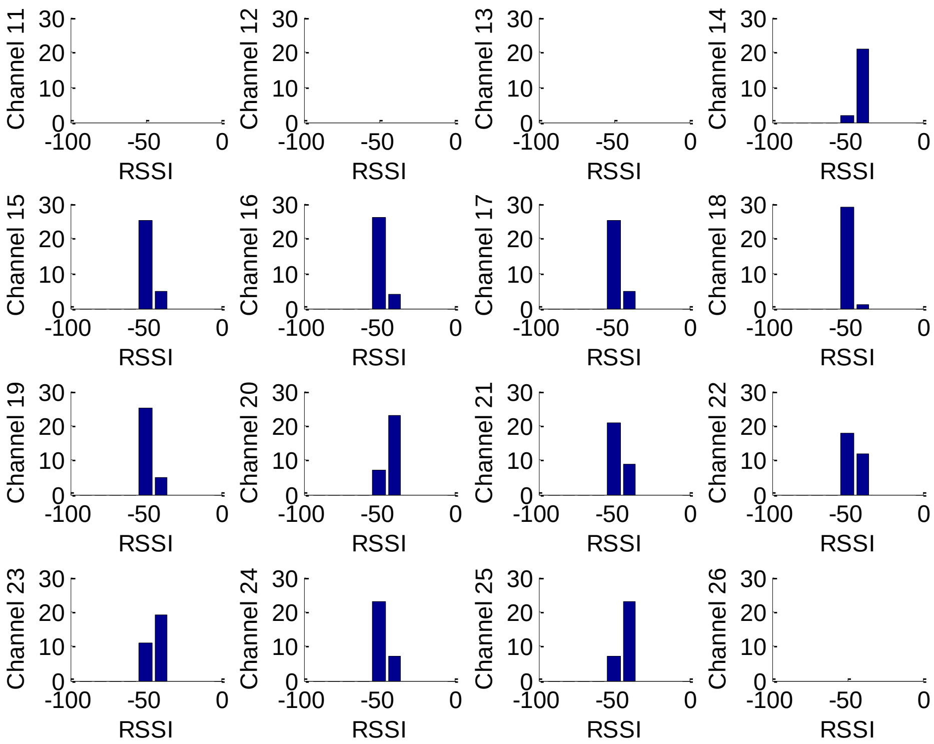


Figure 26. Communication test results.

used during the measurements. In the communication tests one sink node and one measurement node were used, and 30 packets, each consisting 77 bytes of data, were transmitted at full power from measurement node to the sink node. Sink node determined the RSSI (received signal strength indicator) by measuring the power present in received signals. Figure 26 shows results of the communication tests for each available channel (in total 16).

It is seen in the figure that some channels did not work at all even though several trials were done. Among the ones, where communication was established, channels 20 and 25 had the best performances. Channel 20 was chosen for the remaining tests.

4.2.4 Controller Tuning

In this study we investigate the effects of controller settings on the load, structure, and motor vibrations and on control performance. In the laboratory test bed used, there is an ultrasound system that measures the load angle and this load angle can be used as a performance indicator for the controller. However, in practice it is usually neither feasible nor possible to measure the load angle of an industrial crane with ultrasound sensors. In this context, monitoring load and crane vibrations can indicate how well the controller performs. Furthermore, it is useful to monitor system vibrations even when it is used with load angle measurement system since vibration monitoring provides new information about the state of the system.

Wireless sensors collected data when the system worked with different controller settings. The wired control system also recorded the measurements for comparison with wireless sensor measurements. Sampling frequency was 50 Hz for the wireless sensors, 100 Hz for the analog readings taken by the control system of the crane, and 10 Hz for ultrasound angle measurements. Two data sets were chosen for further processing, one representing a poor controller and the other one representing a significantly better controller. From this point on, these two sets of data will be called “good control” and “bad control” for simplicity.

Figure 27 shows the reference trajectory and the measured trajectories of the load. All controllers were implemented by using the same reference trajectory. Processed measurement data taken from wireless sensors (as described in Section 4.2.2) and from the system are also shown on the same figure. Both the data taken by the system and the

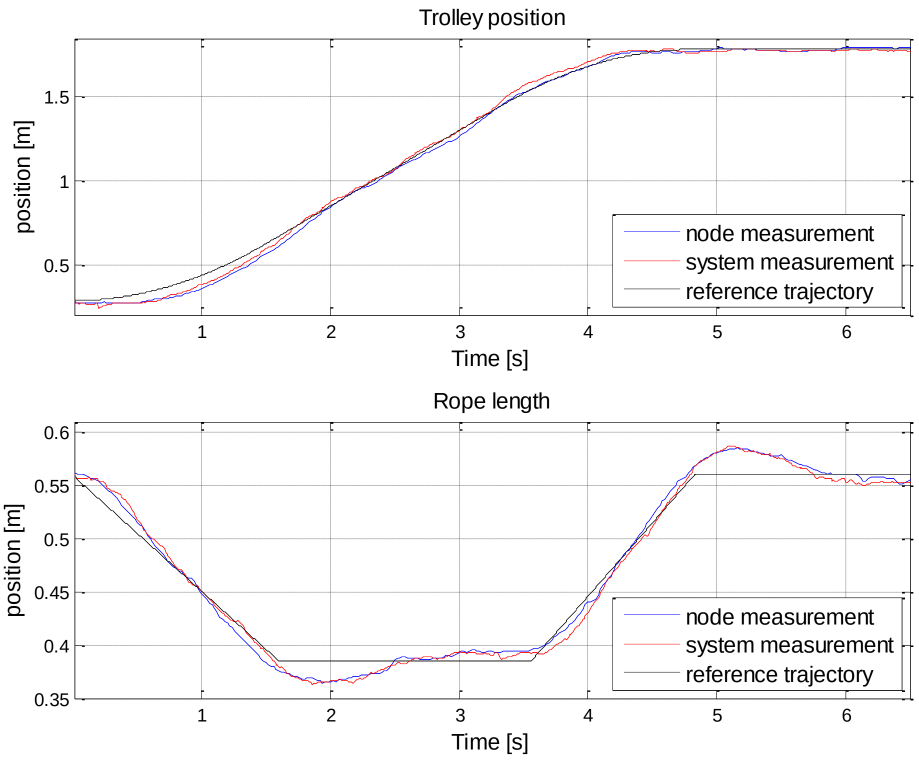


Figure 27. Trolley position and rope length measurements and the reference signal.

Figure 28. Load angle measurements under two different control settings.

wireless sensor data are processed in the same way. First voltage readings were converted to meters by using a calibration table, then a peak filter proposed in (Tervo *et al.*, 2009) is used to remove outliers in the data and finally a low pass filter is used. It is seen from the figure that data taken by the control system and wireless sensors' data are consistent. This means when the system data is out of reach, wireless sensors can be used to monitor the system non-intrusively.

Figure 28 shows the load angle measurements taken under two different control settings. These measurements were taken by ultrasound angle measurement system. It is seen from the figure that control settings labeled as "bad control" cause large changes in load angle whereas the one labeled as "good control" provides a smoother trajectory.

Figure 29 shows vibration measurements taken from the wireless node placed on the load. Effects of controller on load vibrations are clearly seen especially in tangential axis.

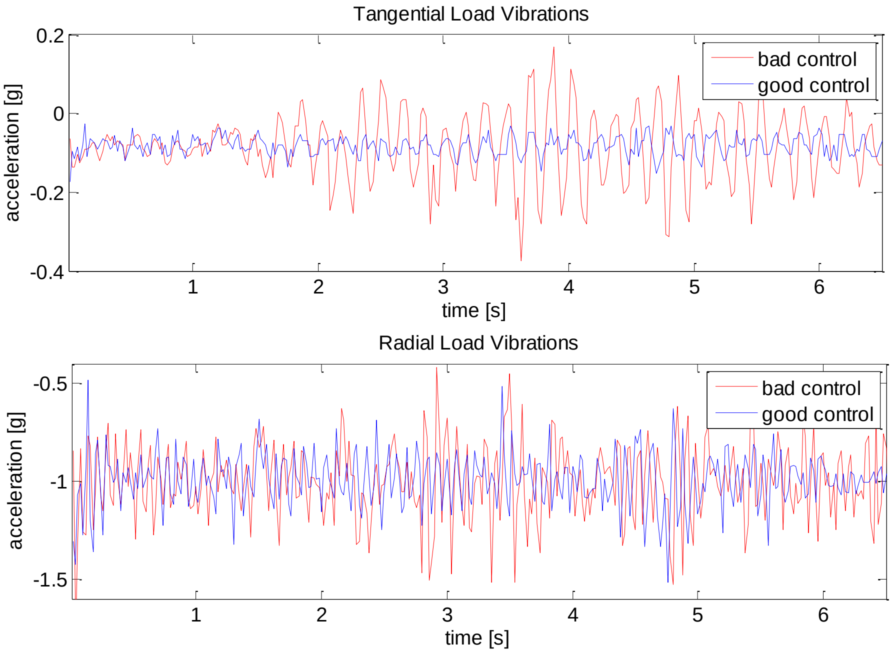


Figure 29. Load vibrations.

Figure 30 shows the spectrum analyses of tangential and radial vibrations taken by the wireless sensor on the load. Analyses are done after removing the means and by using signal processing tool of MATLAB. Welch's method (Welch, P., 1967) is used for analysis with 50 samples overlap, 256 samples Hanning window and 512 samples FFT. Effect of the controller settings on load vibrations can be clearly seen in the spectrum.

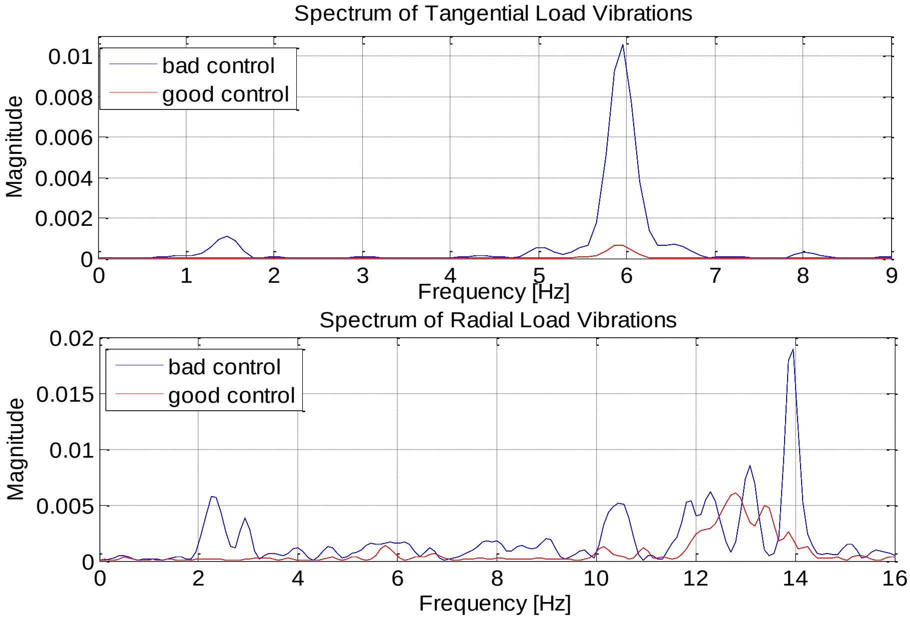


Figure 30. Spectrum of load vibrations.

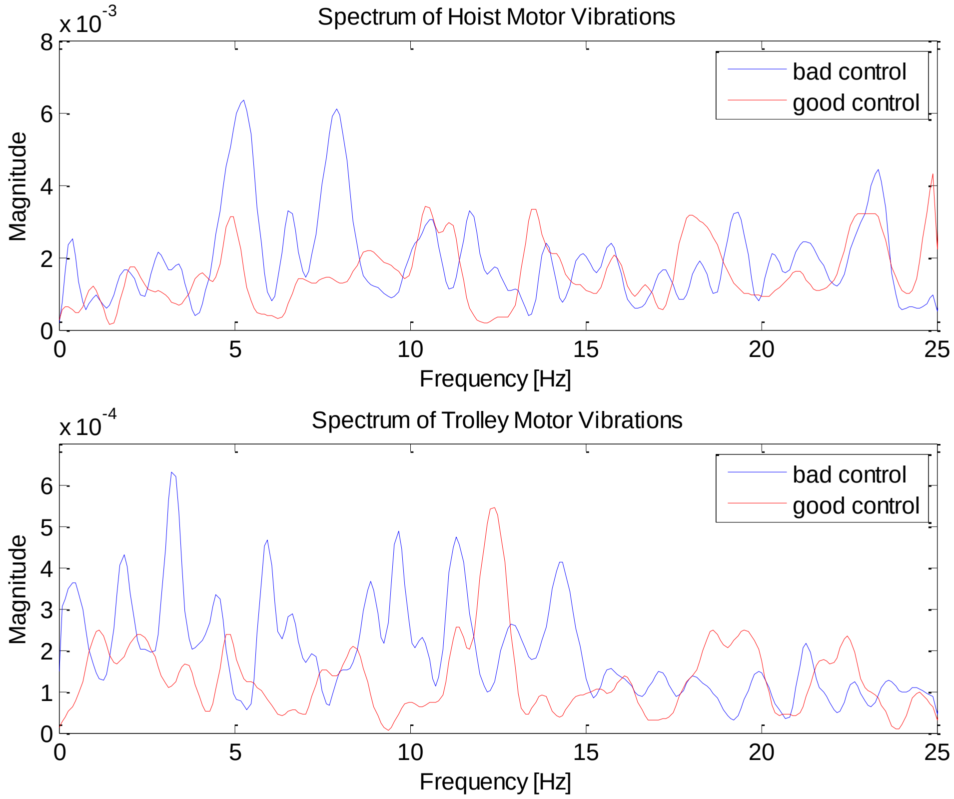


Figure 31. Spectrum of hoist and trolley motor vibrations.

Figure 31 shows the spectrums of vibration measurements on vertical axis taken from hoist and trolley motors. Data for these spectrum analyzes were collected by nodes labeled as 1 and 2 in Figure 24. Same analysis described above was done except in this case a window size of 128 samples was used. The effect of controller settings on vibrations of the crane structure is visible through these spectrum analyses. Note that since the sampling frequency of wireless nodes was only 50 Hz, motor related high frequency components are not visible in this case.

Controller tuning tests show that controller parameters affect the vibrations on the crane and it is possible to evaluate controller performance by monitoring the vibrations either on the load or on the crane structure.

4.2.5 Swing Tests

Swing tests were done with the trolley crane to collect acceleration data when the load was freely swinging and actuators were on rest. Aim of this study is to see the extent of relationship between angle measurements taken by the system and acceleration measurements taken by wireless nodes.

In these tests, trolley position and rope length were kept constant. Load was dropped from an initial height allowing it to swing back and forth. Load angle is measured by the ultrasound system and the accelerometer data is collected by wireless node on the load.

Two acceleration contributions are present on the mass of a swinging pendulum: gravitational and inertial. These contributions result in radial and tangential accelerations on the mass. Overall tangential and radial accelerations can be found by

$$a_t = \alpha r + gSin\theta \quad , \tag{16}$$

$$a_r = \omega^2 + gCos\theta \quad , \tag{17}$$

where a_t and a_r represents tangential and radial accelerations, α is the angular acceleration, ω is the angular velocity of the pendulum mass, r is the length of the pendulum string, g is the gravity constant and θ is the angular displacement of the swinging pendulum (Godfrey *et al.*, 2007).

Angle measurements were taken at 10 Hz and accelerometer measurements were taken at 20 Hz. Figure 32 shows 12.5 seconds raw acceleration and angle measurements that were taken right after the mass was released.

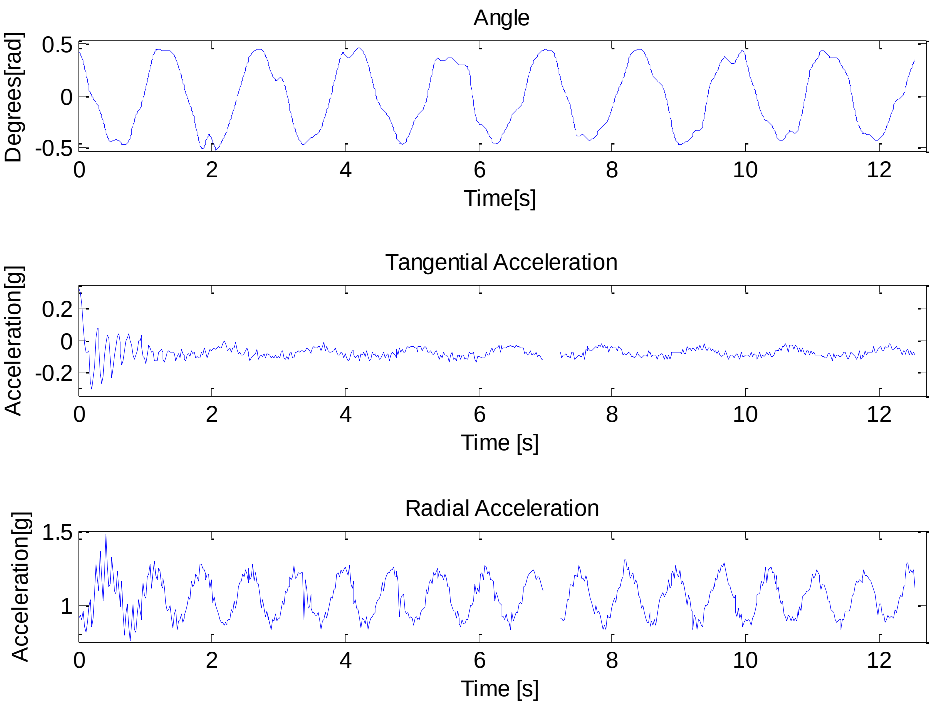


Figure 32. Angle and acceleration measurements.

Figure 33 shows the spectrum analyses of radial and tangential acceleration measurements and angle measurements. Analyses were done after removing means, and the gaps in the acceleration data were filled by linear interpolation. Analyses were done by using Welch's method with 50 samples overlapping, 1024 samples FFT size, and a window size of 512 samples for acceleration measurements and 64 samples for angle measurements.

Rope length was 0.45 m and kept constant during the measurements. Period of oscillation (T_O) for a simple pendulum can be calculated by

$$T_O = 2\pi\sqrt{\frac{l}{g}}\ . \tag{18}$$

where l is the length of string. In the trolley crane, a rope is used instead of an inextendable, massless string, which is the case for an ideal simple pendulum in (18). Applying this formula to trolley crane case gives a period of 1.35 seconds, which means an oscillation frequency of 0.74 Hz. Spectrum analysis of the angle measurements shows a peak at 0.7 Hz, and consistently tangential acceleration measurements have a

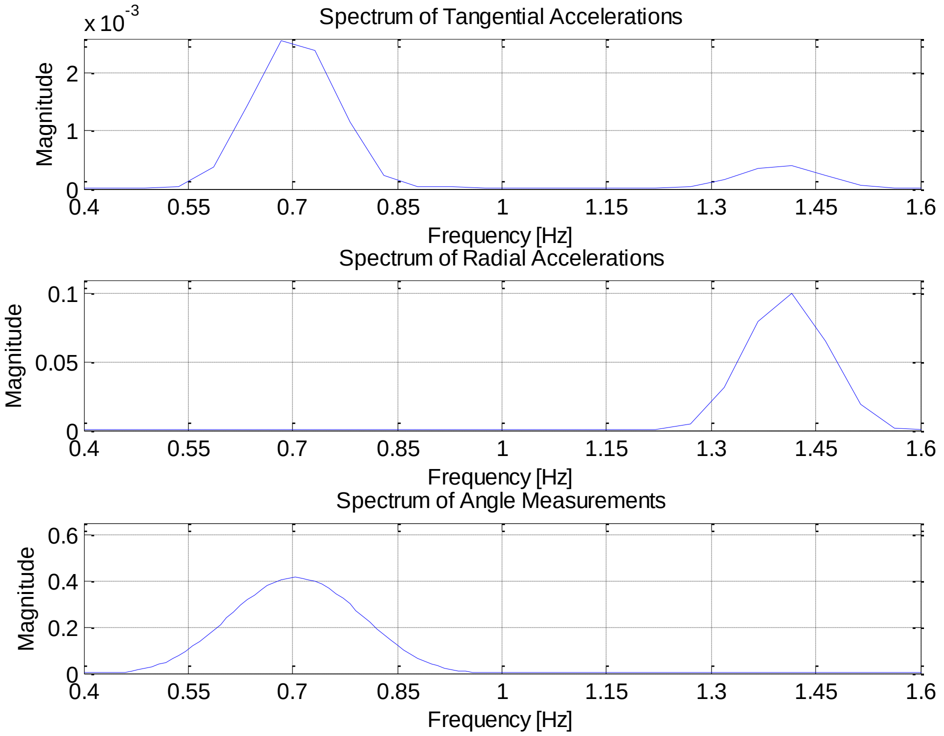


Figure 33. Spectrum analyses of radial and tangential acceleration measurements, and angle measurements.

dominant peak at 0.69 Hz and a smaller peak at 1.40 Hz. On the other hand spectrum analysis of radial acceleration measurements has the dominant peak at 1.41Hz, which is the double frequency component due to the nature of acceleration measurements described in (16) and (17).

Accelerations acting on the load can be derived by using angular displacement measurements. In (16) and (17) the angular displacement θ is employed, which is the angular displacement of the swinging pendulum. To calculate radial and tangential accelerations, θ should be derived once to find angular velocity and twice to find angular acceleration. Simplest way to find derivative of discrete measurements is to divide the difference between two consecutive samples by time interval between two consecutive samples. However this approach magnifies the noise and does not give satisfactory results. To overcome this problem, polynomial methods were used to calculate the derivatives, as described in Godfrey *et al.* (2007). Figure 34 shows a fraction of derived accelerations and measured radial and tangential accelerations by this method.

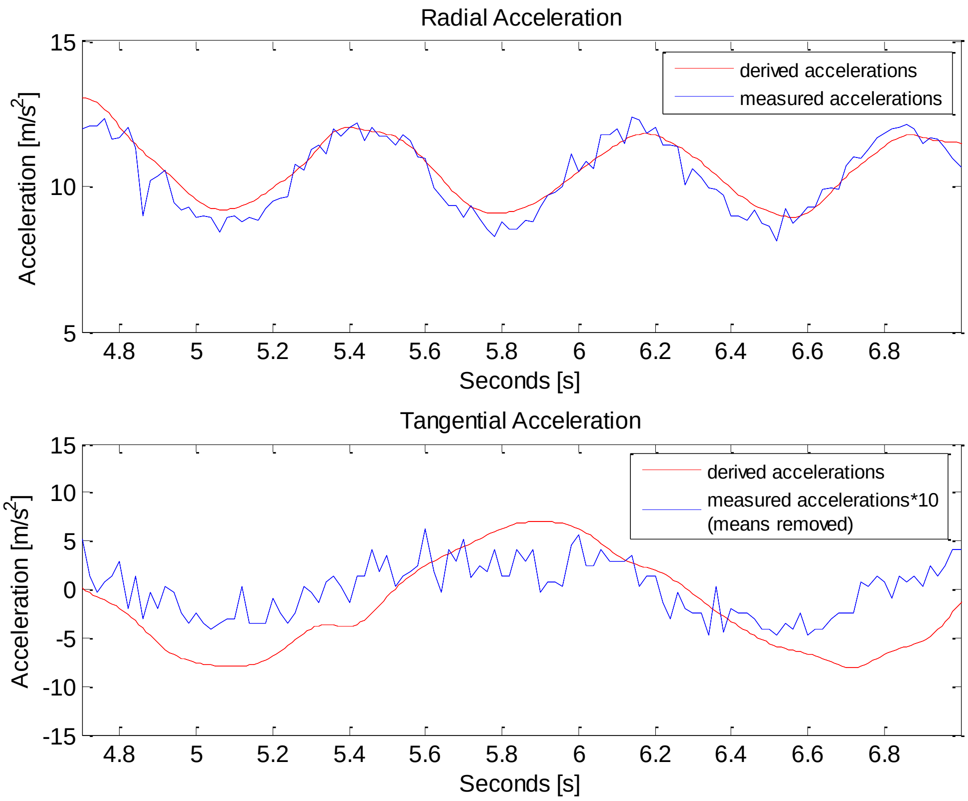


Figure 34. Comparison of derived and measured accelerations experienced by the load in radial and tangential axes.

It is seen that radial accelerations are reconstructed successfully and they match the measurements in both frequency and magnitude. However, tangential accelerations were not possible to reconstruct successfully. Offset and amplitudes were different in measured and derived tangential accelerations. Thus, measured accelerations are plot after removing the means and multiplying the measurement data by 10. Several factors affect the derivation of accelerations. First of all, load is connected with a rope instead of an inextendable string. This causes imperfect swing of the load as can be seen in Figure 32. Since the rope is flexible in every dimension, load actually swings in three dimensions instead of two as assumed in (16) and (17). Accelerometer is placed imperfectly and has an offset. Furthermore the angle measurements taken by the system are not perfect and do not provide a detailed data, since the sampling frequency is only 10 Hz. Finally, the polynomial method used for derivation introduces errors into the results.

Nevertheless, the swing tests showed the close relationship between angular displacement of the load and the acceleration experienced by the load. In our laboratory testbed we had the angular displacement measurements, however, practically it is not feasible to setup such a system on an industrial trolley crane. In practice, wireless nodes equipped with accelerometers can be used to track the angular displacement of the load. An example application scenario would be a monitoring system that warns the operator when the angular displacement of the load exceeds some predetermined threshold.

4.2.6 Results of Trolley Crane Monitoring Case Study

Real-time monitoring and communication test applications have been tested in trolley crane monitoring case study. The main goal of the case study was to show usability and usefulness of the toolkit. Results suggest that wireless sensors could be used for several purposes in industry to enhance the performance of the control system.

Developed applications worked successfully during the tests. Setting up the wireless nodes took less than half an hour and many sets of data were collected in real-time. Packet loss was very little during the measurements.

Data taken by the control system and by the wireless sensors are consistent which means that wireless sensors can be used to monitor the system non-intrusively when the system data is out of reach.

Controller tuning tests showed that it is possible to evaluate the controller performance by monitoring vibrations on the load or on the crane. Swing tests showed the close relation between angular displacement of the load and the accelerations experienced by the load.

4.3 Crane Monitoring in an Industrial Environment

All three applications described in Chapter 3 were tested in an industrial hall with a typical 5 ton bridge crane. This case study was done to observe the performance of wireless communication in an industrial environment and to monitor the changes in acceleration measurements when the crane is in motion.

4.3.1 Communication Tests

Performance of the network was tested with four wireless nodes. Data was collected by using different radio channels. Once an appropriate radio channel was chosen, distance between nodes and the sink node was changed to see the effect of communication distance on wireless communication. First tests were done on the ground, and long distance tests were done when the nodes were placed on the crane, as shown in Figure 35.

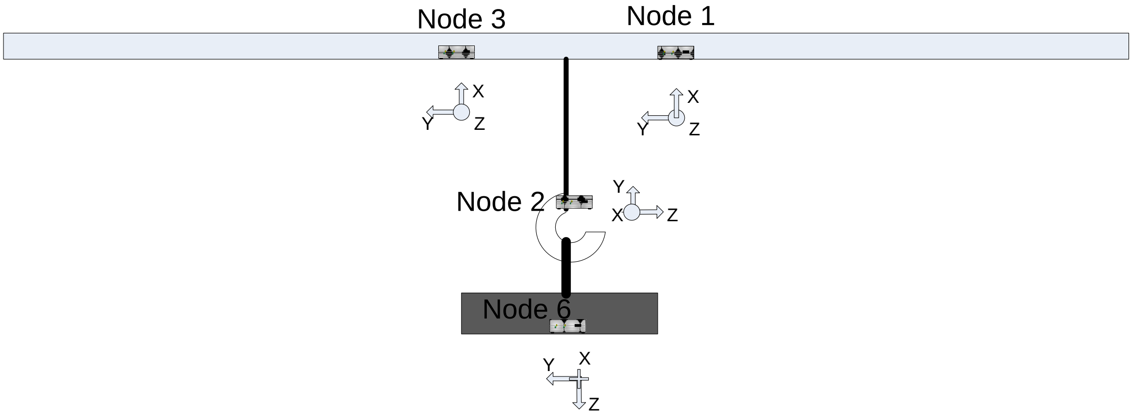


Figure 35. Wireless sensor nodes attached on the test crane.

Table 15. Communication tests.

Range	Nodes	Channels
1m	1,2,3,4	All
2m	1,2,3,4	16
4m	1,2,3,4	16
6m	1,2,3,4	16
8m	1,2,3,4	16
10m	1,2,3,4	16
12 m	1,2,3,4	16
14m	1,2,3,4	16
16m	1,2,3,4	16
18m	1,2,3,4	16
20m	1,2,3,4	16
22m	1,2,3,4	16
22.5m	1,2,3,4	16

Table 15 shows the different ranges and radio channels tested. As seen in the table, in the first test, all the channels were evaluated so that the best performing channel could be set as the operation channel for the rest of the measurements. Figure 36 shows the RSSI values obtained when all channels were evaluated. Operation channel was set as 16 for the rest of the tests.

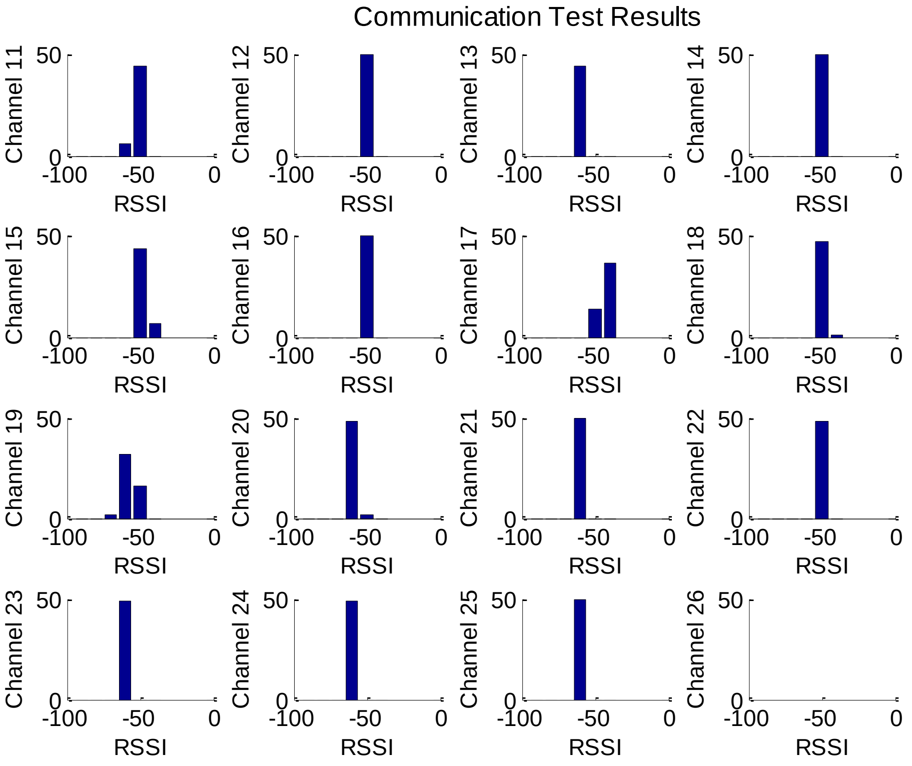


Figure 36. Communication tests in an industrial environment.

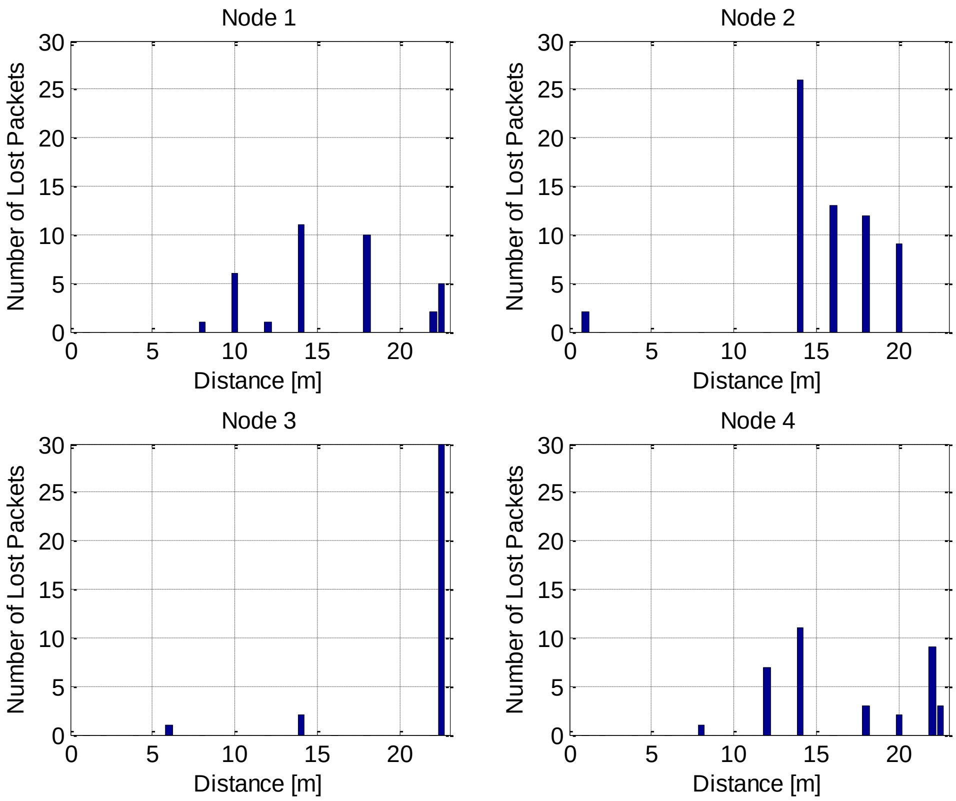


Figure 37. Lost packets vs. measurement distance.

The distance between the wireless sensor nodes and sink node was changed to see the effect of communication distance on wireless communication. Figure 37 shows the number of lost packets at different communication distances. It is seen that packet loss increases as the distance is increased. However this increase is not completely linear and depends on the radio environment and channel conditions. Note Node 3 was not active in the 22.5 m test, which caused the peak in Figure 37.

Figure 38 shows the RSSI measurements for different communication distances. It is seen that the RSSI values fluctuate and there is a decreasing trend in signal strength as the communication distance increases.

In this study, nodes were placed at different locations even though the distance from individual nodes to the sink node was kept the same. This resulted in different communication characteristics which indicate the importance of environmental factors on wireless communication. These findings are useful for further development of wireless sensor applications since the results can be used as a reference for the packet loss and signal strength in industrial environments.

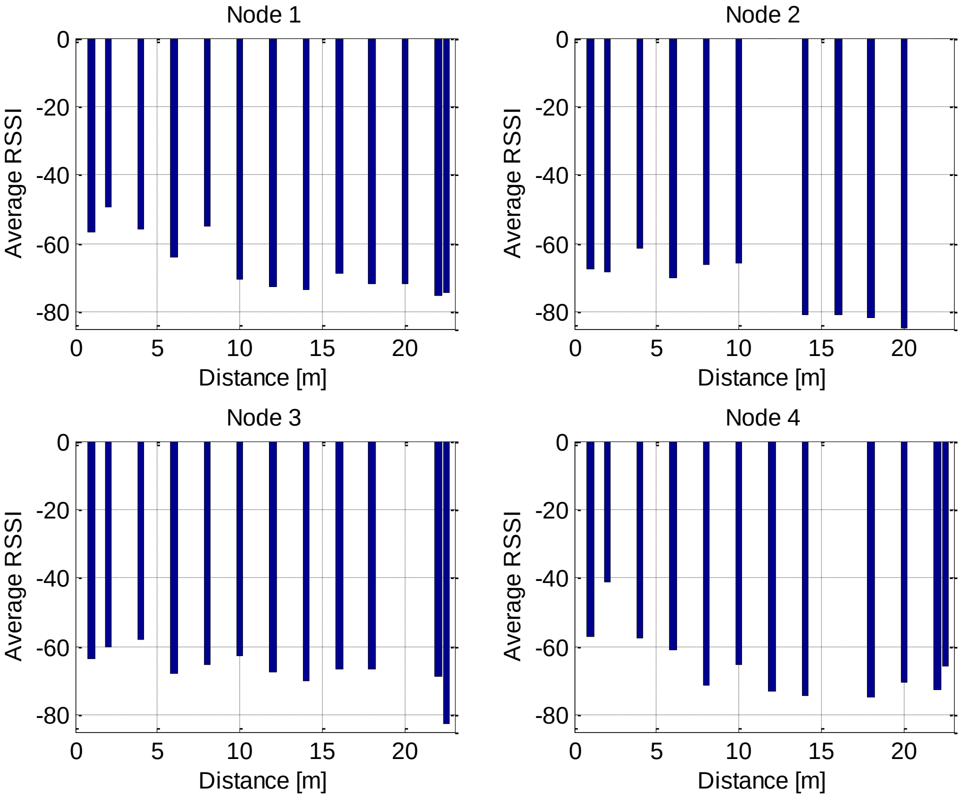


Figure 38. RSSI measurements.

4.3.2 Crane Monitoring with High Sampling Rate Application

In this study, high sampling rate application was tested on the crane. Test crane has three degrees of freedom, i.e., it can move forward-backward, right-left and up-down. Several data sets were collected when the crane was in motion. Seven wireless nodes were placed as shown in Figure 39. One node is placed on the hook and the rest of the nodes were placed on the crane structure. Samples were taken at 100 Hz.

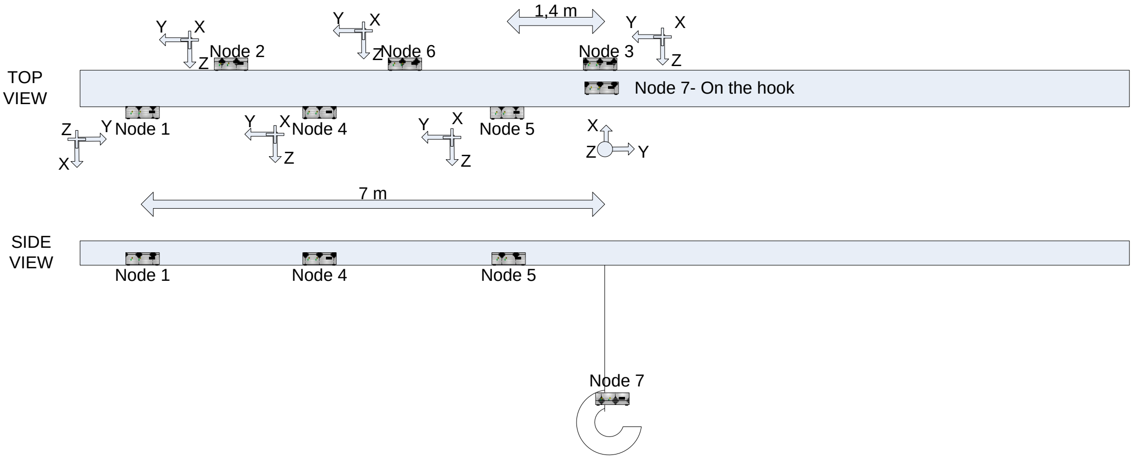


Figure 39. Wireless nodes on the crane.

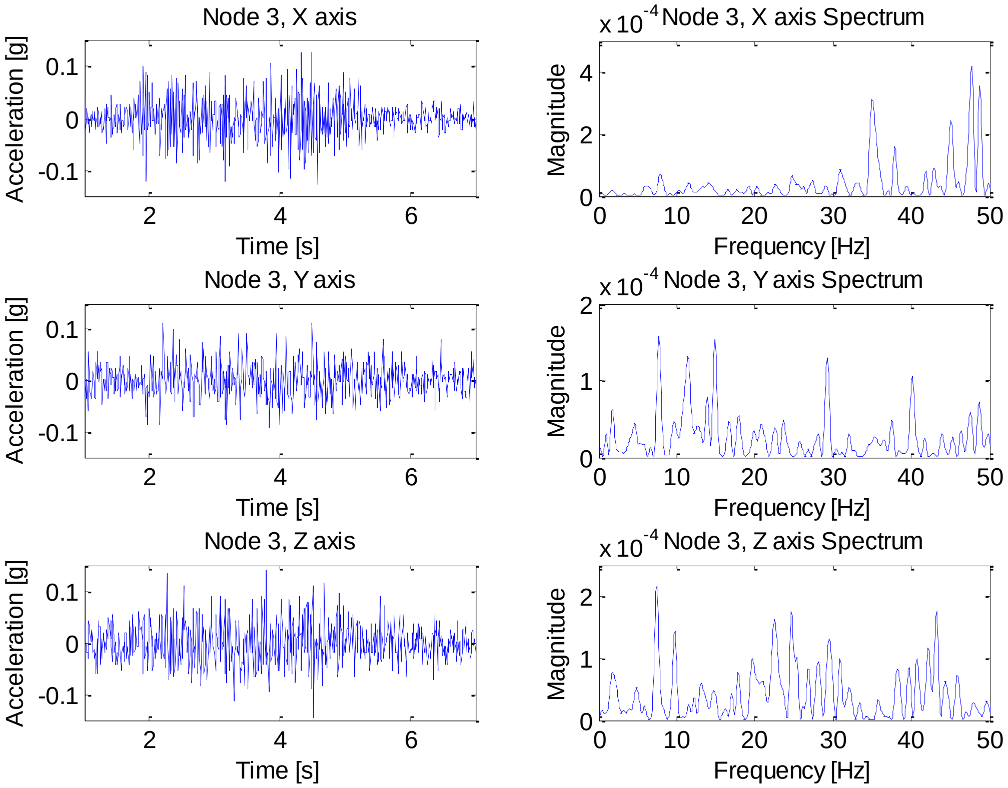


Figure 40. Three axes data collected while the trolley was moving from right to left, and their spectrum.

Figure 40 shows a set of data collected when the crane was moving from right to left. On the left hand side, data collected by Node 3 in three axes are seen, and on the right, frequency spectrum of these data are presented. Spectrum analysis is done by using one portion of the data during which the crane was moving. Means were removed from the data for spectrum analysis and Welch’s method with 1024 samples FFT size, 256 samples Hanning window and 50 samples overlap was used.

In this study data was collected successfully from seven wireless nodes placed on an industrial crane. Effects of crane movement are clearly seen in time series data. Several frequency peaks are visible in spectrum analysis of the data neither one being dominant. During the measurements, crane was not loaded and this is the reason for not having clear frequency peaks.

4.3.3 Real-Time Data Collection

Real-time monitoring application was tested on the crane with four nodes. Nodes were placed as shown in Figure 35. Data was collected when the crane was moving. Sampling frequency of accelerometer sensors was 100 Hz.

In real-time monitoring application, the instants at which a packet is lost can be seen, since a series of gaps are introduced into the data when a packet is lost. Figure 41 shows these instances during forward-backward movement of the crane. During the first half of the test, the crane was moving away from the sink node and during the second half, it was coming back. It is seen that more packet loss occurs as the distance between crane and the sink node increases. However, packet loss trend does not increase linearly, since other environmental factors also affect wireless communication.

Table 16 shows the percentage of lost packets during each operation and for each node. Lost packets increase in forward-backward operation, since the distance between wireless nodes and sink is increased. Furthermore, it is seen that Node 2 (on the hook)

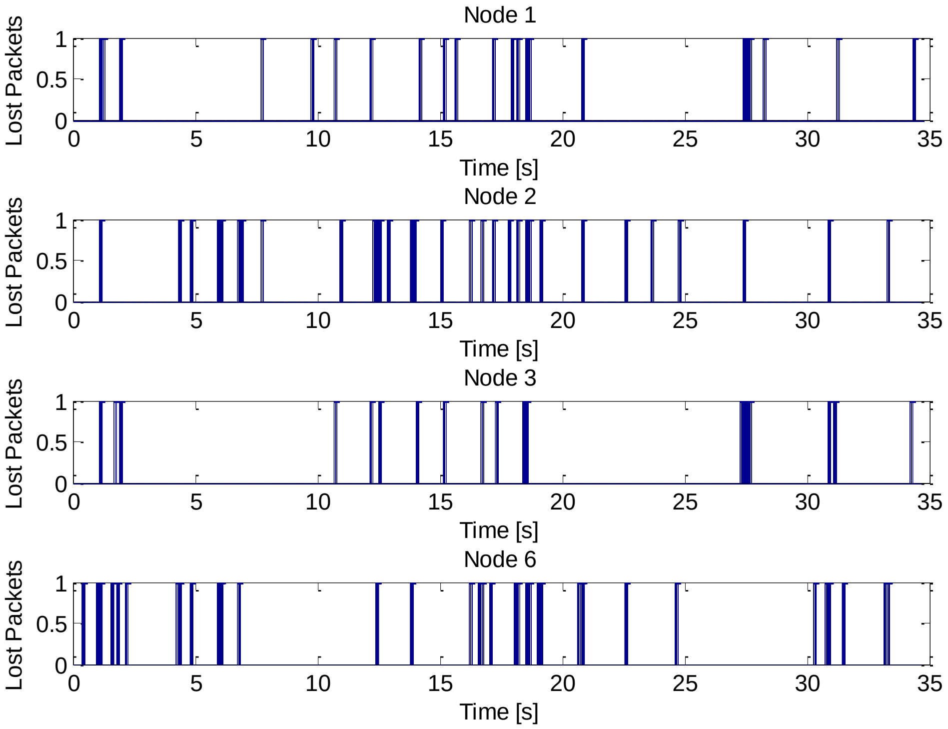


Figure 41. Lost packets when the crane moves forward and backward.

Table 16. Lost packets in the industrial environment.

Percentage lost packets				
Operation	Node 1	Node 2	Node 3	Node 6
Lifting	0,0366	0,0684	0,0263	0,0579
Left-Right	0,0266	0,1065	0,0380	0,1145
Forward-Backward	0,0761	0,1076	0,0660	0,1181
Forward-Backward	0,1164	0,1644	0,1301	0,1336
Down	0,0280	0,0327	0,0329	0,0563
Lifting-Go Right-Lowering	0,0407	0,0816	0,0459	0,0918

and Node 6 (on the load) experienced more packet loss compared to Node 1 and 3 (on the crane). This is most likely because of relatively high mobility of these nodes, whereas the other nodes were attached on the more stable crane structure.

Figure 42 shows data taken when the crane was lifting a load. Data is taken from X axis of the Node 6, which is placed on the load as shown in Figure 35. Load vibrations of the time series data when crane is lifting a load are visible in this figure. Note that the lost packets are replaced by linear interpolation. In the lower plot, frequency spectrum analysis of this data can be seen. Frequency spectrum analysis is done by using Welch’s method with 1024 samples FFT and 1024 sample Hanning window with 50 samples overlap.

This study proved the usability of real-time monitoring system in an industrial environment. Percentage lost packets and instances at which packets are lost were observed when the crane is in motion. Time series data showed the effect of crane motion on the measured vibrations. Spectrum analysis of the data collected by a wireless node on the load showed clear frequency peaks.

4.3.4 Results of Crane Monitoring in an Industrial Environment Case Study

In this case study, developed applications were evaluated in an industrial hall, where a typical 5 ton bridge crane was situated.

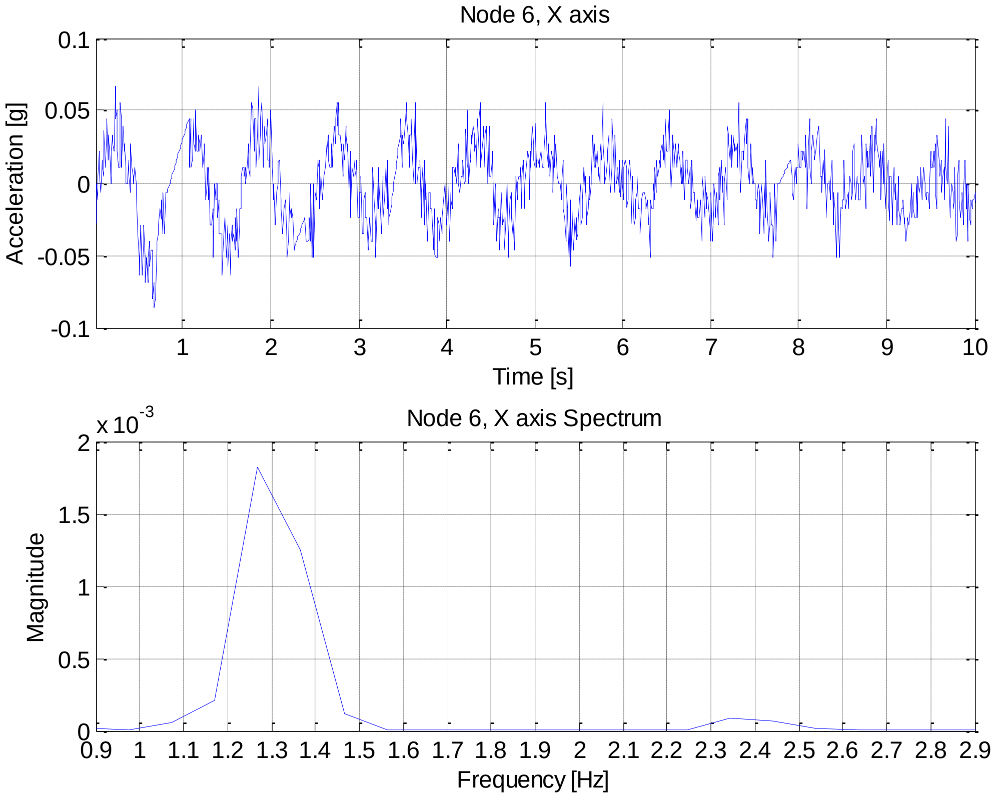


Figure 42. Acceleration measurements when crane is lifting the load. Data was taken from Node 6 which is placed on the load.

Communication test application was used to investigate wireless communication characteristics of the sensor nodes in an industrial environment. Tests showed the importance of environmental factors on wireless communication.

High sampling rate application was used to collect vibration data from seven wireless nodes placed on the crane and on the load. Crane movement was seen to induce vibrations that can be detected by wireless sensors.

Real-time monitoring application was tested on the loaded industrial crane. Percentage lost packets and instants at which packets are lost were observed when the crane was in motion. Collected data was seen to be useful for detecting movement related vibrations.

5 Conclusions

Wireless monitoring field embraces many engineering branches, such as computer science, electronics engineering, mechanical engineering, control engineering and telecommunications. Required skills vary from low-level programming of microprocessors to high-level programming of PCs. Understanding of electrical and mechanical hardware, sensors, data transmission protocols, network design, and data analysis methods are essential for the field. Working with wireless sensors is usually time-consuming and challenging due to many unanticipated problems.

The scope of this thesis was to design, develop and test a general purpose wireless monitoring toolkit to be used for condition monitoring and performance optimization purposes. Within this scope, implementation of a general purpose, easy-to-use, fast and reliable monitoring toolkit was planned.

A review of state of the art wireless monitoring systems has been done to determine framework of a general purpose wireless monitoring system to be used for condition monitoring and performance optimization purposes.

The development of a wireless monitoring toolkit was presented in this thesis. Toolkit consists of three applications, a novel data acquisition system, hardware components (sensors, casing, antennas, etc.), sensor drivers, and user interfaces. Sensor nodes are formed by combining a temperature and humidity sensor, an accelerometer sensor PCB, an off-the-shelf wireless node, antenna, battery, and a switch into a compact case.

An important aspect of the work is optimization of wireless data transfer between the sensor nodes and PC. To establish this, effect of data acquisition methods on performance of networked data logging systems has been investigated. Existing data acquisition methods have been evaluated and a new portable, inexpensive and efficient data logging system has been introduced.

A high sampling rate application that uses the above mentioned data acquisition system was presented. This application is capable of recovering lost packets by using a retransmission algorithm. A communication test application has been developed to evaluate wireless network characteristics. These two applications are combined in one code and user interface.

A real-time monitoring application has been developed for low sampling rate (< 200Hz) applications. With this application, wireless nodes can sample and transmit without storing the measurement data into an external memory which reduces the time spent for measurements. Real-time monitoring application has two very important characteristics: dynamic and multi-task operation. These features provide a flexible, reliable and efficient structure to the application and distinguish it from other wireless monitoring applications.

High sampling rate application was tested on a wooden model bridge. These tests proved the usability of wireless sensors in structural health monitoring applications. The tests also gave important insights on future development directions that will increase reliability of the wireless sensors.

Real-time monitoring application was tested on a laboratory scale trolley crane system. During these tests, multiple system parameters were simultaneously monitored at multiple locations without disturbing the normal operation of the crane. Monitoring system was used to evaluate controller performance and to observe the relation between load angle and accelerations acting on the load.

Wireless monitoring toolkit, as a whole, was tested on a 5 ton crane situated in an industry hall. These tests showed communication characteristics of wireless sensors in a real world environment. Furthermore, vibrations induced due to the movement of the crane were measured and evaluated. Real-time monitoring application and high sampling rate application were both used at 100 Hz sampling frequency in these tests. Even though they seem to be doing the same task, they have different development perspectives. Real-time monitoring application is prone to packet loss, whereas high sampling rate application overcomes this problem by retransmissions. Furthermore, in real-time monitoring case, there is a tradeoff between sampling rate and number of nodes, whereas high sampling rate application can sample at high frequencies regardless of the number of nodes. On the other hand, user has to wait for the wireless transmission when high sampling rate application is used. On the contrary, data are accessible during the measurements when real-time monitoring application is used.

Note also that measurement data are stored in the memory of sensor node, when high sampling rate application is used. This means that a limited amount of data can be taken during one measurement. However, memory is not a limitation in real-time monitoring application since data is not stored in the node. These two applications are designed to complete each other and to give the user more flexibility.

The main objective of this thesis was to determine and implement a framework of general purpose wireless toolkit for monitoring applications. The end result, wireless monitoring toolkit, is equipped with three applications to meet the requirement of being general purpose. A data acquisition system, which improves the speed of data collection, has been developed to meet the fast monitoring system requirement. User interfaces have been developed to hide the low level programming issues from the user which makes the system easy to use. Three case studies proved the reliability of the measurements and the system. At the end, it is fair to say the goals of the thesis were met. On the other hand, there is always room for improvement. Future study on the topic will focus on improving synchronization of measurements and optimizing the code so that all applications are situated in one code. Furthermore, increasing the networking capacity of the nodes will enhance their application areas. Finally, a web based database and control system can contribute to the value of the work.

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