TAMPERE UNIVERSITY OF TECHNOLOGY

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WIRELESS TECHNOLOGIES FOR INDOOR ASSET POSITIONING

Master of Science Thesis

Examiner: Professor Jose L. Martinez Lastra
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ABSTRACT

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The Positioning of assets in a manufacturing industry is one of the milestones in the process to increase the visibility inside the factory and improve the current manufacturing practices. Furthermore, in order to cope with the high mobility of the assets in a factory, the utilization of wireless technologies has been increased in the past few years in order to develop the positioning applications. However, the utilization of these technologies must not increase the complexity of the manufacturing systems. Therefore, the utilization of a common network protocol such as the Internet Protocol is preferred.

The theoretical part of this thesis work presents a general description of the wireless technologies used in industrial environments. Additionally, it discusses the different methodologies and algorithms used for the positioning of assets applications in wireless networks in more detail. Furthermore, an introduction to the latest efforts and systems developed to address the problem of position estimation of assets in wireless networks is provided. In order to understand the realization of the IP-based wireless sensor networks, a brief review of the operating systems supporting this characteristic is presented. Finally a survey about the IP-ready wireless sensor network is performed in order to select the most suitable platform to use in the practical part of this work.

The practical part of this thesis work focuses on the implementation of a real-time position estimation tool for manufacturing assets based on a Wireless Sensor Network for indoor environments. The main purpose is to estimate the position of a pallet allocated on a light assembly manufacturing line. In addition, the wireless sensor network utilizes the Internet Protocol version 6 as the networking protocol. Furthermore, the estimation parameter utilized by the tool is the received signal strength. Consequently, the position estimation methodologies based on the received signal strength are implemented by this tool. Finally, the position estimation tool was tested which is documented in the results section.

PREFACE

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Tampere, Finland. August, 2011.

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LIST OF ACRONYMS

6LoWPAN	Internet Protocol version 6 over Low-power Wireless Personal Area Networks
ADC	Analog to Digital Converter
ADC	Analog to Digital Converter
AES	Advanced Encryption Standard
ANSI	American National Standards Institute
AOA	Angle of Arrival
AODV	Ad-hoc On Demand Vector
ASK	Amplitude Shift Keying
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
BSS	Basic Service Set
CBC-MAC	Cipher Block Chaining Message Authentication Code
CCK	Complementary Code Keying
CCM	Counter Mode with Cipher Block Chaining Message Authentication Code
CIP	Common Industrial Protocol
COFDM	Coded Orthogonal Frequency Division Multiplexing
CRC	Cyclic Redundancy Check
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CSV	Comma Separated Values
CTR	Counter Mode
DAD	Duplicate Address Detection
DSSS	Direct Sequence Spread Spectrum
EEPROM	Electrically Erasable Programming Read-Only Memory
EHF	Extremely High Frequency
EIRP	Equivalent Isotropic Radiated Power
eSONIA	Diagnostics and Control: Towards the Asset-aware and Self-recovery Factory
ESS	Extended Service Set
FFD	Full Function Device
FHSS	Frequency Hopping Spread Spectrum
GFSK	Gaussian Frequency Shift Keying
GUI	Graphical User Interface
HART	Highway Addressable Remote Transducer Protocol
HF	High Frequency
ICMP	Internet Control Message Protocol
IEEE	Institute of Electrical and Electronic Engineers
IP	Internet Protocol
IPv4	Internet Protocol version 4

IPv6	Internet Protocol version 6
IR	Infra Red
ISA	International Society of Automation
ISO	International Organization for Standardization
ITU	International Telecommunication Union
kNN	k Nearest Neighbor
KPI	Key Performance Indicator
LAN	Local Area Network
LF	Low Frequency
MAC	Media Access Control
MB-OFDM	Multiband Orthogonal Frequency Division Multiplexing
MCP	Most Conflicting Position
MCU	Microcontroller Unit
MF	Medium Frequency
MTU	Maximum Transmission Unit
ND	Neighbor Discovery
nesC	Networked Embedded Systems C
NFC	Near Field Communication
NS	Neighbor Solicitation
NTC	Negative Temperature Coefficient
OFDM	Orthogonal Frequency Division Multiplexing
O-QPSK	Offset Quardrature Phase Shift Keying
OS	Operating System
OSI	Open Systems Interconnection
POA	Phase of Arrival
QPSK	Quadrature Phase Shift Keying
R&D	Research and Development
RA	Router Advertisement
radvd	Linux IPv6 Router Advertisement Daemon
RAM	Random Access Memory
RD	Router Discovery
RF	Radio Frequency
RFC	Request for Comments
RFD	Reduced Function Device
RFID	Radio Frequency Identification
ROM	Read-Only Memory
RS	Router Solicitation
RSS	Received Signal Strength
RSSI	Received Signal Strength Indication
RTOF	Round Trip Time of Flight
RTPS	Real Time Positioning System
RUNES	Reconfigurable Ubiquitous Networked Embedded Systems

SDS-TWR	Symmetrical Double Sided – Two Way Ranging
SHF	Super High Frequency
SVM	Support Vector Machine
TCP	Transmission Control Protocol
TDOA	Time Difference of Arrival
TH-CDMA	Time Hopping Code Division Multiple Access
TOA	Time of Arrival
UDP	User Datagram Protocol
UHF	Ultrahigh Frequency
UWB	Ultra Wideband
VHF	Very High Frequency
VLF	Very Low Frequency
WEP	Wired Equivalent Privacy
Wi-Fi	Wireless Fidelity, Trade mark of Wi-Fi Alliance
WLAN	Wireless Local Area Network
WPA	Wi-Fi Protected Access
WPAN	Wireless Personal Area Network
WSN	Wireless Sensor Network

TABLE OF SYMBOLS AND UNITS

(x, y)	Refers to the x-intercept coordinate in a Cartesian coordinate system of a tag node in meters
$(x_{i,}\ y_i)$	Refers to coordinates in the Cartesian coordinate system of the i^{th} anchor node in meters.
$(x_{j,}\ y_j)$	Refers to coordinates in the Cartesian coordinate system in meters of a position at index j
2-D	Bi-dimensional plane
3-D	Tri-dimensional space
A	Coefficient of X in the linear equation in matrix notation
B	Resulting Matrix in the linear equation in matrix notation
d_0	Reference separation distance between the transmitter and the receiver in meters
dBm	Power Radio in decibels of the measured power referenced to one Milliwatt
D_n	Euclidean distance at position n
d_n	Refers to the distance between the n^{th} anchor node and a tag node in meters
f	The frequency of the radio signal in MHz
$f_i(x)$	Position estimation error function in meters
GHz	Gigahertz
j	Denotes the index of a given position where a pallet can be allocated
kk	Number of anchor nodes
Kbps	Kilobits per second
Kbytes	Kilobytes
$L_f(p)$	Floor penetration loss factor in dBm
Log_{10}	Logarithm base 10
$L_{total}(d)_{dB}$	The RSS measured at a wireless node separated a distance d from the transmitter in dBm for the ITU Model
m/s	Meters per second
Mbps	Megabits per second
MHz	Megahertz
mW	Milliwatt
n	Decaying rate of the signal strength with respect to the traveled distance for the Path-loss model
N	Decaying rate of the signal strength with respect to the traveled distance for the ITU model
p	Number of floors that a radio frequency signal penetrates

$p_r(d)_{dB}$	The RSS measured at a wireless node separated a distance d from the transmitter in dBm
$p_r(d_0)_{dB}$	The RSS measured at a wireless node separated a distance d_0 from the transmitter in dBm for the Path-loss model
RSS_j	Vector of either mean or mode values at position j
$S_{i,j}$	Denotes the database values if the ith anchor node at position j
S_j	Denotes either mean or mode values at position j
t_i	Time of the received message at the ith anchor node
v	Velocity of the radio frequency signal propagation in m/s
X	Matrix of the estimated position a tag node in meters. It contains the x and y coordinates in meters.
$X\sigma$	random Gaussian variable with zero mean and variance σ^2
α_i	Reliability of the measurement sample of the signal received at ith anchor node

1 INTRODUCTION

This chapter provides an introduction to the work presented in this thesis. Furthermore, it contains a background of the topic followed by the problem and work descriptions. Subsequently, the objectives, methodology, assumptions and limitations of the scope are described in this section. Finally, the outline of the thesis is given in the last section.

1.1 BACKGROUND

Currently, the manufacturing industry is facing a high competitive scenario in a world where the market has been moving from being supplier-driven towards a customer-driven market. The industrial capacity has increased as well as the customers demand higher quality, cheaper and wider variety of products, making the improvement of efficiency together with cost reduction tasks to play a key role in the business success [Mayer et. al 2009].

The lack of real-time information in the traditional manufacturing process has lead to practices that add unnecessary costs to the production cycle such as scheduling delays, time wasted in manual activities (e.g. searches, inventory checks), the greater risk of the safety protocols violations, the inefficient allocation of equipment, parts and personnel, inefficient maintenance scheduling, among others. Challenges faced by manufacturing industry during last decade have made of such great importance the necessity of having a clearer view of the entire manufacturing process all along the supply chain. The development and implementation of systems to trace the whole history of the product aim for a reduction in the product life cycle, time to market, business risks and cost investments while increasing the flexibility and robustness of the supply chain. The tracing techniques in manufacturing processes can be divided into three applications: status tracking to detect system status, performance tracing to analyze system performance and goal tracing to support the decision making process, giving the opportunity of following the history of events occurred in the process and compare them with the scheduled plans and predefined goals [Cimino and Marcelloni 2010].

In tracking and tracing techniques, the information commonly needs to be represented at asset level and shared between different instances in the system. Therefore, assets positioning in manufacturing industry is one of the milestones in the process to increase the visibility and allow better management of assets leading to better manufacturing practices by feeding this information to the manufacturing and logistics processes [Mayer et. al 2009].

However, the acquisition of the information from the processes requires the utilization of additional resources such as computers embedded in the physical world, also known as smart devices. Thus, the utilization of these resources makes possible the realization of the asset-aware manufacturing schema. As a result, the process automation systems can respond in a faster manner upon disturbances present in the manufacturing processes addressing the optimization of the process. This optimization enhancement can involve, for example, the improvement of the process efficiency, the reduction of energy consumption, the reduction of pollution and waste as well as the improvement of the industrial security [Hui and Culler 2010].

In order to communicate the smart devices among them allowing their interaction and information exchange, a suitable industrial wireless network technology has to be implemented [Hong et. al. 2010]. In this regard, many ad-hoc solutions for wireless networking have been developed in the past few years (e.g. ZigBee, Bluetooth, and Wibree, among others). However, these ad-hoc solutions typically use different proprietary protocols that are not able to interact among them unless the usage of application gateways which increases the design and management complexity of the network. In addition, the usage of gateways also increases the costs of the wireless solution. Consequently, the need for accomplishing the end-to-end communication among the network by using a common networking protocol arises. This networking protocol should be able to work on top of different wireless technologies (e.g. Wi-Fi, Ethernet, and IEEE 802.15.4) in order to enhance the network interoperability. Moreover, the usage of an open communication protocol as the common networking layer provides greater robustness and flexibility to the network making possible its integration to different networks implementing the common communication protocol [Hui and Culler 2010]. An example of an interoperable and open communication protocol is the IP (Internet Protocol) which provides transparency for hosts and servers in the network with no need for using gateways. Additionally, it supports unique addressability, seamless connectivity as well as wide applicability and allows the connectivity to the Internet without requiring additional hardware [Hong et. al. 2010].

Currently many efforts have been directed to the usage of wireless solutions envisioning wide purposes (i.e. from a single task monitoring to the most specialized military applications), not only for positioning applications [Sarwar et. al. 2010]. These efforts include attempts to develop IP-based Wireless Sensor Networks (WSNs) utilizing Wireless Personal Area Networks (WPANs) technologies.

Nonetheless, the utilization of an interoperable industrial wireless solution is just a part of the efforts aimed to solve the problem of the positioning of assets within the asset-aware manufacturing schema. Thus, the utilization of a proper wireless technology along with a suitable position estimation methodology is required. In this regard, different methodologies have been developed in order to estimate the unknown position of an asset connected to a wireless network. Additionally, these methodologies usually involve the measurement of physical variables during the position estimation process, for instance, the received signal strength (RSS), the time of arrival (TOA), the time difference of arrival (TDOA), the angle of arrival (AOA), near-field electromagnetic detection among others [Uribe 2009]. Moreover, these physical variables depend on the characteristics of the wireless technology being utilized in the application. Hence, in order to develop an interoperable position estimation application, a suitable wireless technology must be selected and a proper algorithm should be chosen according to their characteristics.

1.2 PROBLEM DEFINITION

1.2.1 Problem Statement

In a factory, expensive assets (e.g. tools and equipment) need to be shared among different parties while others are fixed to certain positions, products are moved along the production line and personnel is moving constantly. The mobility of the assets makes a wired based positioning system insufficient, arising the need for the usage of wireless based positioning systems working together with the wired based ones or in an independent way. As mentioned previously, the integration of different technologies requires a common network protocol (e.g. IPv6) to avoid the increase of complexity of the system and to support the needed mobility while allowing interoperability as well as reliability among different communication protocols [Hui and Culler 2010].

The wireless positioning applications for manufacturing assets are intended to provide real-time information for the industrial processes. Therefore, the integrity of this information, the accuracy of the position estimation computations and the latency are the targeted key parameters to be accomplished. Besides, the key goal of a manufacturing positioning system is to determine the exact position of an asset with the highest accuracy and precision (ideally zero estimation errors). This estimation has to be performed based on physical measurements taken by the smart devices in the network. Furthermore, the measured parameter depends on the methodology and the technology used to implement the positioning engine which may lead to errors in the estimated results. Consequently, the constrained resources of the embedded devices and their limitations make difficult to achieve the ideal scenario. Nevertheless, a high resolution system can be realized by using a combination of a proper ranging methodology and technology along with a suitable estimation algorithm. However, the required resolution will be given by the application itself. This resolution defines the ability to distinguish among near locations of assets and estimate their position within a certain range [Muñoz et. al. 2009]. Furthermore, the use of a common communication protocol enhances the interoperability of the networks and enables its integration with other networks by means of no additional hardware requirements. This allows the development of a real-time positioning application for manufacturing assets with wide interconnectivity among different technologies.

The problem statement for this work can be formulated as follows: how to address the problem of the positioning of manufacturing assets for indoor environments by utilizing a wireless technology with enhanced interoperability capabilities.

1.2.2 Justification of the Work

Tampere University of Technology is taking part in a European project under the umbrella of ARTEMIS JU, named Embedded Service-Oriented Monitoring, Diagnostics and Control: Towards the Asset-aware and Self-recovery Factory (eSONIA). One of the main objectives of the eSONIA project is to research new techniques and tools for asset-awareness and self-recovery in production plants.

Thus, this research aims to provide methods for positioning and tracking of manufacturing assets and products in real-time using low-powered, low-cost, embedded wireless devices. Furthermore, it is expected that the resulting solution offers enhanced interoperability among different wireless technologies. This can be achieved by using communication protocols such as 6LoWPAN and IP communication protocols. As a result, the wireless network can be easily connected to the Internet without using any gateways.

One of the contributions of TUT to the eSONIA project will be to provide a prototype Real-Time Position Estimation Tool. This tool is expected to integrate a suitable wireless technologies used in industrial manufacturing and a proper position estimation algorithm that can be used as a proof of concept for the positioning of manufacturing assets for indoor environments in a discrete manufacturing domain. Furthermore, the resulting tool is waited to be easily integrated with the rest of the manufacturing systems working over IP protocol.

1.3 WORK DESCRIPTION

1.3.1 Objectives

1. Develop a real-time position estimation tool based on WSN networking with IPv6 communication protocol.
2. Implement a wireless sensor network based on 6LoWPAN standard to enable IPv6 as a common communication protocol.
3. Implement and evaluate a location engine considering the existing and enhanced methodologies for position estimation of wireless assets.
4. Develop a graphical user interface to interact with the real-time position estimation tool.

1.3.2 Methodology

Research of existing Wireless Technologies in Industrial Manufacturing

Review the importance of wireless technologies in current Industrial manufacturing environments. Review the current existing wireless technologies applied in Industrial Manufacturing applications focusing on wireless sensor networks. Moreover, study the challenges and design goals of wireless sensor networks. Review the standardization efforts in industrial wireless sensor networks.

Research of existing implementations of the 6LoWPAN protocol for WSN

A study of the current implementations of the 6LoWPAN protocol for WSN has to be conducted. From this study it will be decided which of the implementations is best suited to implement a 6LoWPAN WSN. Currently NanoStack from Sensinode and uIPv6 from Contiki are the strongest candidates.

Evaluation of a suitable principle for implementing a location engine in the WSN platform

Review of existing position estimation techniques and algorithms applicable to wireless technologies. As a result, of a preliminary research and selection among several existing principles for position estimation, it has been decided to investigate further two possible alternatives for implementation: based on the principle of Time of Arrival (TOA) and based on Received Signal Strength (RSS). An evaluation of the requirements of both alternatives should be made, providing grounds to decide which is better suited for the task at hand.

Research of existing commercial WSN platforms

A suitable commercial WSN platform for implementing the real-time positioning system has to be selected among several candidates. The general requirements that must be considered are: compliance with IEEE802.15.4 standard for radio communications, sufficiency of hardware resources, facilities for user application development, as well as compatibility with existing software developments. Some of the possible candidates are the evaluation kit from Sensinode, TelosB from Crossbow, RZRaven from Atmel, among others.

Porting the selected 6LoWPAN implementation to the selected WSN platform

The selected 6LoWPAN implementation has to be ported to the chosen WSN platform or any modification to specific components of the implementation that might be considered necessary.

Implementation and testing of the mechanism that supports the principle selected before.

Once the location principle (Time-based or RSS-based) has been selected, it must be implemented and tested in the WSN platform. After the completion of this requirement, it should be possible to do a basic location demonstration using a very simple topology configuration on the WSN: For instance the deployment of an ad-hoc single hop wireless local area network.

Development of a user interface for interaction with the position estimation tool

Development of a tool for facilitating the interaction with the position estimation tool, it could be possible to develop a Graphical User Interface (GUI), by which it could be possible to visualize basic information of the sensor nodes in the network and represent a simple positioning/ tracking interface.

1.3.3 Assumptions and Limitations of Scope

The work presented in this master thesis was developed in the domain of a light final assembly where a pallet-based assembly line is considered as the test bed for evaluating the position estimation tool. The target of the work is to implement a location system for manufacturing assets in an indoor environment. The software and platforms used for monitoring the line and its web-service based control system are out of the scope. Besides, the positioning of assets in outdoor environments is also out of the scope.

Assumption 1: The positioning engine is developed in a low-cost, low-power consumption and constrained resources embedded devices.

Assumption 2: Positioning of assets will take place in an indoor environment.

Assumption 3: The end-to-end communication can be achieved by using a common network protocol working on top of different link technologies.

Assumption 4: Direct link communication has to be achieved among tag nodes and anchor nodes to achieve positioning tasks.

Assumption 5: For evaluation purposes, the positioning tasks take place in an ad-hoc, single-hop wireless sensor network. However, this WSN should be able to join the Internet with no need for waterways.

Assumption 6: All the traffic goes to a single sink node connected to a computer hosting the graphical user interface system implementing the location algorithms.

Assumption 7: The positioning algorithm is executed in a centralized manner.

Assumption 8: The position estimation of assets was performed in a bi-dimensional (2-D) plane. The tri-dimensional (3-D) positioning is out of the scope of this master thesis work.

1.4 THESIS OUTLINE

The remaining Chapters of this thesis are organized as follows. Chapter 2 provides a literature and technologies review related with the development of real-time positioning systems in discrete indoor industrial environments. Chapter 3 presents the proposed extensions to the state-of-the-art in order to develop a solution for the position estimation problem. Chapter 4 describes the implementation of the real-time position estimation tool. Additionally, it discusses the test bed and the scenario used to develop the work presented in this thesis as well as the graphical user interface designed to interact with the position estimation tool. Chapter 5 focuses on the results obtained during the implementation and experimentation phases according to the scenario described previously. Finally, the results and the ideas that were shown and discussed along this thesis work are concluded in Chapter 6. Additionally, it provides the future work and lessons learned during the development of this work.

2 STATE-OF-THE-ART

This chapter provides a review of the literature and technologies related to the work presented in this thesis. In the first instance, a review of the wireless technologies used in the field of industrial manufacturing and their standardization are detailed. Subsequently, a survey of positioning technologies and techniques for indoor environments is discussed. Additionally, it provides a survey of existing commercial solutions for indoor position estimation applications. Finally, a review of suitable platforms to develop wireless sensor networks is described in order to understand the technology used for the set-up of the test bed used along the thesis work.

2.1 WIRELESS TECHNOLOGY IN INDUSTRIAL NETWORKS

The need and demands in today's global industrial manufacturing market in conjunction with the aging of manufacturing systems and methodologies have raised the need for more efficient, intelligent and low-cost industrial control and monitoring applications. In order to gain competitive advantage, the companies need to process greater amount of information rapidly. Furthermore, the data collecting methods must be more reliable and spread over larger areas but still must be able to communicate among the system. The information collected by the sensor from the physical world is digitalized and transferred between the components of the system. Finding a solution to these challenges has yielded in the development of industrial automation systems. These systems have contributed to the improvement of efficiency and productivity in industrial manufacturing processes as well as have helped to accomplish the environmental and safety regulations [Gungor and Hancke 2009].

According to [Shelby and Bormann 2009] the industrial automation can be split into two distinct application areas: process control and factory automation. Process control covers applications such as petroleum, chemical or gas production while factory automation is related with appliances, discrete components and consumer products in manufacturing processes. Additionally accordingly to [Christin et. al 2010] industrial automation systems can be divided into two main categories: closed loop and open loop systems. Closed loop systems are usually applied in discrete operations such actuator control while open loop systems are applied in monitoring of continuous processes.

Notwithstanding industrial automation can be classified into two categories using different criteria, both classifications rely on the data collection from the physical world in order to perform dedicated tasks. Such tasks are for instance the monitoring of critical or non-critical processes, the tracking of assets and the control of manufacturing processes or environmental control events, among others. These tasks need information from the process whether to perform corrections or to inform the user or a sub process about an event or process variable behavior. Therefore, industrial automation needs complex systems implementations in order to accomplish the quality of service, safety and security goals required by the companies. This complex implementation signifies the integration of a wide range of field devices into the system and the deployment of industrial sensor networks all over the areas of the factories [Shelby and Bormann 2009].

In this regard, the International Society of Automation (ISA) has defined six different classes for sensor and control applications within the industrial market domain. This categorization ranges from safety to non-critical control and application. A more extensive description of these industrial control and application classes is shown in Table 2.1.

Table 2.1 Classes of sensor and control applications with some examples [Shelby and Bormann 2009]

Class 0	Safety	Emergency action Required • Emergency Shutdown • Automatic Fire Control • Leak Detection
Class 1	Control	Closed Loop Control – Critical • Direct control of actuators , pumps and valves • Automated shut-down
Class 2	Control	Closed Loop Control – Non-critical • Optimizing control loops • Flow diversion
Class 3	Control	Open Loop Control – Human Intervention • Operator performs manual adjustment
Class 4	Monitoring	Alerting – Necessary Maintenance • Event based maintenance • Low battery • Vibration monitoring • Motor temperature monitoring
Class 5	Monitoring	Logging – Preventive Maintenance • Preventive maintenance records • History collection

In industrial applications, sensors are used to transform physical measurable characteristics from the process into signal values that can be transferred to an information processing entity to be analyzed and then fed into a process control system to further controlling tasks either directly or by means of automatic devices or robots [Energy US 2004]. This communication interaction among an industrial automation system is illustrated in Figure 2.1.

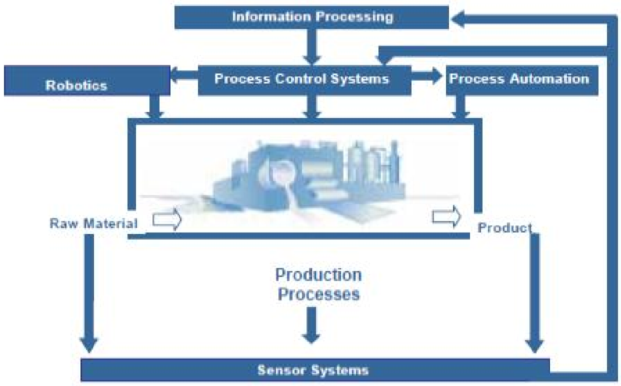

Figure 2.1 Sensor Networks & Automation R&D Focus Areas and Goals [Energy US 2004]

In order to achieve an interaction among the whole system a network has to be deployed. These industrial networks have been traditionally carried out by means of interconnecting wires between the equipment and devices that comprise them. In this sense some protocols and standards have been developed to accomplish the wired communication, this is the case of Foundation Fieldbus, Profibus, HART, CIP, among others [Shelby and Bormann 2009].

However, wired industrial networks are expensive because of their high installation costs, high maintenance costs and the high failure rate of connectors in the network, the constant increasing costs of the wires, cables and accessories used and the difficulty that connectors and accessories present in troubleshooting tasks upon a failure as illustrated in Figure 2.2. The higher costs involved in the deployment and implementation of wired industrial networks contrast with needs of the modern manufacturing industry of a constant cost reduction. As a result, the development of new solutions that fulfill the modern manufacturing industry needs have been motivated [Energy US 2002].

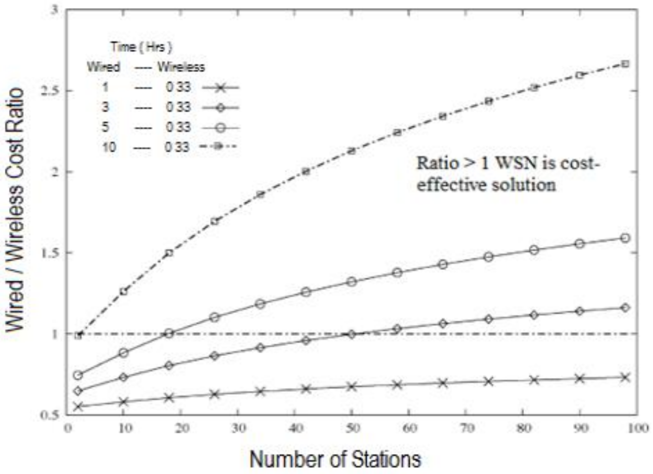

Figure 2.2 Wired / Wireless Network setup and deployment cost ratio comparison [Egea-Lopez et. al. 2005]

The advances over the last decade in the fields of micro-electro-mechanical systems technology, silicon based digital electronics and wireless radiofrequency communications have opened the horizon to a plethora of new applications in industrial manufacturing automation. The ability to embed sensing, processing, storage and communication capabilities into a minute device has provided the possibility to create new low-cost devices and therefore low-cost applications. Moreover, these low-cost devices have the capability to deploy a network comprised by a large number of nodes and interact among them wirelessly in a collaborative effort, arising what presently is known as Wireless Sensor Network (WSN) [Akyildiz et. al. 2002]. These nodes are able to sense or to control physical parameters and can be installed either in the place where the measurements take place or far from the actual phenomenon depending on the sensing or controlling principle.

The communication in a WSN takes place over the air by using electromagnetic waves as the transmission medium, which offers competitive advantages over the wired networks. Some of the competitive advantages are summarized in Table 2.2.

Table 2.2 Competitive advantages of Wireless over Wired Sensor Networks [Energy US 2002]

Lower installation and maintenance costs	Wireless technology costs have been gradually dropping over the past few years, while the costs associated with the installation of wired networks have been following the opposite way. In addition while wires age the probability of failure increases. Therefore the costs involving maintenance, testing, troubleshooting, repair or replacement increase as well.
Reduce connectors and accessories failures	In a traditional industrial network, most of the failures occur in the connectors or accessories used in them. This problem is eliminated in the case of WSNs.
Enhanced physical mobility and freedom	Reconfiguration of processing lines as well as tracking and tracing routines become simpler without the restriction of wires. Besides the nodes can be placed almost everywhere. This enhances the feasibility of the deployment of the network as well as facilitates the replacement activities. Also multiple radio frequency networks can be deployed in the same areas. Hence they can overlap without needing to communicate each other.
Exploitation of minute devices	Minute constrained devices can be embedded in the physical world. These devices have the ability to sense, to process, to store and to communicate with the rest of the network. These in-built capabilities eliminate the failure modes associated with the sensor connection and integration into a wired network.
Rapid commissioning	Ad-hoc or back bone wireless sensor networks can be rapidly deployed, organized and configured, reducing the installation times.

Although the competitive advantages offered by wireless sensor networks, they cannot fulfill the complete range of industrial applications needs. In this regard and taking into account that around the half of the measurement points in industrial factories are intended for monitoring operations, wireless sensor networks are mainly addressed to accomplish the requirements of industrial applications of class 4 and class 5 [Zheng 2010] as illustrated in Figure 2.3.

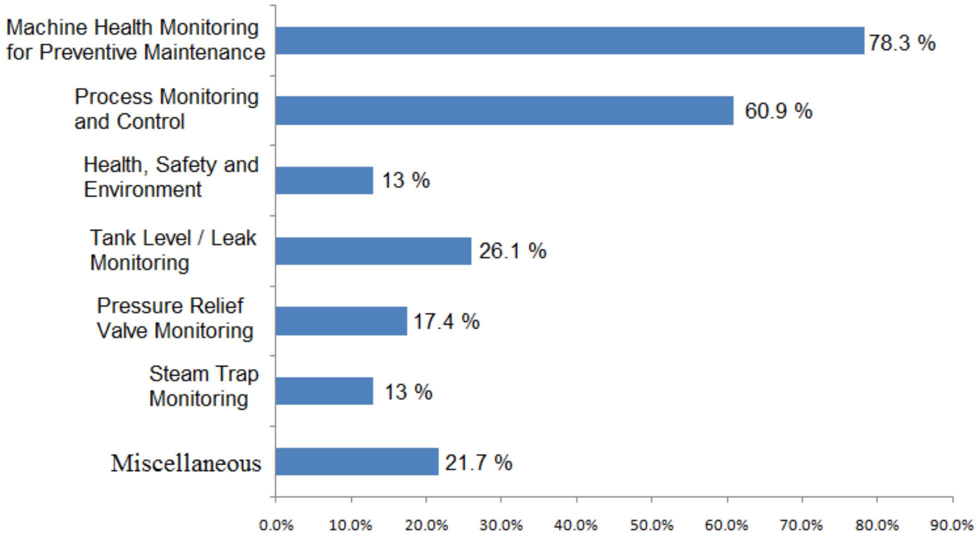

Figure 2.3 Wireless Sensor Network Applications [Amit 2008]

Hence a complete industrial networking in the new manufacturing business is accomplished by the integration in wired and wireless networks working together. A model of modern manufacture industry architecture is shown in Figure 2.4 where the networking cooperation between wired and wireless networks can be appreciated.

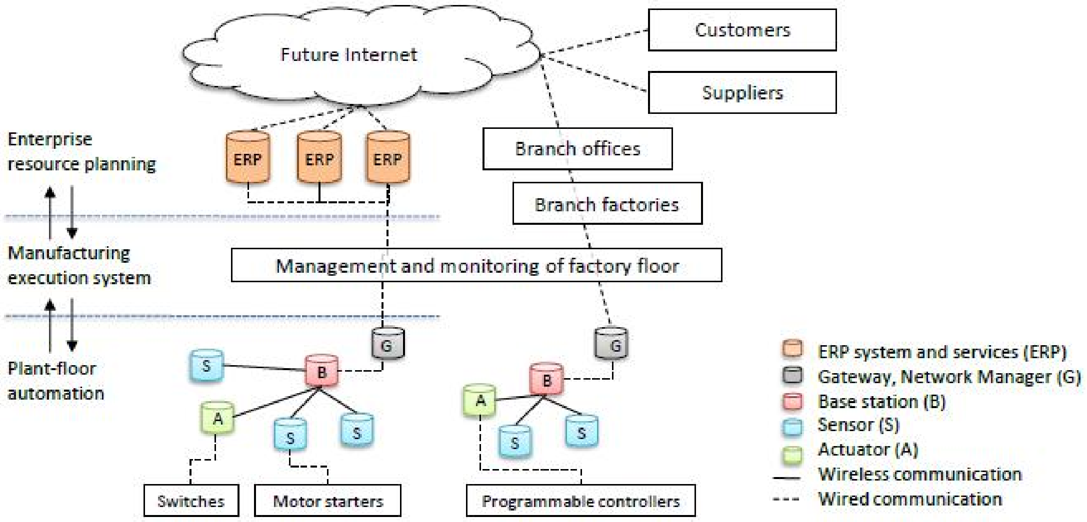

Figure 2.4 Architecture of Modern Manufacturing Industry [Christin et. al 2010]

Moreover, the next generation of wireless networking devices is expected to be comprised by a large number of smart embedded devices. These smart devices share common characteristics such as constrained resources, working with different operating systems and connected with a common networking protocol but with different link layer protocols. Furthermore, mobility and ad-hoc networking has to be considered in the network deployment in order to increase the adaptability and awareness of the systems based on the context where they exist. These envision is pictured in the Technology Roadmap developed by the Reconfigurable Ubiquitous Networked Embedded Systems (RUNES) project illustrated in Figure 2.5.

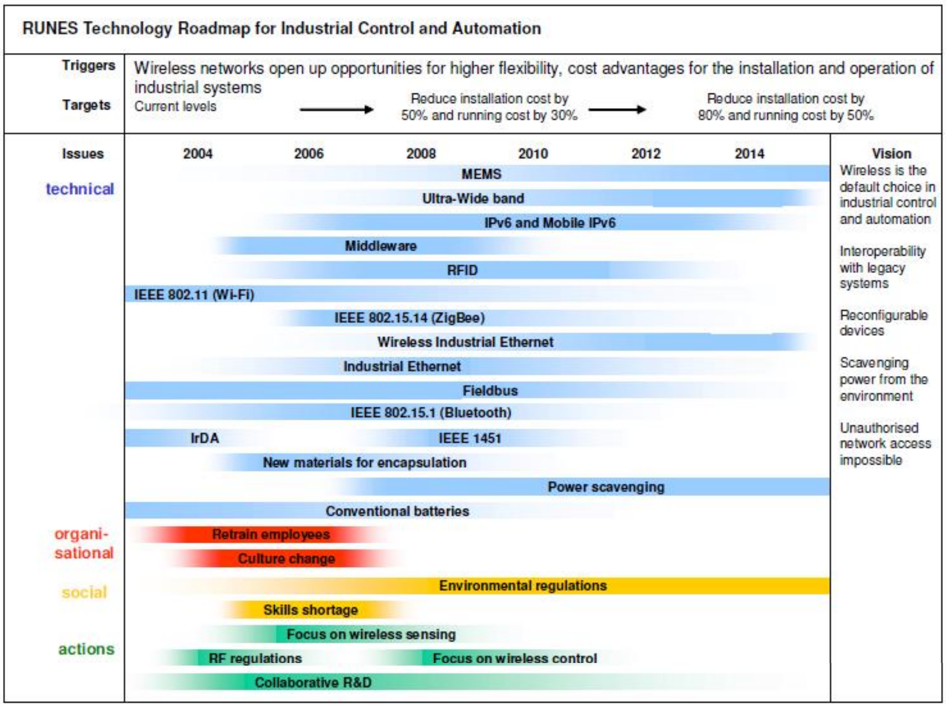

Figure 2.5 The RUNES technology roadmap for industrial control and automation in graphical form [Koumpis et. al. 2005]

In order to pave the road towards the future of the wireless technology in the industrial environment, many efforts have been developed in the field. Such is the case of the RUNES project whose main efforts are pointed to the derive architectures and provide platforms that allow the creation of a large, widely distributed and heterogeneous network comprised by these smart objects.

The realization of a wireless network needs to overcome a series of technical challenges, organizational and social requirements. However, the design and deployment of the industrial wireless sensor networks is not straight forward and requires a combination of knowledge and expertise in different areas.

A summarized relation between challenges and goal designs in an industrial wireless sensor network is presented in Table 2.3.

Table 2.3 Relationships between Challenges and Design Goals in an Industrial WSN [Gungor and Hancke 2009]

Challenges	Design Goals
Resource Constrains	Energy efficient design
Dynamic Topologies and Harsh Environmental Conditions	Adaptive Network Operation
Quality of Service Requirements	Application Specific Design and Time Synchronization
Data Redundancy	In-Network Processing
Packet Error and Variable Link Capacity	Fault Tolerance and Reliability
Security	Secure Design
Large Scale Deployment and Ad-hoc Architecture	Low-cost and Small Sensor Nodes and Self-configuration and Self-organization
Integration with Internet and Other Networks	Scalable Architectures and Efficient Protocols

The design of an Industrial Wireless Sensor network that accomplishes all the design goals is very challenging. This design must consider multiple factors that satisfy the needs of a certain implementation. Fortunately, not all the applications have the same priorities, requirements and objectives. But it is imperative to look for designs that implement highly efficient communication protocols while optimizing the performance of these constrained sensor nodes. Therefore, a balanced compromise among the limitations, requirements, objectives, priorities and design goals must be achieved in order to provide the Quality of Service required by the industrial applications.

Following the classification of the design goals and challenges of industrial WSN proposed by [Gungor and Hancke 2009], a further work extension is provided in the following sections.

2.1.1 Technical Challenges in Industrial Wireless Sensor Networks

Notwithstanding the wireless sensor networks cannot be applied to all industrial applications, in order to exploit the advantages offered by them, the design of an industrial WSN requires a combination of knowledge and expertise in different areas. In the first instance, specific-domain application development requires industrial expertise and knowledge in the field of interest. Secondly, it is highly important to understand the phenomenon to be sensed in order to choose the proper sensing principle, calibration method, and clock-drift and latencies tolerances, among others. Third, understanding of the environment and knowledge in radio frequency signal propagation is needed to overcome interference, noise and communication interruption problems. Finally, networking expertise is required to design a flexible and scalable network hierarchical architecture that integrates heterogeneous applications [Gungor and Hancke 2009].

Consequently, the realization of an Industrial Wireless Sensor Network needs to cope with major technical challenges which according to [Gungor and Hancke 2009] can be enumerated as follows:

Resource constrains: A wireless sensor node is comprised by four main components. These components are the sensing unit, processing unit, transceiver unit and power unit, the last one is typically based on battery solution. The sensing unit is comprised by sensors which transform the physical variables into analog electrical signals and the analog to digital converters (ADC) that transforms the analog signal into digital values that are transferred to the processing unit comprised by the processor and a storage device. The transceiver unit provides the radio frequency connection mechanism to join the network wirelessly [Akyildiz et. al. 2002].

Furthermore, there are three types of identifiable resources present in a wireless sensor node which are memory, energy and processing resources. Presently most of the wireless sensors are based in micro-electro-mechanical systems resulting in minute size devices. Their size is proportional to their memory and processing capabilities, consequently they are limited.

Dynamic topologies and harsh environment conditions: A wireless sensor network is connectivity is highly dynamic, i.e., the network topology is continuously changing. Harmful phenomena to wireless communication can be found in an industrial environment, for instance, power lines or interfering devices such as drives or electromagnetic devices exist in the factory floor that might induce noise into the networks or cause interference. Moreover, the machinery distribution in the factory layout contributes to the multipath and fading effects in the radio communication signal propagation. There harmful phenomena can compromise the data transfer in an industrial wireless sensor networks because of the noise, interference, multipath delay and fading effects produced by them [Egea-Lopez et. al. 2005].

In addition to machinery and interfering devices there are other environmental factors that contribute to the increased dynamicity of the network, for example, many wireless networks operating at the same frequencies can overlap in a factory without needing to communicate each other. This overlapping leads to radio frequency interferences that might affect the communication quality or can conduct to communication failures. Besides interference from radio frequency overlapping other conditions can produce failures in the network such as elevated acid or corrosive environments, high humidity, dusty or dirty conditions. Furthermore highly vibration environments can cause malfunction to the devices and as a result communication failures [Gungor and Hancke 2009].

Quality of Service (QoS) Requirements: The International Telecommunication Union (ITU) defines Quality of Service as “the collective effect of service performance which determines the degree of satisfaction of a user of the service” [ITU 1995].

As mentioned in Section 2.1 the industrial applications of wireless sensor networks are mainly intended to cover a variety range of monitoring and supervisory control activities. Consequently the quality of service requirements and specifications vary as accordingly to the application. Hence the QoS provided by industrial wireless sensor networks can be defined as the accuracy between the data transmitted from the sensor node to the sink node and the actual phenomenon occurring in the process. However not only high accuracy is required to completely describe the QoS, also there is a time variable involved. As a result, the system has to provide the information in a timely manner in order to avoid incorrect control decisions caused by high latency deliveries, signifying the transmission of outdated data to the control system.

Data Redundancy: Data redundancy can lead to anomalies and corruption of information in a wireless sensor network causing malfunctions in the industrial automation systems. For instance, the same process variable can be reported with different values that might cause contradictory control decisions in the process. This phenomenon should be avoided or minimized in the design phase of a project. This represents a challenge in wireless sensor network design because of the high correlation existing between the sensor observations and the space where they are deployed in a high populated network. Also depending on the nature of the phenomenon being sensed, a temporal correlation can exist among consecutive samples measured by the sensor node [Gungor and Hancke 2009].

Packet Error and Variable-link Capacity: The success of the communication and the capacity of the wireless link between the nodes in a network depend on the noise and interference level present at the receiver side when the transaction takes place. Even when the transmission techniques are intended to the best effort communication in order to cope with the high dynamicity of the network topology caused by the conditions encountered in the industrial environment, the Bit Error Rate (BER) in wireless networks is typically two orders of magnitude greater than industrial wired systems. Hence the quality and capacity of the link communication vary continuously because are location-dependant. This represents a challenge to the achievement of the Quality of Service required by the system [Egea-Lopez et. al. 2005].

Security: In the nowadays globalized scenario where the trend in the new technology is the integration of assets into the Internet, the Security plays a key role to maintain the integrity of industrial systems [Shelby and Bormann 2009]. When no protection mechanisms are implemented in the network, it can suffer intrusions that might lead to malfunctions in the systems, for instance, an undesired increasing in the data latency, incorrect or inaccurate decisions about the control loops, perturbations in the processes, breakage in the production chain, undesired behavior of the machinery, information robbery, among others. However, the lack of security mechanism not only compromises the confidentiality of the company. Also compromises the integrity of the people and equipment involved in the process under attack because of harmful behavior of the machinery or even more because of the breakdown of the entire network [Gungor and Hancke 2009].

The main purpose of the Security is to protect the industrial wireless sensor networks against intruders and attackers by guaranteeing four security criteria [Christin et. al 2010]:

- Confidentiality of information: The information is only accessible by authorized parties in the network.
- Integrity of Information: Information must be protected against alterations or modifications intended by malicious parties or unsafe surrounding environments.
- Authentication of communication peers: This guarantees that the exchange of information is performed between trusted and validated partners within the network.
- Availability of information: Is intended to ensure that data and services offered by the parties of the network are available even upon attacks or intrusion.

Large-scale deployment and Ad-hoc Architecture: The networks that are set up to rapidly meet a specific purpose without an associated infrastructure are called Ad-hoc networks. Moreover they are intended to work autonomously, i.e., without manual management or configuration tasks [Karl and Willig 2005].

Industrial wireless sensor networks are comprised by hundreds to thousand nodes spread randomly over large areas in the factory floor. Regardless of the covered area and the node density per network the communication must be achieved to accomplish the Quality of Service criteria. Moreover because of the random distribution of the sensor nodes, there is no network infrastructure defined [Gungor and Hancke 2009]. Hence the communication must be maintained autonomously, involving self-recovery communication mechanisms that reestablish the connection of a node when the link is broken. This is achieved by the deployment of Ad-hoc wireless sensor networks all over the desired field where a backbone is not predetermined [Shelby and Bormann 2009].

Integration with Internet and Other Networks: In the past few years many ad hoc solutions for low-power wireless networking have been developed making possible the realization of Wireless Sensor Networks. However, WSNs that use different proprietary protocols are not able to interact among them unless the use of application gateways. The usage of dedicated gateways increases the design and management complexity. This has encouraged the latest efforts in communication technology towards the accomplishment of an end-to-end communication by using a common network protocol working on top of different link layer technologies (e.g. Wi-Fi, Ethernet, and 802.15.4). The usage of an open standard interface such as Internet Protocol (IP) as the common networking layer provides greater robustness and flexibility to the system [Hui and Culler 2010]. In addition, IP provides transparency for the host and servers in the network with no need for using gateways and support unique addressability, seamless connectivity as well as wide applicability [Hong et. al. 2010].

A new Internet Protocol has been developed, the Internet Protocol Version 6 (IPv6) specified in the Request for Comments (RFC) 2460 [Deering and Hinden 1998], as the successor of the known IPv4. IP addresses are required to be global and unique to each node in the network, satisfying the scenario where networking appliances and assets are expected to outnumber the conventional computer hosts using IPv6 [Hui et. al. 2009].

Notwithstanding IPv6 protocol was meant for nodes with higher capability, it suites better than IPv4 to cope with the needs of WSNs because of the inclusion of the bootstrapping functionality, the support for options and the ability for adapting different link technologies. Moreover, the new protocol supports stateless address auto-configuration and the large IP address allows performing cross-layer compression and the utilization of mechanism widely used in wireless sensor networking [Hui and Culler 2010].

The technical characteristics of the low-powered devices, make impossible the straight forward implementation of IPv6 protocol in them, therefore the usage of an adaptation layer is needed such as 6LoWPAN [Ma and Luo 2008]. Using 6LoWPAN adaptation layer makes possible the deployment an IPv6 low-power wireless personal area network. Providing internet connectivity to low-powered devices can enable new industrial applications where the devices are embedded in industrial assets. Currently many efforts have been directed to the usage of WSNs for wide purposes ranging from a single task monitoring to the most specialized military applications [Sarwar et. al. 2010] including efforts aimed to deploy IP based WSNs.

2.1.2 Design Goals in Industrial Wireless Sensor Networks

Fulfilling the needs of a given application for an industrial WSN with a single solution and overcome the challenges inherent to it is difficult. Consequently a set of design goals has to be established to define measurable parameters that allow the evaluation of the final result when an industrial WSN is designed. These design goals can be enumerated as follows:

Low-Cost and small sensor nodes: The size of a WSN can vary. It can be comprised by a couple of nodes up to the deployment of thousands of sensor nodes. Hence the unit cost per sensor node becomes relevant in the justification of the overall cost-benefit of the network. As a result, the unit cost must be maintained as low as possible in the order of USD $ 1 or less to contribute to the feasibility of the network. Although a node is constructed by different units as power, processing and sensing units that make harder to keep the cost below the targeted one while looking for compact sized nodes as well [Akyildiz et. al. 2002].

Hence all the costs involved in the development of a node up to its deployment within a network have to be considered. This involves the costs associated with packaging, modifications, maintainability and replacement, implementation, logistics, personnel trainee and servicing. Hence the overall cost of the network can be estimated and may be optimized by implementing cost optimization tasks [Gungor and Hancke 2009].

Scalable architectures and efficient protocols: An industrial system can contain several wired and wireless networks interacting homogenously to fulfill the factory requirements. This raises the need to develop flexible and scalable architectures able to integrate the wide variety of applications into the same infrastructure.

The flexibility of an industrial system as well as its robustness and reliability can be enhanced by modular and hierarchical designs of the industrial wireless sensor networks. Moreover these types of designs increase and promote interoperability between the new networks added to the system and the existing legacy networks [Karl and Willig 2005].

In-network processing: Most of the end user industrial applications are interested in certain measurements or values sensed from the manufacturing processes. However the sensors in the network typically transfer raw data that needs to be further processed by the end user application in order to develop the intended tasks.

Nevertheless currently wireless sensor networks have capabilities not only to sense but to process the data collected. These processing capabilities allow them to make decisions based on the processed data; for instance instead of sending raw data to the end user, the necessary and already processed information can be provided. Moreover some control actions can be taken by the node without needing to congest the communication traffic with unnecessary messages. As a result of this in-network processing the communication overheads can be reduced [Karl and Willig 2005].

Energy efficient design: Most of the wireless senor nodes are powered by batteries. Therefore energy-efficient operations are needed in order to prolong the life of the batteries and augment their replacement periods. The maximization of the network lifetime requires a compromise between latency and reliability while maintaining the QoS required by the application [Park et. al. 2011]. Thus the deployment of an industrial WSN requires the integration of network functionalities implemented along with energy efficient protocol such as energy-aware routing on the network layer, the sleep modes on the physical layer, among others [Gungor and Hancke 2009].

Self-configuration and self-organization: Communication breakage in industrial wireless sensor networks can be caused by failures in a node, the depletion of battery power, signal propagation obstructions or fading, noise, interference or mobility, among others. This communication failure causes highly dynamic topologies in industrial WSN. When communication breakage is caused by a faulty node, this must be replaced and must be able to joint into the network. Moreover, even existing nodes working in a proper manner can be removed from the networks or the communication links among the nodes may vary without affecting the networking performance. Hence self-configurable and self-organizing industrial wireless sensor networks must be implemented to overcome the challenges because of the varying network topologies. In addition self-configuration and self-organizing networks contribute to the scalability and robustness of the network [Karl and Willig 2005].

Adaptive network operation: The operation of the network should be able to adapt upon changes driven by modification in the manufacturing processes, i.e., application requirements, variations in the conditions of the wireless channel or dynamical topologies. This adaptability need requires analytical models that describes the relation between the protocol parameters, reliability, latency and power efficiency are needed to support the variations in the network operation requirements while maintaining the QoS [Park et. al. 2011].

Time synchronization: The Quality of Service in an industrial WSN strongly depends on the latency of the delivered data. As a result time synchronization is a key design goal in order to achieve the needs of a certain application in a timely manner. Moreover, routing tasks and power conservation also depend on the time. A time-synchronized network allows a cooperative operation of the sensor nodes and enables them to schedule the data transmissions. Scheduled transmissions help in the reduction of collisions and retransmissions resulting in energy conservation in the network. Otherwise having time accuracy deficiencies in the network may lead to reductions of its lifetime. Nonetheless, the resource constrained nature of the sensor nodes and the absence of a fixed infrastructure together with the dynamic topologies of industrial wireless sensor networks make them non suitable for applying the traditional time synchronization strategies designed for other wired or wireless networks. Thus the need of these industrial WSN is the utilization of adaptive and scalable time synchronization protocols [Yick et al. 2008].

Fault tolerance and reliability: The communication media in a wireless sensor network is susceptible to errors because of a harsh environment, noise, obstructions, among others. Industrial WSN applications rely on the timely and reliable delivery of the data coming from the sensor nodes in order to perform the actions according to the information received. However, communication errors may occur because of the physical constrains aforementioned. Hence, the application must be able to handle and tolerate the communication errors in order to enhance its reliability. Thus the transferred data has to be verified and corrected when needed on each communication layer. Also the usage of self-recovery protocols and procedures helps in the achievement of the QoS provided by the network [Gungor and Hancke 2009].

Application specific design: There is no universal solution applicable to all industrial manufacturing applications. Consequently the design of a solution has to be based in the application specific Quality of Service requirements and on environmental constrains given by the characteristics of the area where the industrial wireless sensors network going to be deployed.

Secure design: Dissimilar to the wired networks where the information travels along the wires, the traffic in a wireless network goes through a prone error medium susceptible to malicious attacks. These attacks can compromise the integrity and confidentiality of the data flowing through the network, for instance, a malicious entity can wirelessly spy the flowing information, alter the data or introduce fake messages and overhead the traffic in the network, to mention some. These threats may produce harmful results to the application.

In addition, the design of security protocols in a WSN has to take into account the storage, processing and energy limitations of the constrained sensor nodes. Thus, a compromise, between the overhead coupled with the security protocols and the constrained resources of the sensor nodes, has to be done. A balanced conciliation is needed to achieve a high networking performance and fulfill the Quality of service required by the application [Yick et al. 2008].

2.2 INDUSTRIAL WIRELESS SENSOR NETWORK STANDARDIZATION

The communication mechanisms in industrial WSNs are based on radio frequency interactions between the sensor nodes. Therefore, a carrier frequency has to be chosen as the working frequency for the system. This carrier frequency defines the way the electromagnetic wave propagates and its ability to penetrate obstacles. However, for communication purposes, a single frequency is not enough to provide the required capacity. Instead, a range from the electromagnetic spectrum known as the frequency band is used. The usable radio communication frequencies range from Very Low Frequency (VLF) up to Extremely High Frequency (EHF) as shown in Figure 2.6.

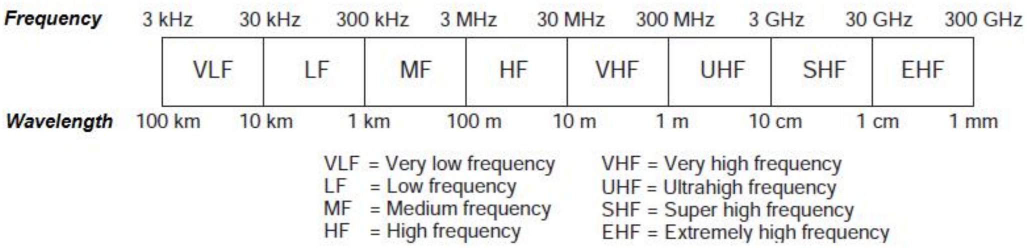

Figure 2.6 Radio Communication Frequencies - Electromagnetic Spectrum [Karl and Willig 2005]

Communication can take place at different frequencies. Likewise, most of the current radio frequency communication systems work at frequency bands below 6 GHz with the exception of the Ultra Wideband (UWB) technology. Moreover, the transmission power has to comply with regulations established by The International Telecommunication Union (ITU). The compliance to these radio frequency regulations is required to avoid harmful interferences among the systems coexisting in the same environment [Koumpis et. al. 2005].

There are some frequency bands that have been licensed to special systems, for example, the GSM system in Europe has the frequency bands from 880 to 915 MHz (GSM 900) and 1710 to 1785 MHz (GSM 1800) reserved to its exclusive usage. Nevertheless there also exist some license free frequency bands. The most widely used are the frequency bands assigned by ITU to the Industrial, Scientific and Medical (ISM) bands. These ISM bands are intended for private and unlicensed applications while complying with power, power spectral density and duty cycle regulations [Karl and Willig 2005]. Table 2.4 presents the ISM radio frequency bands granted by ITU that range from High Frequencies up to Extremely High Frequencies.

Table 2.4 Frequency Allocations in the ISM Bands [Egea-Lopez et. al. 2005]

Frequency Band			Center Frequency	Units
6265	-	6795	6780	kHz
13553	-	13567	13560	kHz
26957	-	27283	27120	kHz
40.66	-	40.70	40.68	MHz
433.05	-	433.79	433.92	MHz
902	-	928	915	MHz
2400	-	2500	2450	MHz
5725	-	5875	5800	MHz
24	-	24.25	24.125	GHz
61	-	61.5	61.25	GHz
122	-	123	122.5	GHz
244	-	246	245	GHz

Nonetheless not all wireless technologies are suitable for implementing industrial wireless sensor networks. The non-suitable technologies do not comply with the cost saving policies of the current manufacturing industry. This cost saving policies have motivated the development of industrial wireless technologies whose communication takes place in the cost-free frequency bands. Additionally, the communication implementations have to cope with the constrained resources of the sensor nodes. Consequently, the license free ISM bands are the most widely used frequency bands in industrial applications [Willing et. al. 2005]. Furthermore, the 2.4 GHz band (2400–2500 MHz) is the most widely used ISM band in industrial WSN communications [Yick et al. 2008].

Regardless of the frequency band used, the radio technologies for radio communication implement a common protocol stack based on the OSI model [Akyildiz et. al. 2002, Sohraby et. al. 2007]. This protocol stack shown in Figure 2.7 is used by all the nodes comprising the network.

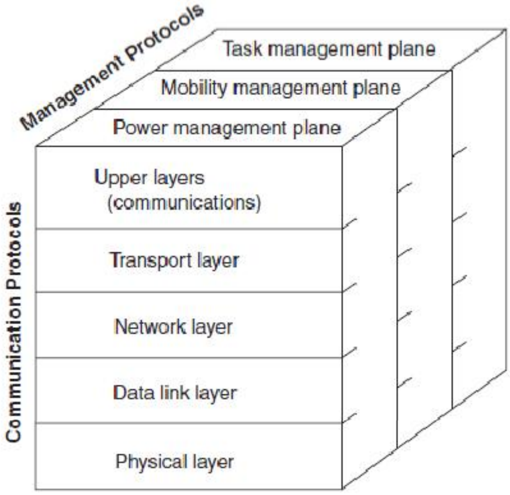

Figure 2.7 The generic protocol stack used by wireless sensor networks [Sohraby et. al. 2007]

The protocol stack shown in Figure 2.7 is comprised by five layers to handle the communication protocol. Unlike the OSI model, this protocol stack does not implement the session and the presentation layers corresponding to the 6th and 7th layers in the OSI model. In addition, the protocol stack contains three planes addressing the problem of power management, mobility management and task management. A summary of the capabilities of each communication protocol layer is provided in Table 2.5.

Table 2.5 Capabilities of generic WSN communication protocol layer [Sohraby et. al. 2007]

Communication Layer	Capabilities
Application layer	In-network applications, including application processing, data aggregation, external querying, query processing, and external database.
Transport layer	Transport, including data dissemination and accumulation, caching, and storage.
Network layer	Networking, including adaptive topology management and topological routing.
Data link layer	Link layer (contention): channel sharing (MAC), timing, and locality
Physical layer	Physical medium: communication channel, sensing, actuation, and signal processing.

The purpose of this communication protocol is to enable power efficient communications over the wireless medium while promoting self-organization capabilities and cooperative efforts among the sensor in the network [Akyildiz et. al. 2002]. Therefore depending on the stack implementation different topologies can be achieved in the network. The basic network topologies are shown in Figure 2.8. Nonetheless a complete network can be comprised by several subnets with different topologies [Lewis 2004].

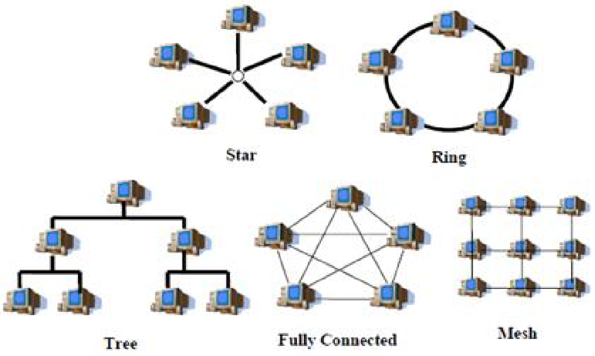

Figure 2.8 Basic network topologies in wireless communications [Lewis 2004]

Presently there is a wide range of wireless sensor technologies. In this regard, many efforts have been made in order to standardize the communications among the industrial wireless sensor networks. These efforts have enabled the realization of standards such as WirelessHART, ISA100.11a, Wibree, IEEE 802.15.3, IEEE 802.15.4, ZigBee, ZigBeePRO, UWB, Bluetooth, Wi-Fi, 6LoWPAN, among others, as illustrated in Figure 2.9. These standards have been developed under the premises of low cost and low power consumption requirements. Furthermore the functions and communication protocols needed to interact with the nodes comprising the network and with other networks are defined by these standards [Yick et al. 2008].

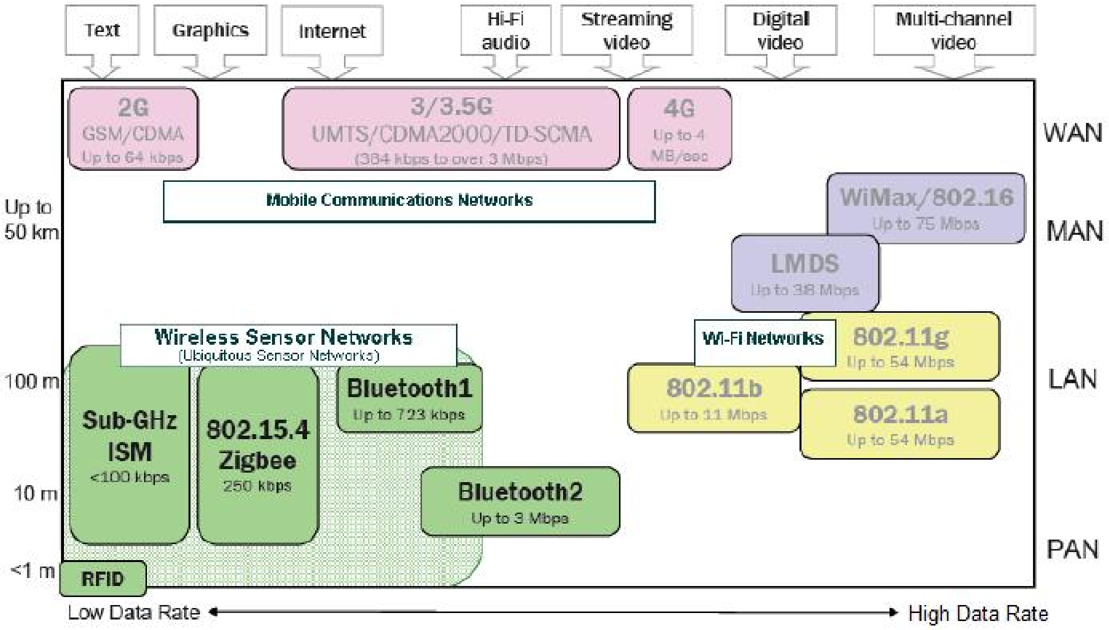

Figure 2.9 Comparison of Industrial Wireless Technologies in terms of Typical Transmission Distances and Data Rates [Methley et. al. 2008]

2.2.1 IEEE 802.11-based standard

This standard is focused in the two lower layers of the protocol stack, i.e., in the physical and data link layers. It specifies a Local Area Network (LAN) where at least two nodes are connected. The IEEE 802.11 standard includes a series of modulation schemes for data transfer over the air. These modulation techniques use the same protocol stack and comprise the family of 802.11-based standard also known as Wi-Fi. The most widely used are defined by the 802.11b and 802.11g standards. Despite the IEEE 802.11-1997 specification was the first wireless networking standard, the IEEE 802.11b was the standard that reached widely acceptance. This acceptance paved the road to the IEEE 802.11g and the IEEE 802.11n standards that appeared later on [Willing et. al. 2005].

IEEE 802.11a has a transmission frequency of 5 GHz with a data rate of 54 Mega bits per second (Mbps). It uses Orthogonal Frequency Division Multiplexing (OFDM) as a digital multi carrier modulation method that allows it to cover a range up to 35 meters in indoor environments. IEEE 802.11b transmits on the ISM frequency band of 2.4 GHz using Direct Sequence Spread Spectrum (DSSS) as the modulation method. The range covered by this technology in indoor environments is within a radius of 28 meters with throughput of 11 Mbps. The transmission frequency of IEEE 802.11g is 2.4 GHz with a throughput of 54 Mbps. The modulation scheme used by this standardization is either OFDM or DSSS while the reachable range is within 38 meters. The IEEE 802.11h protocol has a transmission frequency of 5 GHz with a data rate of 100 Mbps within a range 70 meters in indoor environments [Girão and Enache 2007].

Although the IEEE 802.11 standardization family offer high throughput in the order and large indoor coverage ranges up to 100 Mbps and 70 meters respectively, its power consumption is high. In addition the hardware requirements of this technology involve high costs. Therefore the suitability of this technology in wireless sensor networks is compromised [Christin et. al 2010].

2.2.2 IEEE 802.15.1-based standard

This standard is also known as Bluetooth®. Bluetooth is a short-range, low power and low range wireless technology. The main concern of Bluetooth is to maintain high levels of security and robustness. This protocol operates in the ISM band of 2.4 GHz using a modulation scheme based on Frequency Hopping Spread Spectrum (FHSS) and full duplex signal with a nominal rate of 1600 hops per second and throughputs up to one Mbps. Moreover the number of connections of a single node is limited up to seven. There are three classifications within the Bluetooth technology and its range varies accordingly to them. The approximate range and the maximum permitted transmission power for each classification are summarized in Table 2.6.

Table 2.6 Approximate range and maximum permitted transmission power for Bluetooth classifications [Girão and Enache 2007]

Bluetooth Class	Maximum Permitted Transmission Power	Approximate Range
Class 1	100 mW (20 dBm)	100 meters
Class 2	2.5 mW (4 dBm)	10 meters
Class 3	1 mW (0 dBm)	1 meter

Additionally to Bluetooth, Wibree specification can also be placed in the IEEE 802.15.1 specification. Wibree is a derivation of Bluetooth specification addressed to ultra-low powered devices. Likewise to Bluetooth the transmission throughput is up to 1 Mbps but the coverage distance ranges from 5 up to 10 meters. The transmission frequency used by Wibree is 2.45 GHz. Unlike Bluetooth, Wibree does not use FHSS. Instead it uses an unspecified modulation scheme and a variable length packet structure [Paavola 2007].

Notwithstanding the high robustness and security levels offered by IEEE 802.15.1-based technologies, their design involves high complexity and in case of Bluetooth non suitable power consumption characteristics for wireless sensor node applications. Moreover the size of the network is limited up to eight nodes. Therefore from the design point of view these deficiencies limit the applicability of this technology in WSNs [Gungor and Hancke 2009].

2.2.3 Radio Frequency Identification (RFID)

The international Organization for Standardization (ISO) has developed the ISO 18000 series standardization. These ISO 18000 series address to standardize the automatic identification and device management in RFID technology. This set of standards shown in Table 2.7 considers the wireless communication protocol between nodes comprising the network.

Table 2.7 ISO 18000 Series for RFID Standardization [RFID Journal 2005]

Standard	Description
18000 – 1	Generic parameters for air interfaces for globally accepted frequencies
18000 – 2	Air interface for 135 kHz
18000 – 3	Air interface for 13.56 MHz
18000 – 4	Air interface for 2.45 GHz
18000 – 5	Air interface for 5.8 GHz
18000 – 6	Air interface for 860 – 930 MHz
18000 – 7	Air interface for 433.92 MHz

The RFID network is comprised by at least one minute radio frequency transponder known as tag. This transponder is contains exclusive information that can be read remotely by a node commonly known as RFID reader. In RFID communication there are two types of RFID tags: active and passive tags. The main differences among them are that the active tag uses batteries as power source, handles higher frequencies –

typically 455 MHz, 2.45 GHz or 5.8 GHz – whereas the passive tag uses no internal power supply but the RFID reader transmits it the required power. Additionally, the passive tags work on lower frequencies such as 128 kHz, 13.6 MHz, 915 MHz or 2.45 GHz. Moreover, the reachable range of active tags goes 20 up to 100 meters while the passive tags reach ranges about 10 meters. Therefore the usage of active rags results in a more expensive solution than the passive ones [Weinstein 2005].

The RFID technology is currently used in inventory and tracking applications. Besides it is possible to embed a RFID tag in a manufacturing asset to track its progress down the manufacturing process, for instance, provide pallets on the assembly line with RFID tags and installing readers along the line to enable the tracing and tracking capabilities in the system. However, the RFID technology prevents the realization of a dynamic wireless network because the information programmed in tags is static unless it is reprogrammed. Therefore it cannot be used directly to measure or diagnostic the constantly changing process environment [Paavola 2007]. Moreover, the cost of the tags represents a huge drawback to the deployment of this technology in a large scale. If just the cost of a tag is considered and, since every manufacturing asset of interest needs a tag, the scalability of the network is strongly limited. This is because the cost of one tag is about USD 12.9 cents in quantities of USD one million [Want 2006].

An additional technology related to RFID is the Near Field Communication NFC. NFC is a short range technology whose maximum range is about 20 cm by using point-to-point connectivity. This technology combines the RFID remote identification and interconnection technologies. The RFC working frequency is 13.56 MHz and offers throughputs of 106, 212 and 424 Kbps [Paavola 2007].

2.2.4 IEEE 802.15.3-based standard

The IEEE 802.15.3 standard specifies the physical layer for the UWB radio technology. UWB is a short range wireless communication technology that uses very short impulses transmitted in periodic sequences. The typical operating bands and the corresponding Equivalent Isotropic Radiated Power (EIRP) in UWB radio technology are shown in Table 2.8 [InfoComm 2007]. In addition, the range of the UWB technology is about ten meters with a typical throughput of 100 Mbps and a maximum of 480 Mbps. The radio impulses are transmitted in a modulated manner using either Multi band orthogonal frequency division multiplexing (MB-OFDM) or Direct Sequence UWB (DS-UWB) techniques. The MB-OFDM technique divides the carrier frequency bandwidth of the UWB in sub-bands whereas DS-UWB uses an impulse-based system that multiplies and input with the spreading modulation code and transmits the data using time hopping code division multiple access (TH-CDMA) technology [Elmusrati et. al. 2007, Lee et. al. 2007].

Table 2.8 Typical operating frequency bands and their radiated emission limits for UWB technology

Frequency Band (GHz)	Maximum mean EIRP density (dBm/MHz)	Maximum peak EIRP density (dBm/50MHz)
Below 1.60	– 90	– 50
1.60 – 2.70	– 85	– 45
2.70 – 3.40	– 70	– 36
3.40 – 4.20	– 70	– 30
4.20 – 4.80	– 41.3	0
4.80 – 6.00	– 70	– 30
6.00 – 8.50	– 41.3	0
8.50 – 10.60	– 65	– 25
10.60 – 21.65	– 85	– 45
21.65 – 29.50	– 41.3	– 0
29.50 – 77.0	– 85	– 45

The UWB technology uses high peak energy pulses which make it unsuitable for communication applications over long distances or measuring data from risky or hazardous areas. Moreover the maximum number of elements in the network is limited to eight [Lee et. al. 2007]. Conversely, this technology offers good capabilities for implementing positioning systems and the possibility to share the radio frequency bands afore allocated by hiding signals under the noise floor. Furthermore, the UWB technology offers high throughput with low power transmission. Also offers enhanced security characteristics and robustness to cope with indoor environments because of its distinctive operation mode. However, this technology has been under development in the past few years whose main existing challenges are: the hardware development, development of techniques to address the problem of the multiple access mode and multipath interference altogether with the understanding about the signal propagation phenomenon [Gungor and Hancke 2009].

2.2.5 IEEE 802.15.4-based standard

The IEEE 802.15.4 standard specifies the physical layer for radio communications operating in 868 MHz, 915 MHz and 2.4 GHz frequency bands. 868 MHz and 915 MHz frequency bands are applied to Europe and North America respectively whereas 2.4 GHz is worldwide accepted. Usage of 2.4 GHz unlicensed ISM frequency band has promoted the widespread development of the IEEE 802.15.4 wireless technologies [Willing et. al. 2005]. The IEEE 802.15.4 specification addresses the deployment of a low cost, low power, two-way communication and low complexity WLAN fulfilling the requirements of sensor and control devices. Therefore IEEE 802.15.4 standardization focuses on wireless sensor networks that require short range communications with an extended battery life [Yick et al. 2008].

IEEE 802.15.4 standard used the DSSS modulation technique to comply with the sharing rules of each used frequency band. Furthermore, this technique allows the implementation of a simple analog circuitry to its realization. By using DSSS, the maximum data rate is 250 Kbps on a single channel in 2.4 GHz frequency band. A total of 16 channels can be accommodated in this frequency band with a 5 MHz separation gap. Additionally, the 915 MHz band can accommodate 10 channels with a single channel maximum throughput of 40 Kbps whereas 868 MHz band consists of a single channel with a maximum data rate of 20 Kbps. Nonetheless the maximum reachable data rates are smaller than the nominal ones [Christin et. al 2010].

Two different devices are defined in the IEEE 802.15.4 standardization, full-function device (FFD) and reduced-function device (RFD). A FFD can act as a network coordinator because of its enhanced capabilities in comparison with a RFD that is limited to data exchanging with a FFD. Therefore the communication can take place in a peer-to-peer manner comprised only by FFDs. In addition an Ad-hoc and self-configuring network can be deployed. This Ad-hoc network is comprised by both types of devices FFDs and RFD. In order to control the access to the radio channel, the IEEE 802.15.4 implements the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) methodology in the MAC layer. Moreover the frame validation, the frame delivery, the network interface, the network synchronization, the device association, and secure services take place in the MAC layer as well [Yick et al. 2008].

Likewise the standard supports two different operation modes: beaconless and beacon mode. In the beaconless mode, a node introduces a random waiting time to initiate the transmission of a data packet to avoid collisions instead of performing the carrier sensing before transmitting. Dissimilar to the beaconless mode, the bacon mode uses a network coordinator which transmits a super frame structure periodically. This periodicity may vary and be chosen in a range from 15.36 to 251.65 milliseconds. Therefore, a beaconless network can be seen as an asynchronous network whereas the beacon mode can establish a synchronized network. However, the throughput in a beaconless mode is higher than in the beacon mode. Furthermore in both operation modes there is an inactive period where the node puts itself in a sleepy mode in order to save energy. This sleepy mode implies that there are no communication incoming or outgoing. An additional characteristic of the IEEE 802.15.4 standard is the capability to transmit the data in a secure manner. Therefore for security purposes, this standard enables the authentication, encryption and integrity services. In this regard there are three different security modes: No security mode, an access control list and a 32 to 128 bit Advanced Encryption Standard (AES) encryption with authentication [Willing et. al. 2005].

Currently there are four standards based on the IEEE 802.15.4 specification applicable to the Industrial WSNs. These standards are: WirelessHART, ZigBee and ZigBeePRO, ISA100.11a and 6LoWPAN.

WirelessHART: WirelessHART is a proprietary standard based on the IEEE 802.15.4 specification. The WirelessHART standard is suitable for industrial process measurements and control applications. It was released by the HART Communication foundation in 2007. The devices comprising the network can form either star or mesh topology. However, the star topology is not recommended [Christin et. al 2010].

This technology implements frequency hopping, redundant data paths and retries mechanisms. Besides, all the devices complying with WirelessHART standard can interoperate whereas they use wired or wireless communications. In a mesh WirelessHART network each device on the factory floor has the capability to transmit its own information as well as forward information from other nodes in the network. In addition, due to the path redundancy, the data flow can follow two routes: the primary and the alternative routes. The alternative route is used when the primary route is not viable either by physical blocking or interference. Furthermore, if a route remains blocked for long time it can be considered as permanently blocked. Thus the network establishes a new route within a range of 200 meters between the nodes [Gungor and Hancke 2009]. The routing tasks in WirelessHART standard take place at the network layer. Additionally, there are two routing protocols that may be used to perform these routing tasks: the graph and source route. In the graph routing the network manager determines the routing graphs which are stored in each node whereas in the source routing each device stores and maintains routing tables. Thus broadcast, multicast and unicast transmissions are feasible in WirelessHART [Christin et. al 2010].

At the data link layer the WirelessHART implements Time Division Multiple Access (TDMA) to coordinate and manage the transmission of each device. In WirelessHART, this transmission scheduling is done by using a series of timeslots whose duration is 10 milliseconds each. At the MAC layer the standard uses CSMA/CA to allocate each time slot to one source or to share them between several sources. Moreover, in this standard, the MAC header supports the co-existence with other IEEE 802.15.4 compliant networks. The WirelessHART technology is addressed to develop new wireless applications rather than replacing the existing wired solutions [Paavola 2007].

Notwithstanding WirelessHART standard is targeted to industrial WSNs, it does not support multiple protocols affecting its interoperability capabilities. Thus WirelessHART technologies can only support communication and applications using HART messages over a wireless physical media. Besides, this standard was created to support process control. Hence additional applications such as factory automation applications are not supported [Shelby and Bormann 2009].

ZigBee and ZigBeePRO: ZigBee is a proprietary standardization developed by ZigBee Alliance and addressed to the problem of home automation. In 2007 a new release was launched, ZigBeePRO intended to intended to fulfill the industrial automation requirements. Both standards are compliant with IEEE 802.15.4 specification but offer enhanced security attributes. Furthermore in the ZigBeePRO standardization the communication channel is selected accordingly to the interference level. After scanning all the communication channels the one with least interference is selected and used by the ZigBee network [Christin et. al 2010].

ZigBee technology can be used in industrial monitoring and control applications as well as in building and home automation, embedded sensing applications and energy system automation by deploying low cost and low power consumption devices.

Furthermore the standard supports different topologies – star, tree or mesh topologies – which make it suitable for a wide range of applications. However, it cannot meet all the industrial requirements; for instance, low latencies cannot be achieved in a dense wireless network [Gungor and Hancke 2009].

The network layer specified by ZigBee is responsible to manage the network formation, the addressing of the nodes as well as the routing tasks. Moreover the network layer is complementary to MAC layer taking care of the bootstrapping of the network. This MAC layer uses CSMA/CA to access the radio channel in a slotted or non slotted way depending whether the network is deployed in a beacon or beaconless way respectively. The routing algorithm used by ZigBee to establish the data routes in a mesh network is the Ad-hoc On Demand Vector (AODV) algorithm. On the other hand, the application layer specified by ZigBee proposes a framework for distributed application development and communication. This application framework can be comprised by a maximum of 240 application objects. Furthermore, each application object consists of software units handling dedicated hardware distributed all over the network. Also they manage a set of variables that can be accessed with special commands through the network enabling managerial capabilities such as reading, setting, or reporting changes in the managed variables [Christin et. al 2010].

Despite the standard supports low powered wireless control applications, it does not provide sufficient latency and message flow determinism required in industrial applications to achieve the required QoS. What is more it only supports proprietary ZigBee protocols which limit its interoperability with other platforms such as HART, WirelessHART, Profibus, among others [Shelby and Bormann 2009].

IETF 6LoWPAN RFC4944: The 6LoWPAN standardization was developed by the Internet Engineering Task Force (IETF) as an effort to enable the end-to-end communications by using a common network protocol working on top of different radio technologies such as Wi-Fi, Ethernet, and 802.15.4. The usage of an open standard interface such as IP protocol as the common networking layer provides greater robustness and flexibility to the system [Hui and Culler 2010]. In addition, IP provides transparency for the host and the servers in the network with no need for using gateways and support unique addressability, seamless connectivity as well as wide applicability [Hong et. al. 2010].

However, in an Industrial environment the IP addresses are required to be global and unique to each node of the network. In this regard, the IPv6 protocol offers a space of 128 bits for IP addressing, expanding the 32 bits offered by IPv4. Moreover, IPv6 increases the MTU to 1280 bytes, unlike IPv4 MTU of 576 bytes. In order to increase performance and simplify routers the fragmentation is performed at endpoints rather than in intermediate routers. Also, IPv6 includes link-local scoped multicast to facilitate the bootstrapping of the network such as ND, DAD and router discovery. Moreover, the IPv6 protocol supports stateless address auto-configuration and the large IP address allows performing cross-layer compression and the utilization of mechanism widely used in wireless sensor networking [Hui et. al. 2009].

Since the 6LowPAN standard is IEEE 802.15.4 compliant, it implies the utilization of low-powered devices and a maximum size of the data packets of 127 bytes. The narrow resources of the low-powered devices and the limitation of data packets, make impossible the straight forward implementation of IPv6 protocol in them, therefore the usage of an adaptation layer is needed triggering the development of the 6LoWPAN specification. This adaptation layer works on top of physical and MAC layers, defining how IPv6 datagrams are transmitted using 802.15.4 frames by implementing the compression/decompression of IPv6 headers, assuming common values and eliding them when they can be derived from link-layer information over the 802.15.4 or making assumptions based on communication context information. In addition, IPv6 packets might be fragmented/ defragmented to make the minimum MTU requirement fits in the link-level frames. The 6LoWPAN specification also supports the layer-two forwarding of IPv6 datagrams, but using stateless or shared-context compression to elide adaptation, network and transport layer fields to help in the reduction of the length of each datagram [Ma and Luo 2008].

Additionally, 6LoWPAN adaptation layer addresses the problem of the time-varying link relationship among the nodes comprising the WSN. It has to support the implementation of routing protocols at either link layer or network layer, i.e., mesh under routing or route over routing respectively. The mesh under algorithm does not implement IP-based routing within the WSN. Instead it performs the routing and the forwarding tasks over multiple radio hops looking for the emulation of a local multicast and avoiding obstructions. On the contrary, the route over algorithm performs IP routing, using each node as an IP router and supporting three forwarding mechanisms. This allows the use of network layer capabilities such as IPv6 routing and ICMPv6 for network configuration and management functions [Hui et. al. 2009].

Thus by using 6LoWPAN adaptation layer makes possible the deployment an IPv6 low-power wireless personal area network, providing internet connectivity to low-powered devices that can be embedded in industrial assets for gathering information that allows the improvement of efficiency and cost reductions in manufacturing processes. However a trade-off between power consumption and functionality has to be performed while looking for the maximization of the network potential.

ISA100.11a: The ISA100.11a is an open standard supported by the International Society of Automation (ISA) and targeted to the development of low data rate monitoring and process automation applications. The main focus of this standard is to address the problem of non-critical monitoring, alerting and supervisory control as well as to overcome the needs of process control where latencies about 100 milliseconds can be tolerated [Agha et. al. 2009]. Furthermore, this standard defines the specifications for the Open Systems Interconnection (OSI) model as well as for the security management and system management planes. Since the ISA100.11a standard is compliant with IEEE 802.15.4, it uses 2.4 GHz frequency band and implements channel hopping to increase the reliability of the network and to minimize the interference. Besides it supports mesh and star topologies and makes available the implementation of simple, flexible and scalable security functionality [Yick et al. 2008].

Furthermore the network and transport layer in ISA100.11a standard are based on 6LoWPAN, IPv6 and User Datagram Protocol (UDP) standards. The data link layer implements graph routing as and TDMA algorithm to schedule the access to the radio channel and to avoid collisions. Thus an ISA100.11a network supports mesh and star topologies, non routing sensor nodes (RFD), connection and coexistence with other networks via gateways, device interoperability, data integrity, privacy, and replay and delay protection, robustness upon interferences and enhances scalability up to 30,000 nodes while intends to widespread the usage of open standards [Shelby and Bormann 2009].

All the standards developed in the Industrial WSN field are intended to fulfill the requirements of industrial applications. However the utilization of certain wireless technology depends on the application itself. Thus compromise between its requirements and the characteristics of the technology has to be done. A comparison between the different standards in Industrial WSNs is shown in Table 2.9.

Table 2.9 Industrial Wireless Sensor Network Standardizations [Lee et. al. 2007]

Standard	**IEEE 802.11**	**IEEE 802.15.1**	**IEEE 802.15.3**	**IEEE 802.15.4**
Frequency Band	2.4 GHz, 5GHz	2.4 GHz	3.1 – 10 GHz	868/915 MHz, 2.4 GHz
Max. Throughput	54 Mbps	1 Mbps	110 Mbps	250 Kbps
Nominal Range	100 m	10 m	10 m	10 – 100 m
Nominal Transmission power	15 – 20 dBm	0 – 10 dBm	–41.3 dBm/MHz	(–25) – 0 dBm
RF Channels	14 (2.4 GHz)	79	1 – 15	1/10, 16
Bandwidth per channel	22 MHz	1 MHz	500 MHz – 7.5 GHz	0.3/0.6 MHz 2 MHz
Modulation Type	BPSK, QPSK, CODFM, CCK, M-QAM	GFSK	BPSK, QPSK	BPSK (+ ASK), O-QPSK
Spreading	DSS, CCK, OFDM	FHSS	DS-UWB MB-OFMD	DSSS
Coexistence Mechanism	Dynamic Frequency Selection, Transmit Power Control (802.11h)	Adaptive Frequency Hopping	Adaptive Frequency Hopping	Dynamic Frequency Selection
Basic Topology	BSS	Piconet	Piconet	Start

Additional Topologies	ESS	Scatternet	Peer-to-peer	Tree, Mesh
Max. Nodes per Ad-hoc Network	2007	8	8	> 65,000
Encryption	RC4 stream cipher (WEP), AES Block cipher	E0 stream cipher	AES Block cipher, (CTR, counter mode)	AES Block cipher, (CTR, counter mode)
Authentication	WPA2 (802.11i)	Shared secret	CBC-MAC (CCM)	CBC-MAC (ext. of CCM)
Data Protection	32-bit CRC	16-bit CRC	32-bit CRC	16-bit CRC

RFID Near field Technology: ISO 18000-Series Standard, 135 MHz within a range of 20 cm and typical throughputs of 106, 212 and 424 Kbps.

Acronyms: ASK (Amplitude Shift Keying), GFSK (Gaussian Frequency Shift Keying), BPSK/QPSK (Binary/ Quardrature Phase Shift Keying), O-QPSK (Offset- Quardrature Phase Shift Keying), OFDM (Orthogonal Frequency Division Multiplexing), COFDM (Coded OFDM), MB-OFDM (Multiband OFDM), M-QAM (M-ary Quadrature Amplitude Modulation), CCK (Complementary Code Keying), FHSS/DSSS (Frequency Hopping/Direct Sequence Spread Spectrum), BSS/ESS (Basic/Extended Service Set), AES (Advanced Encryption Standard), WEP (Wired Equivalent Privacy), WPA (Wi-Fi Protected Access), CBC-MAC (Cipher Block Chaining Message Authentication Code), CTR (Counter Mode), CCM (Counter Mode with Cipher Block Chaining Message Authentication Code), CRC (Cyclic Redundancy Check).

In addition the IEEE 802.15.4 standard allocates some Industrial WSNs standardizations such as WirelessHART, ZigBee and ZigBeePRO, ISA100.11a and 6LoWPAN. Among these technologies, the main difference relies in its interoperability capabilities. In this sense, WirelessHART and ZigBee standards present a big shortcoming from the design point of view since both of them are proprietary stacks. Thus the integration of these devices with other networks requires the usage of gateways which means the increase of the installation and maintenance costs. On the other hand, ISA100.11a and 6LoWPAN are addressed to deploy WSNs networking with a common protocol, specifically with IPv6 protocol at the network later. According to [Methley et. al. 2008] the most used radio technology standards in industrial automation is the IEEE.802.15.4 as shown in Table 2.10, based on the results of a survey performed by ON World Inc. to US industrial automation suppliers and end users.

Table 2.10 Usage of WSN radio technology in Industrial Automation [Methley et. al. 2008]

Radio Technology	**Usage**
IEEE 802.15.4	49.10%
Proprietary	23.60%
IEEE 802.11x	11.00%
ZigBee and ZigBeePRO	7.80%
IEEE 802.15.1	4.30%
Others	4.30%

The main reason for the widespread usage of the IEEE 802.15.4 radio technology is that it operates in a license free frequency band. Furthermore, the hardware requirements of this technology result in cheaper solutions in comparison with the other ones. Additionally, the interoperability has been a designing key in the past few years. The trends in WSNs in the industrial manufacturing aim towards the systems integration and the creation of a smart grid. This means the integration of smart embedded devices in the industrial networks able to achieve end-to-end communication and provide valuable information for the processes in real-time. As a result, the manufacturing techniques can be improved in order to overcome the challenges imposed by the current market.

2.3 POSITIONING TECHNOLOGIES IN INDUSTRIAL MANUFACTURING

The lack of real-time information in the traditional manufacturing process has lead to practices that add unnecessary costs to the production cycle such as scheduling delays, time wasted in manual activities (e.g. searches, inventory checks), greater risk of violations of safety protocols, inefficient allocation of equipment, parts and personnel, inefficient maintenance scheduling, among others. The development and implementation of systems to trace the whole history of the product aim for a reduction in the product life cycle, time to market, business risks and cost investments while increasing the flexibility and robustness of the supply chain [Cimino and Marcelloni 2010].

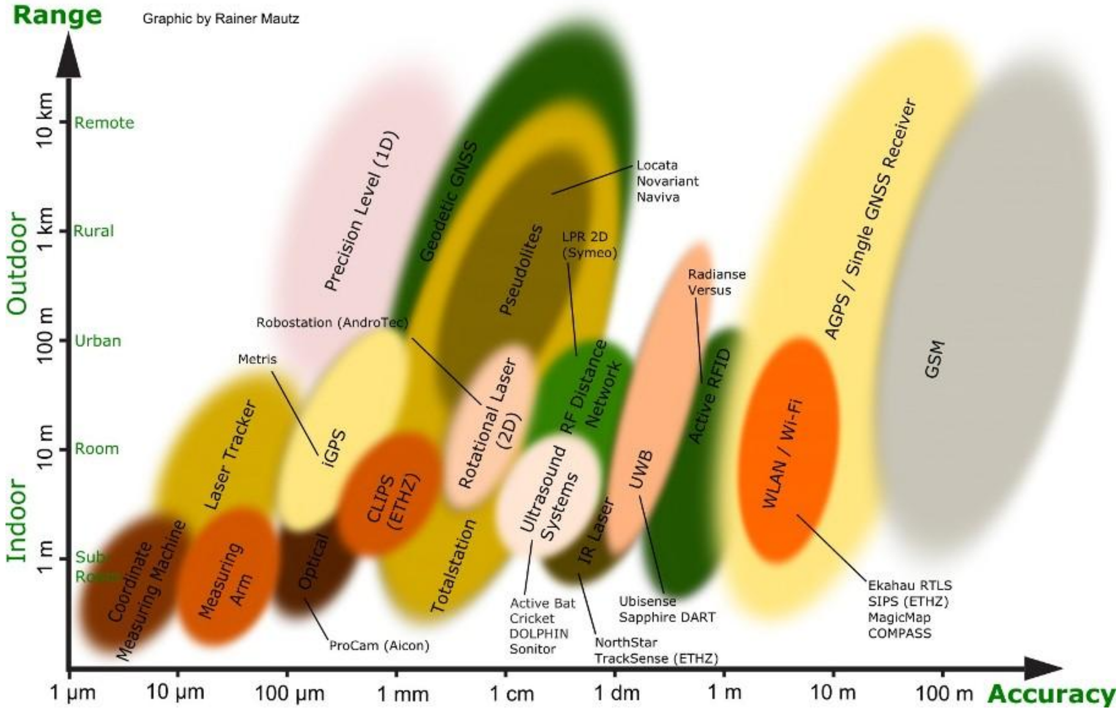

Figure 2.10 Positioning System classifications according to their accuracy and coverage area [Mautz 2009]

Therefore, the needs of a modern manufacturing industry have provoked an increasing in the popularity of real time positioning. This interest has leaded to the development of the widely known location-aware technologies or position technologies in the last decade [Giaglis et. al. 2002]. These mobile technologies are mainly classified according to their accuracy and area of coverage as shown in Figure 2.10.

The advances in positioning technologies have enabled the design of new applications in the field of industrial automation. Such applications have to work in an automatic and reliable manner in order to provide valuable information for the industrial manufacturing systems [Liu et. al. 2007]. However not all of the wireless technologies are suitable for developing these kind of applications. As a result, in the scope of this work only the indoor positioning technologies applied in industrial manufacturing are considered; For instance Infra Red (IR), ultra-sound, Radio-Frequency Identification (RFID), IEEE 802.15.4 based Wireless Local Area Networks (WLANs), Bluetooth, UWB, among others technologies [Gu et. al. 2009].

2.3.1 Challenges and Performance Criteria of Indoor Real Time Positioning Systems

The indoor environments represent a big challenge to modeling the wireless technologies signal propagation. When a signal emitted from an antenna can propagate in three different modes which are: the ground wave, the sky wave or line of sight. The wavelength of signals with frequencies higher than 800 MHz are too small in comparison with the dimensions of buildings features. Therefore, the signals can be treated as rays propagating in the line of sight mode. Although in indoor environments the signal can suffer from transmission impairments caused by attenuation, free space loss, fading, multipath, refraction, noise or atmospheric abortion [Pahlavanand Krishnamurthy 2002].

Attenuation refers to the signal power diminishing over the distance traveled by the signal. Free space loss stands for the dispersion of the signal with distance in the media. This effect is one form of attenuation but inherent to the nature of the signal propagation. Fading is the variation in the received signal power received by an antenna over the time. This is caused by changes in the transmission media or the propagation path and represents the most challenging technical problem in wireless communication systems. A wide range of disturbances producing fading effect exist, for example, changes in atmospheric conditions, the relative position and orientation of the transmitter and receiver antennas, the obstacles along the transmission path, among others.

Multipath refers to the phenomenon that a transmitted signal can follow different routes up to the receiver. Hence the signal can reach the receiving antenna throughout different paths. Reflection, diffraction and scattering are the mechanisms that cause the multipath effect. Reflection is the most affecting mechanism in indoor environments. This occurs when the signal reaches a surface and is bounced away, for instance signals hitting walls or floors in indoor environments. Diffraction and scattering occur when the signal is obstructed by an obstacle resulting in a bending effect. The outgoing wave presents different characteristics as the incoming one. The difference between diffraction and scattering relies in the size of the obstacles and their number per unit volume. The scattering phenomenon results from smaller obstacles and higher density than in diffraction. For instance scattering is caused by rough surfaces, small objects or radio channel irregularities. As a result of multipath effect the development of a proper propagation model is hard to achieve.

Refraction occurs when a signal passes though an obstacle. Then the signal experiences a variation in its signal velocity due to the change in the propagation media. Hence the outgoing wave from the obstacle exhibits a change in its direction. This change causes that only part of the signal or non signal reaches the antenna of the receiver. Moreover in any wireless transmission, the received signal is composed by the original one plus some distortions from the propagation medium. These unwanted distortions are known as noise and affect the propagation signal by modifying some of their characteristics such as amplitude, the addition of extra frequency components, among others. The last mentioned effect is the atmospheric absorption. This effect causes attenuation in the signal propagation due to atmospheric elements such as water vapor, gases as oxygen, helium, hydrogen, among others.

Consequently indoor real time positioning systems have to cope with the challenges intrinsic to the propagation medium and the environment where they are applied. In addition the systems have to achieve certain performance requirements. Therefore, in order to evaluate the performance of a positioning system, a set of evaluation metrics has to be defined. Unlike typically perceived, the performance of a positioning system does not rely only in its accuracy. Moreover parameters such as precision, complexity, scalability, robustness and costs must be added to the evaluation criteria [Liu et. al. 2007, Gu et. al. 2009].

Accuracy: Also referred as location error represents the most important criterion in the evaluation of the performance of the system. Typically, the evaluation parameter is the average Euclidian distance between the estimation and the actual position also known as mean distance error. Higher accuracies expressed in per cent mean better systems.

Precision: Unlike accuracy that only considers the value of the mean distance error precision considers the consistency or repeatability of the positioning results. This criterion can be considered as a measurement of the robustness of the positioning technique. The cumulative probability function of the distance error is used as the evaluation parameter to measure the precision of a system. If two systems have the same accuracy, the one with higher precision is preferred.

Complexity: The complexity attainable to hardware, software and functionality factors. Higher complexity results in higher power consumption because of longer duty cycles. Moreover higher complexity means most expensive hardware. Therefore a straight relationship exists between design and implementation costs and the complexity of the system. Typically, the complexity of a system is measured in terms of time. Hence the location rate or the location lag can be used as evaluation parameters to measure the complexity of the system.

Robustness and fault tolerance: Positioning systems have to be able to overcome the interruptions or damages during the process. The system must be able to provide reliable information upon failures in the network by means of self-organization or self-recovery communication protocols.

Scalability: A system must be able to keep their quality of service even when the covered area increases or the node density in the networks increases. Congestion, higher collision rates, increasing in positioning computations, higher power consumption, among other are direct results of a scaling up of the system. Thus the evaluation parameter of the scalability of a system is their physical limitations in terms of density and covered area.

Cost: Money, time, space, weight and energy are the main factors affecting the cost of a real time positioning system. Installation and maintenance costs are related with the time needed to develop such tasks. Space costs depend on the scale of the network, large coverage areas and high density populated networks results in more expensive architectures. Weight and energy costs are associated with the hardware architecture and the wireless technology infrastructure used to develop the positioning application. An increase in the robustness and capabilities of the system result in a more expensive solution.

Besides the environmental challenges faced by indoor positioning systems the designers have to address the problem of the limitations of the wireless technologies used in these systems. Therefore a compromise has to be done among the achievement of given performance metrics and the limitations of the resource constrained devices to overcome the challenges aforementioned inherent to the indoor environments.

2.3.2 Measuring Principles and Position Estimation Algorithms

In accordance with [Drane et. al. 1998], the position estimation can be performed in three different manners. As a result, they can be classified as self-positioning, remote positioning and indirect positioning systems. In a self-positioning system, the asset performs the measurements of a physical variable, processes the information and estimates its position. Therefore the asset knows its position at any time. In a remote positioning system, the measured information is sent from the asset to a centralized application that computes the information and estimates the position of the asset involved in the measurements. Hence the asset has to be notified about its position if needed. The third manner can be classified into two categories: the indirect remote positioning and the indirect self-positioning system. When a self-positioning node sends its position data to a remote peer is called indirect remote positioning. When a node receives its positioning data from a remote peer is known as indirect self-positioning.

Therefore in order to implement a position-aware system a wireless communication must be carried out at least between two nodes. The implementation of these systems can exclusively use the existing network infrastructure or can incorporate additional dedicated hardware to perform the location task. These implementations are known as network-based and non-network-based method respectively. The network-based approaches are preferred over the non-network-based because involves no extra cost for the network [Gu et. al. 2009].

Notwithstanding the limitations faced by wireless technologies in the development of indoor real time positioning systems they have been gaining popularity in the last decade. This popularity is mainly attributed to their lower cost in comparison with outdoor systems. As described in Section 2.3.1 multipath and fading effects along with obstructions strongly influence the signal propagation characteristics and make difficult the modeling of the signal propagation.

Therefore a positioning system cannot be based only on the measurement of a single physical parameter to estimate the position of an asset. Moreover it has to implement an algorithm or use network infrastructure to gather and process information that allows it to estimate the position. In general there exist four position estimation techniques for indoor environments: triangulation, fingerprinting, proximity and vision analysis. The first three estimation positioning techniques are able to provide absolute, relative and proximity position information unlike the last one that only gives proximity position information [Gu et. al. 2009].

Triangulation

Triangulation technique uses geometrical relationships to estimate the position of the target. Triangulation techniques can be divided into two different approaches: lateration and angulation. Lateration or range measurement approach consists in the position estimation of a node based on measuring the distance between the node itself and multiple reference points. Nevertheless the distance measurement is performed in an indirect way by measuring a physical signal parameter. These parameters can be measured by the wireless platform such as the Received Signal Strength (RSS), Time of Arrival (TOA), Time Difference of Arrival (TDOA) and Round Trip Time of Flight (RTOF) or Phase of Arrival (POA). Unlike lateration where distance is used to estimate the position, angulation is based on the computation of the angles formed by a node and multiple reference points using the Angle of Arrival (AOA) parameter [Liu et. al. 2007].

Lateration Techniques

The position estimation is based on the distance estimation between the tag and the anchor nodes [Rencheng et. al. 2009]. In order to position a node in a bi-dimensional space at least three anchor nodes are needed. Assuming that a tag has coordinates (x, y) and the anchor nodes are located at coordinates $(x_1, y_1), (x_2, y_2), \dots, (x_i, y_i)$ and the distances between the tag and the anchor nodes are $d_1,\ d_2, \dots, d_i$ respectively. Therefore the relation between the distances between the tag and the anchor nodes can be expressed as in Equation (1).

$$\begin{aligned}(x-x_1)^2 + (y-y_1)^2 &= {d_1}^2 \\ (x-x_2)^2 + (y-y_2)^2 &= {d_2}^2 \\ &\vdots\end{aligned} \qquad (1)$$

$$(x - x_i)^2 + (y - y_i)^2 = {d_i}^2$$

Thus Equation (1) can be expressed as a linear equation in the form $AX = B$. The solution of this equation results in the coordinate estimation of the tag and is given by Equation (2):

$$\hat{X} = (A^T A)^{-1} A^T B$$

where:

$$\begin{aligned} A &= \begin{bmatrix} 2(x - x_i) & 2(y - y_i) \\ \vdots & \vdots \\ 2(x_{n-1} - x_i) & 2(y_{i-1} - y_i) \end{bmatrix} \\ B &= \begin{bmatrix} x_1^2 - x_i^2 + y_1^2 - y_i^2 + d_i^2 - d_1^2 \\ \vdots \\ x_{n-1}^2 - x_i^2 + y_{i-1}^2 - y_i^2 + d_i^2 - d_{i-1}^2 \end{bmatrix} \end{aligned} \tag{2}$$

$$X = \begin{bmatrix} x \\ y \end{bmatrix}$$

Signal parameter measurement for distance estimation

Time of Arrival (TOA): Time of arrival (*TOA*) is the time that a signal that propagates at certain velocity (v) over the air takes to travel from a transmitter to a receiver node along the separation distance (d) between them. Therefore the TOA can be expressed as in Equation (3):

$$TOA = \frac{d}{v} \tag{3}$$

At transmission frequencies from 3 kHz to 300 GHz, the propagation velocity of the signal over the air is close to the speed of light. For practical effects, the speed of light is considered $3x10^8\ m/s$. Therefore in order to accurately measure the TOA high resolution clocks are needed. Additionally accurate time synchronization between the receiver and the transmitter is required [Pandey and Agrawal 2006].

A bi-directional (2-D) positioning approach by applying lateration technique requires TOA measurements between a node and at least three reference points. From this point onwards the node to be positioned is known as tag while the reference points are known as anchor nodes. Based on the TOA measurements and applying Equation (3) the distance between a tag and the anchor nodes can be derived. The position estimation is based on a geometrical method where reference circles are depicted around the anchor nodes. The radius of each reference circle is the distance computed from the ranging measurements respectively. Therefore the estimated position of the tag is the intersection point between the reference circles as shown in Figure 2.11 [Muñoz et. al. 2009].

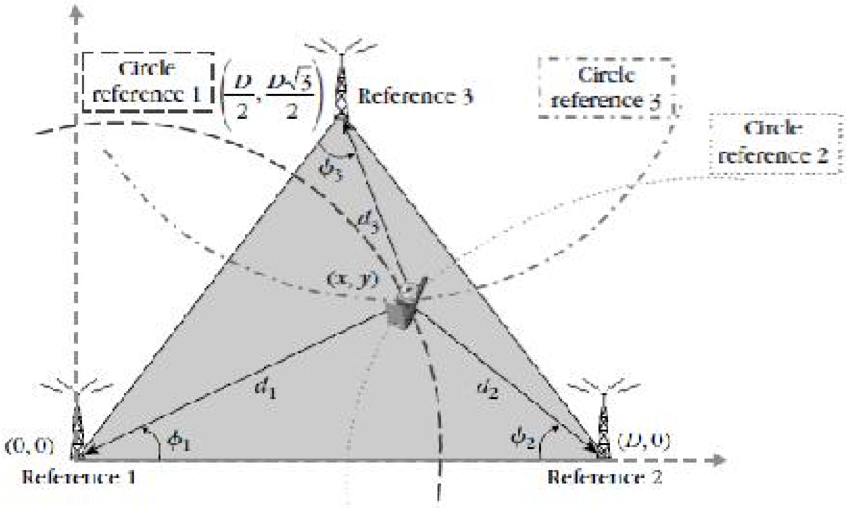

Figure 2.11 Lateration Technique using TOA ranging method [Muñoz et. al. 2009]

Besides the straight forward geometrical algorithm, the position of a tag can be estimated using the least-square error minimization algorithm. This method assumes that a signal is transmitted at time t_0 by a tag that is located in coordinates (x_0, y_0) to the N anchor nodes located at $(x_1, y_1), (x_2, y_2) \dots (x_N, y_N)$ and is received at times $t_1, t_2 \dots t_N$ respectively. The position estimation consists of the minimization of the cost function given by Equation (4):

$$F(x) = \sum_{i=1}^{N} {\alpha_i}^2 {f_i}^2(x) \tag{4}$$

Where α_i reflects the reliability of the measurement sample of the signal received at i^{th} anchor node. The error function $f_i(x)$ in Equation (5) is expressed in terms of the propagation velocity of the signal (v), the ranging measurements (t_i, t) and the position of the tag and the anchor nodes.

$$f_i(x) = v(t_i - t_0) - \sqrt{(x_i - x_0)^2 + (y_i - y_0)^2} \tag{5}$$

In addition to the aforementioned algorithms, there exist other alternatives that use the TOA ranging measurements, for example, the closest neighbor (CN) and the residual weighting (RWGH). The first one estimates the position of the tag as the position of the closest anchor node. The second algorithm can be seen as a weighted least-square error minimization approach [Liu et. al. 2007].

As an example of suitable technologies [Gezici and Poor 2009] propose a position estimation technique based on TOA measurements using UWB technology. Also [Hwang et. al. 2009] propose a Time of Arrival estimation technique using UWB technology. Unlike [Gezici and Poor 2009], [Hwang et. al. 2009] focus on the reduction of the calculating time in the ranging process instead than in reducing the positioning error. Moreover an experimental approach using UWB technology is presented by [Gigl et. al. 2007] who report a positioning error of one and a half meter in a 7 x 7 meters room.

Additionally to UWB technology [Bingham et. al. 2007] reports the usage of Direct Sequence Spread Spectrum Signaling for range estimation in underwater environments.

The realization of a positioning system based on TOA measurements faces two main shortcomings. The first one is the precise global synchronization required in the network. The second one is the need for high resolution clocks in the nodes. Moreover a time stamp has to be imprinted in the message in order to differentiate from the actual time the signal is traveling and the processing time of the information. Both shortcomings result in the need of additional hardware into the system. Thus higher costs are expected while using this approach [Liu et. al. 2007]. In addition the hardware requirements the UWB technology also requires higher power consumptions [Gezici and Poor 2009].

Time Difference of Arrival (TDOA): A variation of TOA is Time Difference of Arrival (TDOA) that consists in the measurement of the time of arrival at different times on the same node. The distance estimation can be computed based on the difference of the TOA. Thus instead of the intersection of circles, TDOA algorithm uses the intersection of hyperbolas as shown in Figure 2.12.

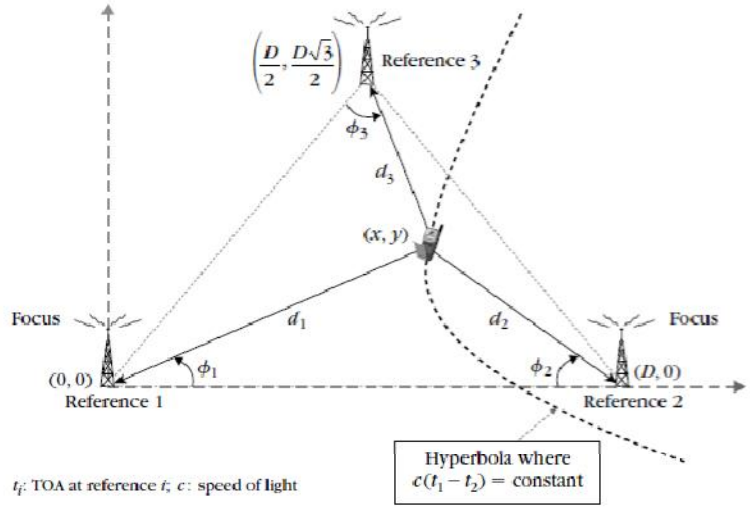

Figure 2.12 Lateration Technique using TDOA ranging method [Muñoz et. al. 2009]

One of the advantages that TDOA presents over TOA is that time synchronization among tag and anchor nodes is not required. However time synchronization between the anchor nodes is still needed. Consequently as well as in TOA approach additional hardware for global time synchronization in the network as well as high clock resolution in the nodes is required [Bensky 2008].

Moreover the obstruction of the line of sight and the intense multipath effect makes this approach not suitable for practical indoor implementations [Kaemarungsi 2005].

Round Trip of Flight (RTOF): The RTOF ranging approach uses the same principle as TOA. The task is to measure the time taken by the signal to travel from a transmitter to a receiver. The main difference is that RTOF measures the complete cycle time of the signal transmission, i.e., towards the receiver and backwards from the receiver. This approach resembles the radar application. The tag sends a message to the anchor node and waits for an acknowledgement to the message. Thus a distance between the tag and the node can be computed based on the ranging measurements.

Unlike TOA approach, the RTOF does not need accurate global synchronization in the network since all the measurements are with respect to the local clock. But the anchor node expends some time processing the information and sending back the acknowledgement. This processing time cannot be differentiated from the actual time the signal is traveling over the air by using RTOF. Moreover typically the processing time is larger than the traveling time of the signal whose velocity is close to the speed light that leads to large error in the positioning system [Liu et. al. 2007].

However one-way ranging methodology is not good enough to provide proper results in indoor environment. As a consequence, many efforts have been aimed to improve the ranging methods based on the two-way ranging methods for measuring the round trip time of a signal more accurately. These efforts have enabled the development of new algorithms that looks to overcome the need for global synchronization and increase the degree of detail in the ranging measurements. A schematic description of the ranging process is depicted in Figure 2.13.

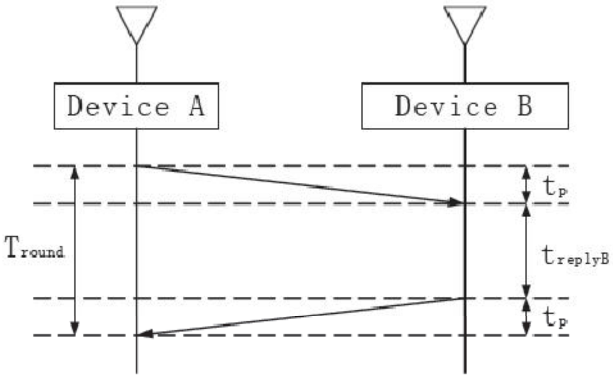

Figure 2.13 Two-Way Ranging Process [Jiang and Leung 2007]

As an example of these efforts [Jiang and Leung 2007] propose the Asymmetric double Sided Two-Way Ranging methodology to cope with crystal drifts in the clock of the devices. Additionally [Kim 2009] presents an improvement to the Symmetrical Double-Sided Two-Way Ranging (SDS-TWR) to reduce the ranging time and communication efforts. Both approaches enable the realization of measurements in both the tag and anchor nodes. The measurements are done with respect to their local clock respectively. Therefore no synchronization is needed. However all these time based methodologies require high resolution and precise clocks in order to achieve accurate positioning results. [Izquierdo et. al. 2006] report an experimental performance test using IEEE 802.11-based wireless technologies and the RTOF ranging method. They claim a distance estimation accuracy of 2.3 m with 90 per cent of confidence. In addition [Prieto et. al. 2009] report a position estimation error of 3.51 for at least 50 % of the samples in an indoor wireless network based on IEEE 802.11 technology.

Phase of Arrival (POA): The Phase of Arrival method is also known as the Received Signal Phase Method. This approach exploits the phase shift of the signal or the phase shift difference between signal transmissions among tag and anchor nodes. Based on the measurements, a time delay can be computed and consequently the distance between the tag and node can be derived. Once the phase measurements are in terms of time, TOA and TDOA methodologies can be applied whether phase shift or phase shift measurements are used respectively. Besides the synchronization and the high resolution clock shortcomings, this approach has to overcome another problem. It requires a line of sight between the tag and the anchor nodes in order to provide reliable and accurate data. Otherwise it leads to higher positioning errors in indoor environments. Consequently, the implementations of positioning systems using the phase of arrival methodology in indoor environments are impractical [Liu et. al. 2007].

Signal Attenuation-based (RSS): In wireless communication the power of a transmitted signal decreases logarithmically as long as the signal propagates over the air as shown in Figure 2.14. Thus there is a relationship between signal strength at a receiving point and the distance traveled from the source. This relationship can be established by means of a proper signal propagation model [Muñoz et. al. 2009].

Figure 2.14 Path gain curve for indoor propagation at 2.45 GHz [Bensky 2008]

RSS-based techniques offer some advantages over time-based methods. One of the most promising is that no additional hardware is needed, for example, platforms based on the IEEE 802.15.4 standard offer a built-in functionality to read the Received Signal Strength Indication (RSSI) which is a measurement of the RSS. Additionally the modulation method, data rate, and system synchronization are not needed for RSS-based techniques. Therefore the position estimation capability can be implemented with lower or none incremental costs in comparison with time-based techniques [Bensky 2008].

Although RSS measurements represent no additional efforts from the design point of view but modeling the signal propagation in a proper an accurate manner might be the opposite. Modeling the signal propagation behavior in indoor environments typically requires extensive measurement campaigns. Moreover the measurements are strongly dependant on the specific scenario [Muñoz et. al. 2009].

The propagation model of a signal can be achieved either analytically or empirically. Accordingly to [Muñoz et. al. 2009] analytical models are based on the log-normal path-loss model expressed in Equation (6). This equation is a generalization of the free-space Friis equation.

$$p_r(d)_{dB} = \overline{p_r}(d_0)_{dB} + 10 \cdot n \cdot \log_{10}\left(\frac{d}{d_0}\right) + X_\sigma, \qquad d > d_0 \tag{6}$$

The RSS at distance d from the transmitter node is denoted by $p_r(d)_{dB}$. The decaying rate of the signal strength with respect to the traveled distance is expressed by n. Also a random Gaussian variable with zero mean and variance σ_X^2 is included in the model and denoted by X_σ. The term $\overline{p_r}(d_0)_{dB}$ represents the average RSS at a reference distance d_0 in meters. Typically d_0 is considered one meter between the receiver and transmitter nodes.

In addition to the analytical model, the signal propagation model can be derived empirically. One of the most widely used empirical is reported by ITU [ITU 2007]. This model is shown in Equation (7).

$$L_{total}(d)_{dB} = 20 \cdot \log_{10}(f) + N \cdot \log_{10}(d) + L_f(p) - 28, \qquad d > 1\,m \tag{7}$$

The model is valid for separation distances between the receiver and transmitter nodes greater than one meter. The term $L_{total}(d)_{dB}$ denotes the RSS at distance d from the transmitter in meters. The frequency of the signal in MHz is expressed by f and its decay ratio is given by N. This model also considers the floor penetration loss factor represented by L_f in dB while p represents the number of floors between the nodes. This value must be greater or equal to one.

Whether the analytical or empirical approach is used to model the signal propagation in indoor environment the RSS measurements can be used to estimate the position of a tag in a wireless network. 2-D position estimation can be achieved by applying lateration techniques and measuring the RSS with respect to at least three anchor nodes [Muñoz et. al. 2009].

RSS positioning techniques have been widely investigated and many efforts have been made in order to improve the position accuracy. This interest is mainly raised because of the lower cost compared with other approaches; for instance [Tay et. al. 2010] report an improved methodology for a RSS based position estimation using the two way ranging method. However, this approach introduces extra communication efforts among the nodes within the network. Moreover an empirical RSS modeling methodology is presented by [Chen et. al. 2009] who used a piecewise linear model instead of the log-normal one. They report a position estimation error around one meter but in ideal environment, i.e., no obstructions are considered. An experimental analysis of RSS-based indoor localization using IEEE 802.15.4 platform is presented by

[Goldoni et. al. 2010] reporting localization errors about 3-4 meters in a 230 m^2 room using lateration technique. Additionally to the modeling methodologies [Bhuvaneswari et. al. 2010] presents a location approach based on RSS measurements and utilizing a one-dimensional Kalman estimator to reduce the positioning error. The algorithm is simulated in MATLAB and results show position estimation error less than one meter.

Although the advantages offered by RSS-based methods over time-based ones from the cost point there are some implementation shortcomings. The accuracy of the estimated position using the RSS technique is typically less than the one obtained with time-based techniques. The RSS is highly susceptible to multipath, shadowing effects, transmission frequency and moving objects. Moreover within the moving objects, people represent the most harmful moving objects to the radio frequency communications. This is because the human body strongly attenuates the radio frequency waves. In other words, the signal propagation depends on the specific conditions of the environment where it takes place. Consequently, the signal propagation model has to be tailored to the place where the positioning system is being used [Bensky 2008].

Angulation Techniques

Angle of Arrival (AOA): The location of a tag is based on a geometrical approach. The intersection point of the lines formed by the radius of the reference circles from the anchor nodes towards the tag as illustrated in Figure 2.15.

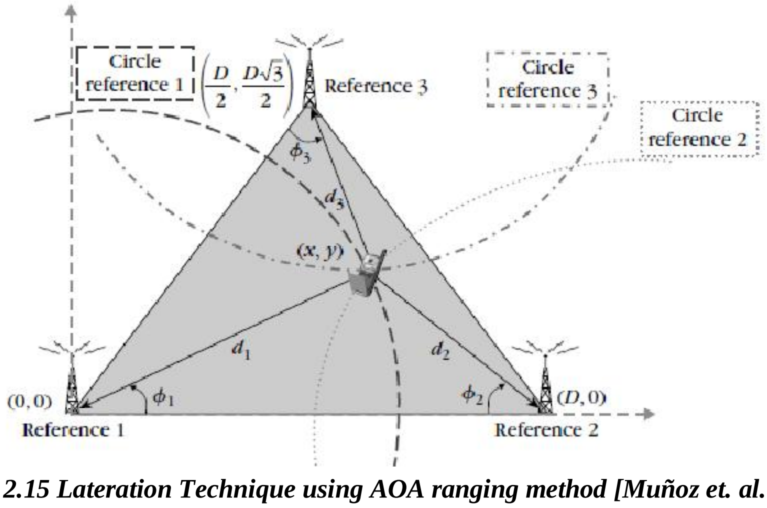

Figure 2.15 Lateration Technique using AOA ranging method [Muñoz et. al. 2009]

In order to position a tag in a bi-dimensional plane at least two anchor nodes are needed. This approach offers some advantages over the time based techniques. AOA requires no time synchronization and fewer anchor nodes are required in order to position a tag. On the contrary, it requires larger and more complex hardware. Besides as long as the tag is moving away from the anchor nodes the position estimation accuracy degrades. Moreover in indoor environments AOA accuracy suffers because of multipath reflections effects and from the antenna characteristics of the nodes [Bensky 2008]. Therefore the obstruction of the line of sight and the intense multipath effect makes this approach not suitable for practical indoor implementations [Kaemarungsi 2005].

Fingerprinting

Fingerprinting refers to a RSS-based algorithm that relies on the collection of a given number of samples of a specific location. As a consequence, the fingerprint approach depends on the location of the tag node and the specific signal propagation characteristics presented in that position [Liu et. al. 2007].

The fingerprint algorithm is composed by two stages: off-line and run-time stages. The off-line stage consists on the recording of RSS measurement samples between the tag and the anchor nodes in a predefined position. The tag is moved all over the predefined positions all over the area of interest. Then all the measured RSS values are stored in a relational data base. This data base relates a specific position with a characteristic RSS value with respect to each anchor node. Afterward in the run-time stage the position estimation takes place. This estimation is done by matching the current RSS observation with the previously stored measurements [Bensky 2008].

Fingerprinting has a potential advantage over other techniques because in the database the effects of fading and multipath are already included. Nevertheless when the multipath and fading effects are included in the data base the randomness of the RSS patterns strongly affects the accuracy of the method. This randomness is the strongest factor of positioning errors in the fingerprint approach. Also the separation of the predefined positions in the grid affects the performance. If the separation between the grid positions is too short, the variations of the RSS might not be representative. Thus the algorithm cannot distinguish between the involved positions. Besides the aforementioned shortcomings the non considered phenomena or disturbances during the off-line stage may lead to errors in the position estimation. These non considered disturbances can be for instance people or mobile equipment passing between the nodes, changes in the atmospheric conditions, among others [Kaemarungsi 2005].

There are some algorithms for in indoor environments that use the fingerprint technique. These algorithms can be classified into deterministic and probabilistic algorithms. Among them the most widely used algorithms for indoor positioning are: k nearest neighbor (kNN), neural networks, the probabilistic and the support vector machine methods (SVMs) [Kaemarungsi 2005].

Fingerprinting Algorithms

k Nearest Neighbor (kNN): This algorithm is also known as the case-based method is a deterministic approach. The RSS value sampled in run-time is compared with the values stored in the data base during the offline stage. But a discrepant function has to be used to determine the position of the tag node. The minimum Euclidean distance algorithm is typically used for this purpose. Therefore the measured value is evaluated accordingly to this function and then a set of k positions is selected. The positions are selected by matching the cases with the minimum root mean square error [Roos et. al.

2002]. Moreover the candidate results can be averaged either in a weighted or non-weighted manner. Therefore an interpolation can be performed to estimate the position of the tag [Liu et. al. 2007].

The performance of the kNN algorithm depends on the matching error. It means that depends on how well the algorithm can discern among different positions. One of the advantages of this method is its rapid deployment. Moreover there is no need of trainee or tuning task to implement the algorithm additional to the offline phase. Although the implementation kNN algorithm is simple, the complexity of the computations needed to estimate the position increases as the number of anchor nodes increases. Also an increasing of the granularity of the locations results in an increased complexity in the computations [Kaemarungsi 2005]; for instance [Li et. al. 2006] report accuracies ranging from 1.23 to 2.98 meters using the kNN algorithm with k equal to four. The difference relies on the amount of anchor nodes or reference points used. The best accuracy was obtained when 132 anchor nodes were deployed while the worst one used 16 anchor nodes. Thus the scalability of the kNN method might lead to shortcomings in a large space building. Additionally, [Saha et. al. 2003] report accuracy of 85% when the distance between the tag and the anchor node is 3.12 meters.

Neural Networks: This approach can be seen as a back box that uses a generalized structure called the neuron to process the information. During the offline phase, the neuron is feed with the RSS values and the locations associated with each fingerprinted position. This RSS values are used as inputs to the neuron while the corresponding positions are used their target outputs. As a result, the offline stage serves as a training phase for the neuron. After the training phase, the neural network establishes a set of weights for each trained position. These weights are known as synaptic weights. During the run-time phase, the RSS samples are multiplied by their corresponding synaptic weights and added together. Afterward the sum is multiplied by a non-linear function that limits the amplitude of the output of the neuron. Moreover a neural network is comprised by multiple neurons interconnected in both parallel and serial manner. This interconnection is known as the multilayer perceptron. Thus the signals travel from the input to the output layer and from the output of a neuron the input of another one in a sequential mode. The layers in between the input and output layers are called hidden layers [Kaemarungsi 2005].

Accordingly to [Liu et. al. 2007] the neural networks used for indoor wireless positioning tasks are comprised by a multilayer perceptron with one hidden layer. The output of this type of neural network is whether a two-element vector or a three-element vector for bi-dimensional or three-dimensional position estimation respectively. Experimental results have been presented by [Saha et. al. 2003] showing accuracies less than one meter with 72% of probability of occurrence. Moreover it presents accuracies less than 2.6 and 3.3 meters with a probability of occurrence of 95% and 98% respectively. Besides, [Battiti et. al. 2002] present a neural network approach with accuracies about 2.3 meters with 70% of occurrence using five anchor nodes.

Although the precision and accuracy of neural networks are slightly better in comparison with kNN approach the complexity involved in their implementations is higher. The training phase is time consuming especially if high accuracy is targeted. Besides an over training, i.e., iterations above 3000 may result in high position estimation errors [Kaemarungsi 2005].

Probabilistic method: This algorithm assumes that the tag node can be in a set of candidate positions. Thus the position estimation is performed based on conditional probability by using the concept of Bayesian inference to estimate the location. Nonetheless this method requires prior knowledge of the probability distribution of the position of the tag. This knowledge can be obtained from the signal propagation model or via the offline fingerprinting database creation phase [Liu et. al. 2007].

In accordance with [Kaemarungsi 2005] a conditional probability density function or likelihood function can be estimated for each position of interest using the offline stage information. This likelihood function can be estimated by using any of two different methods: the kernel or the histogram method. Whether method is used to calculate the likelihood function the result is feed to the algorithm where an *a posteriori* probability distribution is computed. Therefore the algorithm classifies the fingerprinted locations according to their maximum estimated posterior probability. Consequently the position with the smallest probability of error is selected as the estimated position of the tag.

Even when the probabilistic method has the possibility to offer better performance than deterministic ones, the dependence on the characterization of the signal propagation affects their results. This signal propagation modeling is hard to accomplish and introduces large opportunities for errors especially in indoor environments where multipath and fading effects cause strong disturbances.

A probabilistic approach to position estimation in a WLAN is reported by [Roos et. al. 2002]. A comparison nearest neighbor, the kernel and the histogram method is presented. The results are shown in Table 2.11.

Table 2.11 Location estimation errors (Average, 50th, 67th and 90th percentiles in meters using 1 or 20 test observations [Roos et. al. 2002]

1 Test Observation				
Method	Average	50 %	67 %	90 %
Nearest Neighbor	3.71	3.21	4.38	7.23
Kernel Method	2.57	2.28	2.97	4.60
Histogram Method	2.76	2.32	3.11	5.37
20 Test Observation				
Nearest Neighbor	1.67	1.60	2.04	2.80
Kernel Method	1.69	1.56	2.01	3.07
Histogram Method	1.56	1.45	1.81	2.76

Additionally [Youssef et. al. 2003] presents a Bayesian probabilistic approach claiming accuracy of 2.13 meters (7 feet) within the 90th percentile.

Support Vector Machine Method (SVM): This methodology combines statistics, machine learning and neural networks techniques. Besides it does not require additional information such as propagation model data as in the probabilistic method. The strongest advantage of this method is its ability to generalize classification which reduces the efforts during the training phase and enhance the efficiency of the process. The concept behind the SVM algorithm is based on the principle of Structural Risk Minimization. The purpose of this principle is the minimization of the bound on an expected generalization error. In other words, this function tries to minimize the position estimation by bounding the overall risk function. Hence it minimizes the number of candidate solutions for the position of the tag. This overall risk function is bounded by Vapnik-Chervonenkis (VC) confidence interval and an empirical risk function describing the expected value of the estimated position of the tag [Liu et. al. 2007].

Although SVM involves statistics, the machine learning and neural networks techniques its performance is comparable to the weighted k nearest neighbor method performance [Kaemarungsi 2005]. Accordingly to [Battiti et. al. 2002] the position estimation error using weighted k nearest neighbor methodology results in 3.93 meters within the 75th percentile. While a position estimation error of 3.96 within the 75th percentile results from the SVM algorithm implementation. Moreover the SVM approach is more suitable for classification problems, for example, SVM can be used to determine if a certain area is either inside or outside the room. Therefore a SVM practical implementation for designing an indoor positioning system results in unsuitable complex solution from the theoretical point of view.

Proximity

Proximity algorithms are based on a dense grid of anchor nodes with a well-known position. This approach provides symbolic information about the relative position of the tag. The principle of operation is the detection of an asset that is in the reachable area of an anchor node. Therefore, when a tag is detected, the position estimation relies on the information about the anchor node that detected the tag. On the other hand, when multiple anchor nodes detect a tag in proximity, the position is estimated based on the anchor node holding the strongest signal reading. The implementation of this method is comparatively simpler than the previous ones since it does not require complex computations or formulations in the algorithm. Typically the technologies used to implement this approach are Infrared Radiation (IR) or Radio Frequency Identification (RFID). Although its simplicity for deployment, the proximity based technologies generally require line of sight and a dense population of anchor nodes. Consequently the implementation costs increase because of the quantity of the hardware required. Besides in indoor environments the line of sight condition is hard to achieve in mobile assets with random trajectories [Liu et. al. 2007].

Vision analysis

Vision-based positioning systems provide a reliable way to track an asset in a complex indoor environment. Additionally it can enable the identification functionality because of the image processing capability. The implementation of this type of systems does not need the installation of an identification tag or any kind of device in the targeted asset. Because of the capabilities of the vision-based positioning systems, more complex information can be acquired, for instance, the system can provide information beyond the simple position of the asset such as status, orientation, shape, color, among others. However, the complexity associated with the image processing increases the implementations cost, installation cost as well as the power consumption of the system. Moreover the accuracy of the system is susceptible to interferences or obstructions in the dynamic indoor environments such as changes in the weather, light intensity, objects passing between the objective and the camera, among others. Therefore its accuracy cannot be guaranteed [Gu et. al. 2009].

A summarized comparison between the positioning techniques is presented in Table 2.12.

Table 2.12 Comparison between the position estimation techniques for indoor environments

Technique	**Estimation Method**	**Description**	**Pros and Cons.**
Lateration	TOA	Computes the distance between two nodes based on the arrival time of a message.	- Requires precise synchronization. - Requires high resolution and accurate clocks - Time of flight cannot be distinguished from processing time, therefore provides moderate resolution.
	TDOA	Computes the distance between two nodes based on the arrival time of two or more consecutive messages.	- High resolution and accurate clocks are needed - Precise Synchronization only between anchor nodes - Not suitable for practical implementations in indoor environments due to multipath effect.
	RTOF	The round trip time of a message between two nodes is used to calculate the distance	- No synchronization needed. - Accurate and high clock resolution. - High estimation accuracy. - Crystal drift affects.
	RSS	Uses the relation between the RSS and the distance to estimate the distance between the nodes.	- Signal propagation model is needed - High randomness in RSS measurements distribution - Is simple to implement and does not require additional hardware - Highly affected by fading and multipath effect.

	POA	Measures the phase shift of the received signal or consecutive received signals, calculate the time and therefore the distance between two nodes.	- LOS and precise sync are needed. - Requires high resolution and accurate clocks - Higher hardware requirements. - Multipath effect makes not suitable for indoor estimation.
Angulation	AOA	Measures the angle of arrival of the signal. Then by geometrical projection estimates the position the transmitter	- Higher hardware requirements - Not suitable for indoor environments
Fingerprint	RSS	kNN uses the least mean root square error to determine the closest pattern matching the position. "k" determines the number of candidate solution. Weighted or non weighted interpolation is used to estimate the position.	- This approach involves two stages, off-line and run-time stages. - Requires an extra effort to build up the RSS data base during the off-line phase. - Is affected by multipath and fading effects. - Obstructions affect the RSS measurements. - kNN is the simplest algorithm but offers results with accuracies compares with neural networks. - SVM is a novel approach but involves high complexity in the implementation. Moreover has not shown high difference from kNN. - Probabilistic requires signal propagation model which is hard to accomplish in indoor environments.
		Neural Networks use a trained intelligent system to estimate the position. Involves high complexity during its implementation.	
		Probabilistic method estimates the position by conditional probability based on Bayesian inference.	
		SVMs combine statistics, machine learning and neural networks techniques to estimate the position.	
Proximity	RF, IR	The position is estimated by relating the position of a detected node in proximity with a well known positioned anchor	- Simple implementation - Short range - Requires LOS which is difficult in industrial indoor environments with high mobility.
Vision Analysis	Pattern matching	An image is analyzed to identify the asset; therefore the position is derived from the analysis.	- Requires additional hardware. - Typically result in expensive solutions. - Requires LOS which is difficult in industrial indoor environments with high mobility. - Requires an off-line preset and not suitable for dynamic environments such industrial ones.

The indoor environments offer unique challenges to the positioning problem. This problem is more evident in the industrial environments where scalability, mobility, security and accuracy requirements have to be achieved at the lowest possible cost. Therefore a suitable technique along with a proper position estimation algorithm has to be chosen among the existing ones in order to overcome these aforementioned challenges.

2.4 WIRELESS PLATFORMS FOR ASSET POSITIONING IN INDOOR ENVIRONMENTS

A wide variety of positioning systems have been developed in the past few years. Moreover the technologies used in the development of these systems also ranges in a wide variety. For instance, IR technology has been used in the development of the Active Badge system. In the same order of ideas, the Active Bat positioning system was developed based on ultrasound technologies. The cricket system was developed based on the ultrasound technologies too. Moreover RF technologies have gained interest among the developers of positioning systems because of their low cost solutions such as the RADAR system that was developed using RF communications in a WLAN [Gu et. al. 2009, Liu et. al. 2007].

However, not all the positioning techniques are applicable to the whole range of existent wireless technologies. But the position technique is dependent on the used technology. In the literature, many surveys on the existent positioning systems can be found such as the presented by [Pandey and Agrawal 2006], [Gu et. al. 2009], [Koyuncu and Yang 2007], [Mautz 2009] and [Liu et. al. 2007]. These surveys are summarized and presented in Table 2.13.

Table 2.13 Comparison between different Indoor Positioning Systems

System/ Solution	Wireless Tech.	Positioning Algorithm	Accu-racy	Com-plexity	Scalability/ Space Dimension	Robust-ness	Cost
Microsoft RADAR	WLAN RSS	kNN, Viterbi-like Algorithm	3 to 5m	Moderate	Good / 2D, 3D	Good	Low
Horus	WLAN RSS	Probabilistic method	2m	Moderate	Good /2D	Good	Low
DIT	WLAN RSS	Neural Nets, SVM	3m	Moderate	Good /2D,3D	Good	Low
Ekahau	WLAN RSS	Probabilistic Method (Tracking assistant)	1m	Moderate	Good /2D	Good	Low
SnapTrack	Assisted GPS TDOA	Lateration	5 to 50 m	High	Good /2D, 3D	Poor	Med
WhereNet	UHF TDOA	Least mean root square error / Residual Weighting	2 to 3m	Moderate	Very Good /2D, 3D	Good	Low

Ubisense	UWB TDOA + AOA	Least mean root square error	0.15m	Real time response (1 to 10 Hz)	2-4 sensor per cell (100 to 1000m) 1 Tag per object /2D, 3D	Poor	Med to High
Sappite Dart	UWB TDOA	Least mean root square error	< 0.3m	Response frequency (0.1 – 1 Hz)	Good /2D, 3D	Poor	Med to High
SmartLOCUS	WLAN RSS + Ultrasound RTOF	N/A	0.2 to 0.15m	Moderate	Good /2D	Good	Med to High
EIRIS	IR + UHF + RSS + LF	Proprietary Design	< 1m	Moderate to High	Good /2D	Poor	Med to High
SpotON	Active RFID RSS	Ad-hoc lateration	Depends on cluster size	Medium	Cluster at least two tags/2D	Good	Low
LANDMARC	Active RFID RSS	kNN	< 2m	Medium	Nodes placed densely	Poor	Low
TOPAZ	Bluetooth (RSS) + IR	Proprietary Design	2m	Delay 15 to 30 sec.	Nodes placed every 2 – 15 m	Poor	Med
MPS	QDMA (Proprietary)	Ad-hoc lateration	10m	1 sec	Excellent / 2D, 3D	Good	Med
GPPS	Digital enhanced cordless telecom cellular system	Gaussian process (GP), kNN	7.5m (GP); 7m (kNN)	Medium	Good /2D	Good	Med
Robot-based	WLAN RSS	Bayesian approach	1.5m	Medium	Good /2D	Good	Med
MultiLoc	WLAN RSS	Smallest m-vertex polygon	2.7m	Low	Good /2D	Good	Med
TIX	WLAN RSS	Triangulation, interpolation and extrapolation	5.4m	Low	Good /2D	Good	Med
PinPoint 3D-ID	UHF RTOF	Bayesian approach	1m	5 sec	Good /2D, 3D	Good	Low
GSM fingerprinting	GSM cellular network (RSS)	Weighted kNN	5m	Medium	Excellent/ 2D, 3D	Good	Med
Active Badge	IR TOA	Lateration	0.07m	Low	Good /2D, 3D	Poor	Med
Active Bat	Ultrasound TOA	Lateration	0.09m	Medium	Good /2D, 3D	Poor	Med
Cricket	Ultrasound TOA	Lateration	0.02m	Low	Good 2D	Good	Low
Dolphin	Ultrasound TOA	Lateration	0.02m	Medium	Good 2D	Good	Med

Wave LAN	WLAN RSS	Triangulation	3m	Low	Excellent / 2D,3D	Good	Med
UWB	WLAN TOA	Lateration	0.1m	Low	Poor /2D,3D	Poor	Med
Comp Vision	Vision Analysis	Image process	0.1m	Low	Poor /2D, 3D	Good	High
INS/RFID	WLAN RSS	Inertial navigation System (INS)	2m	Moderate	Excellent / 2D,3D	Good	Med
FPM/RFID	WLAN RSS	Inertial navigation System (INS)	1.7m	Moderate	Excellent / 2D,3D	Good	Med

The positioning systems in industrial manufacturing have to be aligned to the business goals where the most important is the necessity for keeping the cost as low as possible. Therefore the wireless technology used to develop a positioning system must provide a cost-effective solution. In addition this technology must provide sufficient capabilities to overcome the needs of robustness, scalability, complexity and accuracy of the positioning system. But besides these requirements an additional one must be fulfilled. The usage of a common communication protocol must be accomplished because of the trends in the new manufacturing market scenario towards the creation of the smart grid. However, none of the aforementioned positioning systems can satisfy the communication need unless the usage of gateways.

On the other hand as mentioned in Section 2.2, the most used wireless technology in industrial manufacturing is the IEEE 802.15.4. The reason for this widespread usage is precisely its low cost. Moreover the implementation of a common networking protocol in order to enhance the networks interoperability is feasible with this technology by implementing the 6LoWPAN standardization. However the hardware compliant with the IEEE 802.15.4 standard has limited resources. These limitations might affect the outcome of the positioning system as well as its performance.

However, the applications running on a node as well as the implementation of 6LoWPAN communication in a WSN must be supported by an Operating System (OS). Typically, this OS runs in a microcontroller unit (MCU) and is in charge of scheduling and managing all the resources in the device with real-time functionalities. In addition, the OS must implement the communication stack described in Figure 2.7 in Section 2.2. The efforts towards the realization of WSNs have encouraged the development of these OSs. Thus a variety of OS implementations can be found in the literature, for instance, TinyOS, Contiki, FreeRTOS, Mantis, BTnut, SOS, NanoRK and Dream [Mazzer and Tourancheau 2009].

Although some operating systems for WSNs are currently available, not all of them have been used to develop communication stacks implementing 6LoWPAN standardization. In the past few years, some 6LoWPAN stacks have been developed to enable the realization of IPv6 WSN mainly based on TinyOS, Contiki or FreeRTOS operating systems as shown in Table 2.14.

Table 2.14 Current 6LoWPAN stack implementations [Mazzer and Tourancheau 2009, Rodrigues and Neves 2010, Korte et. al. 2009]

6LoWPAN Stack	OS	6LoWPAN Std. Compliant	License	Status
Jacob's	TinyOS	No	Open Source	Not Maintained
Blib	TinyOS	Yes	Open Source	Active
ArchRock	TinyOS	Yes	Proprietary	Active
uIPv6	Contiki	Yes	Open Source	Active
NanoStack v1.1.0	FreeRTOS	Yes	Open Source	Not Maintained
NanoStack v.2.0	FreeRTOS	Yes	Proprietary	Active
Hitachi	Proprietary	Yes	Proprietary	Active
Jennic 6LoWPAN	Proprietary	Yes	Proprietary	Active

According to [Rodrigues and Neves 2010], among the OS the most popular ones are TinyOS and Contiki. This popularity is not only because both of them are open source and support the implementation of 6LoWPAN communication. In addition they support a good amount of hardware platforms. These characteristics allow the developers to have an enhanced degree of freedom in the implementation of WSNs without extra porting efforts. Consequently, the developers have no need to know underlying hardware design because the drivers of the hardware are already provided. Besides TinyOS as well as Contiki offer simulation tools and graphical user interfaces that facilitate the development phase. Furthermore, they are currently supported and maintained by a big community of developers all over the world.

Currently many efforts have been aimed to deploy IP based WSNs. The research in the field of wireless communication based on IP protocol for embedded devices has made possible the development of platforms that enable the IPv6 networking on top of the MAC layer and the physical layer by implementing the 6LoWPAN adaptation layer. [Mazzer and Tourancheau 2009, Korte et. al. 2009, Sarwar et. al. 2010, Rodrigues and Neves 2010]. A summarized survey on available platforms and the required OS to develop IPv6 enabled WSNs is shown in Table 2.15.

Table 2.15 WSN Platforms implementing 6LoWPAN communications

Platform	Hardware				OS / 6LoWPAN Stack	License	Price (USD)
	MCU	Transceiver	RAM	ROM			
Crossbow IRIS	Atmel ATmega 1281	Atmel RF230	8 KB	128 KB	TinyOS /Blib	Open Source	115
Crossbow MICAz	Atmel ATmega 128L	TI CC1000	8 KB	128 KB	TinyOS /Blib	Open Source	99
Crossbow MICA2	Atmel ATmega 128L	TI CC1000	8 KB	128 KB	TinyOS /Blib	Open Source	115–125
Crossbow MICA2	Marvel PXA271	TI CC2420 (IEEE 802.15.4)	32 MB	32 MB	TinyOS /Blib	Open Source	299

Crossbow TelosB	TI MSP480	TI CC2420 (IEEE 802.15.4)	10 KB	48 KB	TinyOS / /Blib Contiki OS / uiPv6	Open Source	99 – 139
RZRAVEN	Atmel ATmega 1284P + 3290P	Atmel RF230	16 KB + 2 KB	128 KB + 32 KB	Contiki OS / uiPv6	Open Source	119 (Kit)
Scatternode	Centering TI MSP430	ISM band/19.2 Kbps	5 KB	55 KB	Proprietary / Contiki OS / uiPv6	Proprietary / Open Source	N/A
Shimmer	TI MSP430	TI CC2420 (IEEE 802.15.4)	10 KB	48 KB	TinyOS 1.x / uiPv6	Open Source	220
Coalesenses ISense	Jennic JN5139	Integrated in JN5139	96 KB	128 KB	Proprietary	Proprietary	N/A
Sun SPOT	ARM920T	TI CC2420 (IEEE 802.15.4)	4 KB	512 KB	J2ME CLDC 1.1 JavaVM / Proprietary	Proprietary	399 (Kit)
Sensinode	RC2301AT Integrated Module with MCU 8051	TI CC2431	8 KB	128 KB	FreeRTOS / NanoStack v1.1.0 / NanoStack v2.0	Open Source / Proprietary	3656
PhyNet	TI MSP430	TI CC2420 (IEEE 802.15.4)	10 KB	128 KB	TinyOS / ArchRock	Proprietary	N/A

Therefore the implementations of WSN applications utilizing IPv6 communication protocol can rely on two of the major open source operating systems available for embedded systems: TinyOS and Contiki OS. The first one was created by The University of Berkeley, CA and it is currently maintained by them. This OS supports most of the sensor nodes developed by Crossbow Technology. Moreover, TinyOS is available for free download from the Internet and runs on a XUbuntu virtual machine[1]. Also a programming manual in the form of an e-book is available for developers along with additional documentation in the webpage. The development language used by TinyOS is networked embedded systems C (nesC) whose syntax is close to American National Standards Institute (ANSI) C. However, nesC and ANSI C differs in the programming model which signifies an adaptation time and learning curve for new developers. The TinyOS implementation of 6LoWPAN performs IPv6 neighbor discovery, default route selection and point-to-point routing. Additionally it supports Internet Control Message Protocol (ICMP), UDP and includes a prototype Transmission Control Protocol (TCP) stack [Rodrigues and Neves 2010].

On the other hand, Contiki OS was developed by The Swedish Institute of Computer Science and currently maintained by them. This OS supports ESB platforms, Tmote Sky, Telos B, RZRAVEN platform, Sentilla, Micaz and Sensinode motes, among

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[1] http://docs.tinyos.net/tinywiki/index.php/Getting_started

others. The Contiki OS runs on an Ubuntu 8.04 virtual machine fully configured for Contiki developments. This OS is an open source available for free downloading from its official website[2]. Tutorials and documentation are also available in the official webpage. Additionally to the official webpage documentation there is an open forum for Contiki developers[3] as well as a wiki page[4] where valuable information can be obtained and discussed. The Contiki Os is an event driven kernel written in standard C. The programming model is a threading-like model using proto threads enhancing the memory allocation efficiency. Moreover it allows the recompilation of several platforms with minimum changes in the source code. The uIPv6 stack is tightly coupled to the UDP and TCP protocol implementations. It performs the neighbor discovery structures, the network interface management, the stateless address auto configuration and ICMP, UDP and TCP protocols [Rodrigues and Neves 2010]. A comparison between TinyOS and Contiki OS is presented in Table 2.16.

Table 2.16 Comparison between TinyOS and Contiki OS

TinyOS	Contiki OS
Event-driven OS with non pre-emptive multitasking.	Event-driven OS with optional pre-emptive multitasking.
Static Linking	Dynamic linking
Written in nesC programming language.	Written in C programming language
Performs UDP, ICPM and a prototype of TCP protocols	Tightly coupled to the UDP and TCP protocol implementations. Implements UDP, TCP and ICMP protocols.

Accordingly to [Rodrigues and Neves 2010] the uIPv6 stack using Contiki OS has shown to be a more robust implementation of the 6LoWPAN protocol for embedded devices than the Blib stack implemented with TinyOS. Furthermore the uiPv6 stack was awarded the IPv6 ready silver seal granted by The IPv6 Forum. This certification ensures the interoperability of the stack with other certified implementations working with the IPv6 protocol.

Summing up the advantages offered by Contiki OS such as standard programming language, online support and documentation along with the IPv6 ready certification makes it a proper choice to develop the real-time position estimation tool for indoor environments utilizing an ad-hoc WSN communicating over IPv6.

Therefore a suitable WSN supported by Contiki OS and uIPv6 is needed. [Durvy et. al. 2008] report that RZRAVEN platform was used to implement the uIPv6 stack in constrained devices that lead uIPv6 to its aforementioned IPv6 ready certification. This platform is equipped with an ATMega 1284P MCU which has 128 Kbytes of ROM available for flashing plus 16 Kbytes of RAM. Therefore it offers enough memory and

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[2] http://www.sics.se/contiki/

[3] http://sourceforge.net/mailarchive/forum.php?forum_name=contiki-developers

[4] http://www.sics.se/contiki/wiki/index.php/Main_Page

processing capacities for the implementation of the 6LoWPAN stack. Moreover an ATMega 3290P MCU is available in the hardware. This MCU is responsible to manage an LCD display useful for debugging purposes during the development phase and as a user interface during the runtime phase. The footprint of the implementation reported by [Durvy et. al. 2008] is shown in Table 2.17.

Table 2.17 Code and memory footprint for the Contiki uIPv6 stack in bytes [Durvy et. al. 2008]

Function	ROM	RAM
ND Input/output	4800	20
ND Structures	2128	238
Network Interface Management	1348	118
Stateless Address Auto Configuration	372	16
IPv6 compression / decompression	1434	44
Packet Buffer	0	1296
ICMPv6	1406	16
Total	11488	1778
* For a UDP and TCP transport layer add 1.3 Kbytes and 4 Kbytes respectively		

Thus the RZRAVEN platform represents a viable and cheap option for the development of a real-time position estimation tool compliant with the 6LoWPAN standardization. However the constrained resource nature of this platform limits the utilization of position estimation algorithms to the ones based on the RSS since the oscillator used by this platform as a real time clock has neither enough resolution nor accuracy for the utilization of time based position estimation algorithms. As a result the lateration technique based on RSS ranging measurements as well as fingerprinting will be exploited to develop the position estimation tool. This tool will integrate the technologies mentioned before and can be used as a proof of concept for the position estimation of assets in a discrete indoor manufacturing environment.

3 METHODOLOGY SELECTION

The evaluation of available technologies and methodologies used in the development of positioning systems has been performed. According to the review, the accuracies of the reviewed systems range from a fraction of meters up to tens of meters. These accuracies depend mostly on the technology and the position estimation methodology used by a given system. As a result, a high resolution system can be achieved by using a combination of a proper ranging methodology and technology along with a proper estimation algorithm as the ones discussed in Chapter 2. However, the required resolution is given by the application itself. This resolution defines the ability to distinguish among the near locations of the assets and the ability to estimate their position within a certain range. Besides, the position estimation solution should be able to interoperate among different link technologies. This can be achieved by using 6LoWPAN adaptation layer. As a result, the deployment of IPv6 WSNs is feasible. Therefore, the integration of a proper technology and position estimation methodologies in an IPv6 based WSN might lead to the development of a real-time positioning application for manufacturing assets with wide interconnectivity among different technologies.

According to the discussion developed in Section 2.4, the uIPv6 stack using Contiki OS has shown to be a more robust implementation of the 6LoWPAN protocol for embedded devices than the other open source OS presented in Table 2.14. Furthermore, the uiPv6 stack was awarded the IPv6 ready silver seal granted by The IPv6 Forum. This certification ensures the interoperability of the stack with other certified implementations working with the IPv6 protocol.

Summing up the advantages offered by Contiki OS such as standard programming language, online support and documentation along with the IPv6 ready certification makes it a proper choice to develop the real-time position estimation tool for indoor environments utilizing an ad-hoc WSN communicating over IPv6.

The remaining sections of this Chapter describe the selected uIPv6 6LoWPAN protocol stack and its areas of opportunity. Subsequently, an explanation of the proposed position estimation algorithms is provided. Finally, the last section focuses on the position estimation engine proposed for the real-time position estimation tool.

3.1 THE 6LOWPAN PROTOCOL STACK (UIPV6)

The deployment of a WSN working with IPv6 communication protocol over IEEE 802.15.4 technologies can be achieved by utilizing the 6LoWPAN standardization as described in Section 2.2.5. Moreover, considering the review performed in Section 2.3 and Section 2.4, the utilization of the uIPv6 communication protocol stack in the development of a real-time position estimation tool based on RSS measurements is proposed. This communication protocol stack was implemented by [Durvy et. al. 2008] running on top of Contiki OS.

Although the uIPv6 is a phase 1 IPv6 ready implementation, it presents some deficiencies in its implementation. These shortcomings represent a challenge for the development of the real-time position estimation tool based on RSS values. Therefore, additional work is required in order to align the performance of the protocol stack implementation with the requirements of the positioning application. The schematic of the current uIPv6 communication protocol stack implementation (at the time this thesis work development) is presented in Figure 3.1. As can be noticed from Figure 3.1, the uIPv6 protocol stack does not explicitly implement the presentation and session layers of the OSI Model.

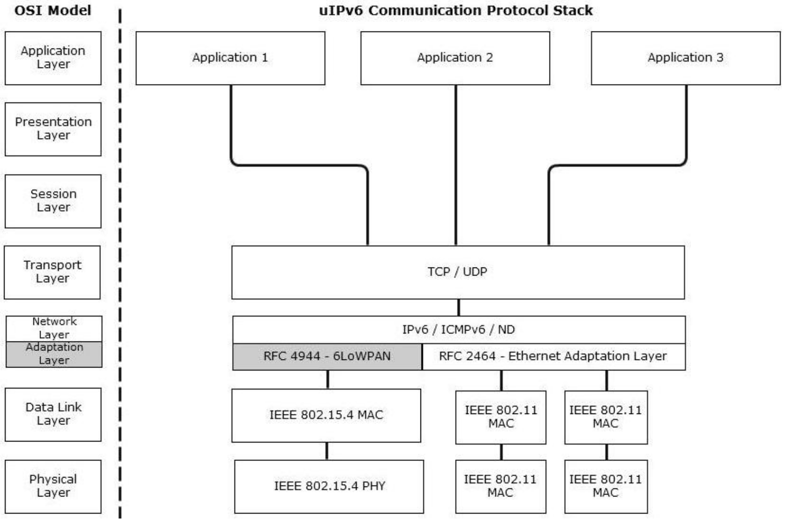


Figure 3.1 6LoWPAN Protocol Stack Architecture (uIPv6)

The uIPv6 stack is the new version of the former uIP protocol stack (the implementation of IPv4 for WSN). Furthermore, this uIPv6 meets all the obligated IPv6 node requirements of the RFC 4294 [Loughney 2006] with the exception of the multicast listener discovery support and redirect function support. This RFC 4294 states that an IPv6 node must comply with the following standards: the RFC 2460: Internet Protocol Version 6 Specification [Deering and Hinden 1998], the RFC 4291: IPv6 Addressing Architecture [Hinden and Deering 2006], the RFC 4861: Neighbor Discovery for IPv6 [Narten et. al. 2007], the RFC 4443: Internet Control Message Protocol for IPv6 [Conta et. al. 2006], the RFC 4862: IPv6 Stateless Address Auto configuration [Thomson et. al. 2007], the RFC 3484: Default Address Selection for IPv6 [Draves 2003]and the RFC 2710: Multicast Listener Discovery for IPv6 [Fenner et. al. 1999] and RFC 3810: Multicast Listener Discovery Version 2 for IPv6 [Vida and Costa 2004].

One of the key characteristics of the uIPv6 stack is that it does not depend on a specific physical or data link layer. The interaction between the network layer and the lower ones is carried out by two wrappers for input/output functions, addresses and some built-in constants at the link layer. This wrapping facilitates the integration of different protocols in the physical and data link layers. Furthermore the stack implements route over techniques as routing mechanism instead of mesh under techniques. Therefore, the routing decisions are performed in the network layer.

The protocol stack is strongly tied to the implementations of UDP and TCP protocols in the transport layer. At this level, the stack sorts the packets and delivers the data to the application layer in the same order as they were received. The same approach is implemented in the opposite direction. The transport layer sorts the data received from the application layer and passes the packets downwards in the same order as they were received.

Although the tightened implementation of the stack, there is a key limitation that compromises the implementation of the position estimation tool based on the RSS. As previously mentioned, the IEEE 802.15.4 radio technology possesses an in-built function to measure the signal strength of the received packets. However, these values are only available at the Physical, the Data Link and the 6LoWPAN adaptation Layer. Therefore, the layers above the adaptation layer do not have knowledge about the RSS value associated to the received message being processed. In addition, the uIPv6 utilizes a single global buffer to handle both, the input and the output messages. As a result, the uIPv6 stack should be tailored in order to make available the RSS values associated to the messages upwards the stack up to the application layer. The proposed customization of the processing flow of the uIPv6 stack is illustrated in Figure 3.2, where the main suggested changes are highlighted inside darker boxes.

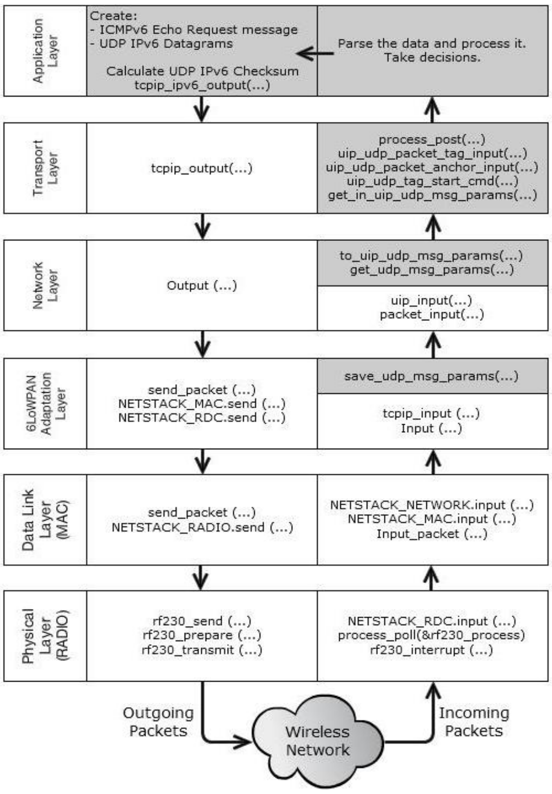


Figure 3.2 Proposed modifications to the uIPv6 Protocol Stack

In addition to lack of availability of the RSS values in the layers above the Data Link Layer, there another major problem in the implementation of the stack. This limitation refers to errors in the implementation of the Transport layer, specifically, the implementation of the UDP protocol. The major concern in this regard is an error related with the checksum of the UDP datagrams. Notwithstanding the checksum calculation is done correctly, the memory allocation for this value is corrupted. The usage of a single global buffer for incoming and outgoing messages may influence this error. As a result, the stack discards the UDP packets because of the checksum error and the communication between applications cannot be completed. Thus, additional work is required in order to overcome the UDP implementation errors and to enable the proper functionality of the stack.

Consequently, the proposed flow of the message processing, upwards and downwards the stack, is outlined subsequently according with the suggested customization. Upon the reception of a message at the Physical layer, the physical data frame should be allocated in the global buffer and the control must be passed to the Data Link Layer for further processing operations. Therefore, at the Data Link Layer, the stack needs to parse the input frame and accommodates the parsed information in an IEEE 802.15.4 data frame structure as the one shown in Figure 3.3. However, verification of the destination address should be performed before passing the control to the 6LoWPAN adaptation layer. This verification is intended to ensure that the packet is intended to the node processing it. If the message is meant for the receiver node, the control should be passed upwards to the next layer. Otherwise, the message must be discarded.

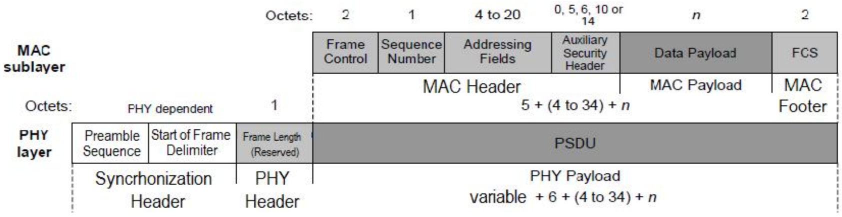


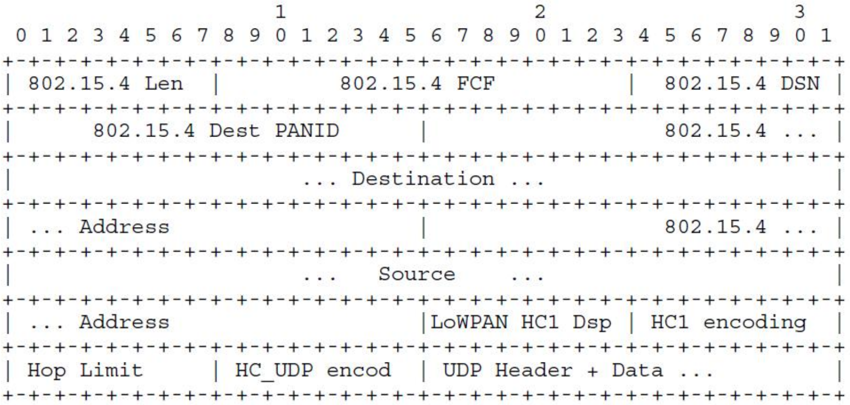
Figure 3.3 IEEE 802.15.4 PHY and MAC data frames [IEEE 802154 2006]

The payload in the IEEE 802.15.4 MAC protocol data unit is known as LoWPAN encapsulation and its maximum capacity is 127 bytes. Similarly, the payload of the LoWPAN encapsulation corresponds to the IPv6 packet. Furthermore, LoWPAN encapsulated packets transmitted over IEEE 802.15.4 are prefixed by an encapsulation header stack. Each header in the header stack contains a header type followed by zero or more header fields. An example of a typical 6LoWPAN header stacks is shown in Figure 3.4.

Figure 3.4 Typical 6LoWPAN Header Stack [Hui et. al. 2009]

The adaptation layer is in charge of compress / decompresses the IPv6 headers, fragmentation and reassembly of IPv6 packets and support layer-two forwarding messages. Moreover, this adaptation layer in the uIPv6 stack implementation is based on the RFC 4944: Transmission of IPv6 Packets over IEEE 802.15.4 Networks [Montenegro et. al. 2007], the Interoperability Test for 6LoWPAN [Hui et. al. 2007] and Compression Format for IPv6 Datagrams in 6LoWPAN Networks [Hui 2008].

Regardless of the position of the IPv6 compressed headers in the stack, it must contain: addressing, hop-by-hop options, routing, fragmentation, destination options, and finally the payload. These contents must appear sequentially as they were listed in compliance with RFC 2460 [Deering and Hinden 1998]. Analogously, the header sequence for the LoWPAN header is: mesh addressing, hop-by-hop options, fragmentation and the payload. An example of a fully-compressed UDP IPv6 message is shown in Figure 3.5.



```
                     1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
| 802.15.4 Len  |         802.15.4 FCF          | 802.15.4 DSN  |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|      802.15.4 Dest PANID      |               802.15.4 ...    |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                       ... Destination ...                     |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
| ... Address                   |               802.15.4 ...    |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                       ...   Source    ...                     |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
| ... Address                   |LoWPAN HC1 Dsp | HC1 encoding  |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
| Hop Limit     | HC_UDP encod  | UDP Header + Data ...         |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Figure 3.5 Fully compressed UDP packet over Link-local IEEE 802.15.4 Unicast [Hui et. al. 2007]

Therefore, when the adaptation layer handles the incoming packets, it should implement the reassembly process when needed. Furthermore, it must decompress the IPv6 headers and allocates the complete IPv6 datagram in the global buffer. However, before passing the control to the next layer, the RSS values must be saved. As a consequence, the RSS measurements should be stored in different memory allocation. Each memory allocation is managed by the different remaining layers. This is necessary because of the existence of only one buffer to handle both, incoming and outgoing packets and threading-like model used by Contiki OS. Therefore, the implementation should ensure that the message being processed at a certain layer corresponds to the RSS value stored in the corresponding memory. After saving the RSS values the stack must pass the control to the Network Layer.

Once the control is at the next level, the first step should be to copy the RSS measurements from the previously allocated memory to a new one managed by this layer. Afterwards the message IPv6 headers must be processed, passing the control to the appropriate protocol in the Transport Layer when the process finishes.

Likewise the previous level, the first step at the Transport Layer should be to copy the RSS values from the previous memory allocation and save them to a new one under its control. Additionally, because of the aforementioned limitations of the Transport Layer implementation, additional functionalities are proposed. The first one is intended to call an application upon the reception of an ICMPv6 Echo Reply message. This is useful to identify the neighboring nodes. The second proposed functionality is the identification and parsing of input UPD messages that may be used to implement customized communication between the wireless nodes. The last suggested functionality at this level is the calling function for a given application depending on the input messages. This calling function should pass information to the next layer along with the processing control.

At the Application Layer, the customized application ought to process the transferred information and take the necessary decisions according to the requirements programmed by the user.

In the opposite direction, when an IPv6 packet needs to be sent, the Application layer should create the IPv6 packet. This packet ought to be allocated in the global buffer. Additionally, if the packet to be sent is an UDP datagram, the application must compute the computation of the checksum. This checksum has to be saved in the proper allocation as well. Once the packets are completely created, the Application Layer should pass the control downwards to the next level.

In the subsequent processing flow, the stack presents no additional difficulties that interfere with the development of the position estimation tool. Hence, no additional modifications are required. As a result, the upper layers of the stack need to pass the control to the adaptation layer. The adaptation layer must perform the compression of the IPv6 datagram previously allocated in the global buffer. Afterwards, when the LoWPAN packet is ready, it ought to be allocated in the global buffer and the control should be passed to the Data Link Layer in order to continue building the header stack down to the physical layer. Once the packet headers are fully assembled, the physical layer has to transmit the frame to the destination address.

3.2 POSITION ESTIMATION ALGORITHMS

According to the review presented in Section 2.4 and the objectives presented in Section 1.3.1, a strong platform candidate, for the development of the real-time position estimation tool, is an IEEE 802.15.4 2.4 GHz platform. Nevertheless, this type of hardware is usually equipped with low resolution clocks. Furthermore, the usage of high resolution clocks results in additional costs. Therefore the implementation of time-based position estimation algorithms for indoor environments is not suitable for this type WSN platform. Regardless the clock resolution, the candidate platform offers an in-built function to measure the signal strength of the received packets at the physical layer. As a result, the estimation position tool may be developed based on RSS measurements. This requires no additional hardware to implement it. Thus, RSS-based algorithms and ranging methodologies can be applied in order to estimate the position of a manufacturing asset.

As discussed in Section 2.3.2, there are two different techniques to estimate the position of an asset using RSS-based algorithms. The first technique employs triangulation to estimate the position a target node while the second one matches the real-time RSS measurements with a set of database values stored during a previous site survey.

3.2.1 Lateration based on the Received Signal Strength Attenuation

Lateration based on RSS attenuation is a subset of triangulation technique that is comprised by two stages. The first stage, known as the off-line stage, consists on the determination of a relationship between the distance among two wireless nodes and the signal strength of the packets transmitted among them. The second stage, known as the run-time stage, exploits the distance-RSS dependency to establish the geometrical relationships between a node, whose position is unknown, and a number of fixed nodes with well-known positions. Afterwards, these geometrical relationships can be used to estimate the unknown position of a given asset.

The relationship between the distance traveled by a RF signal and its attenuation can be determined in different manners. However, the proposed methodologies for this thesis work consider two different models previously described in Section 2.3.2: the normal path-loss model and the ITU model for indoor environments. Furthermore, the mathematical representations of these models, expressed on Equations (6) and (7) respectively, are presented in the aforementioned section. In addition, the signal propagation spectrum corresponding to each model is depicted in Figure 3.6.

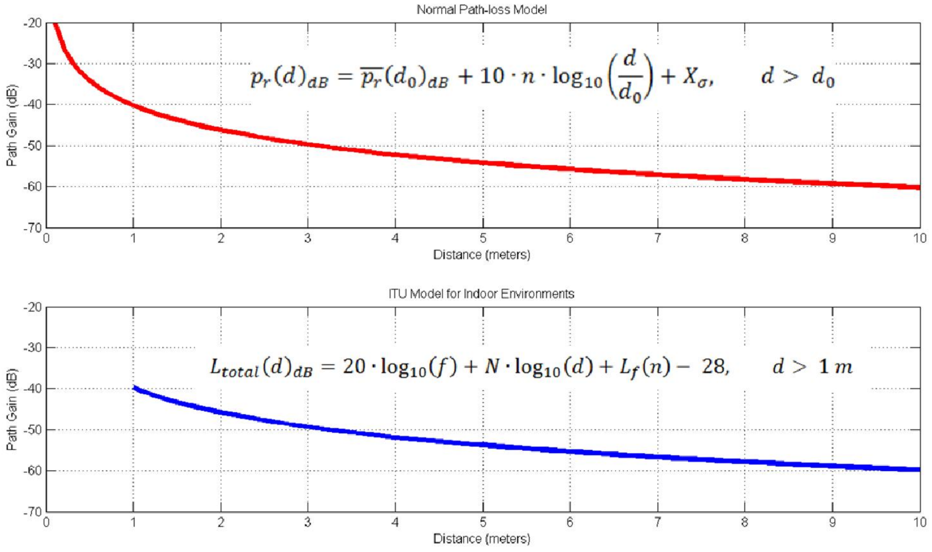


Figure 3.6 Signal propagation models for indoor environments: Normal path-loss Model (upper) and ITU Model (lower)

These models can be achieved either analytically or empirically. Though the indoor environments produce high variations of signal propagation conditions according to the review presented in Section 2.3. Consequently, it is difficult to adequately predict the RSS behavior analytically. Instead, the propagation models can be accomplished by using curve fitting. Regarding this thesis work, the curve fitting using least square algorithm is suggested. However, other algorithms may be implemented in order to minimize the fitting error.

The curve fitting must be implemented using a set of RSS samples between two nodes separated by certain distance. This process has to be repeated at different separation distances along a straight line. However, it is important to notice that the measurements should be taken with the line of sight between the nodes. In addition, as stated in Section 1.3.3, the orientation of the antenna must remain the same during the entire experiment. These assumptions might lead to estimation errors during the run-time stage if these conditions cannot be accomplished.

After completing the off-line stage, the position estimation can be performed during the run-time stage following a given algorithm. The proposed algorithm for the run-time stage of the position estimation based on lateration technique is illustrated in Figure 3.7.

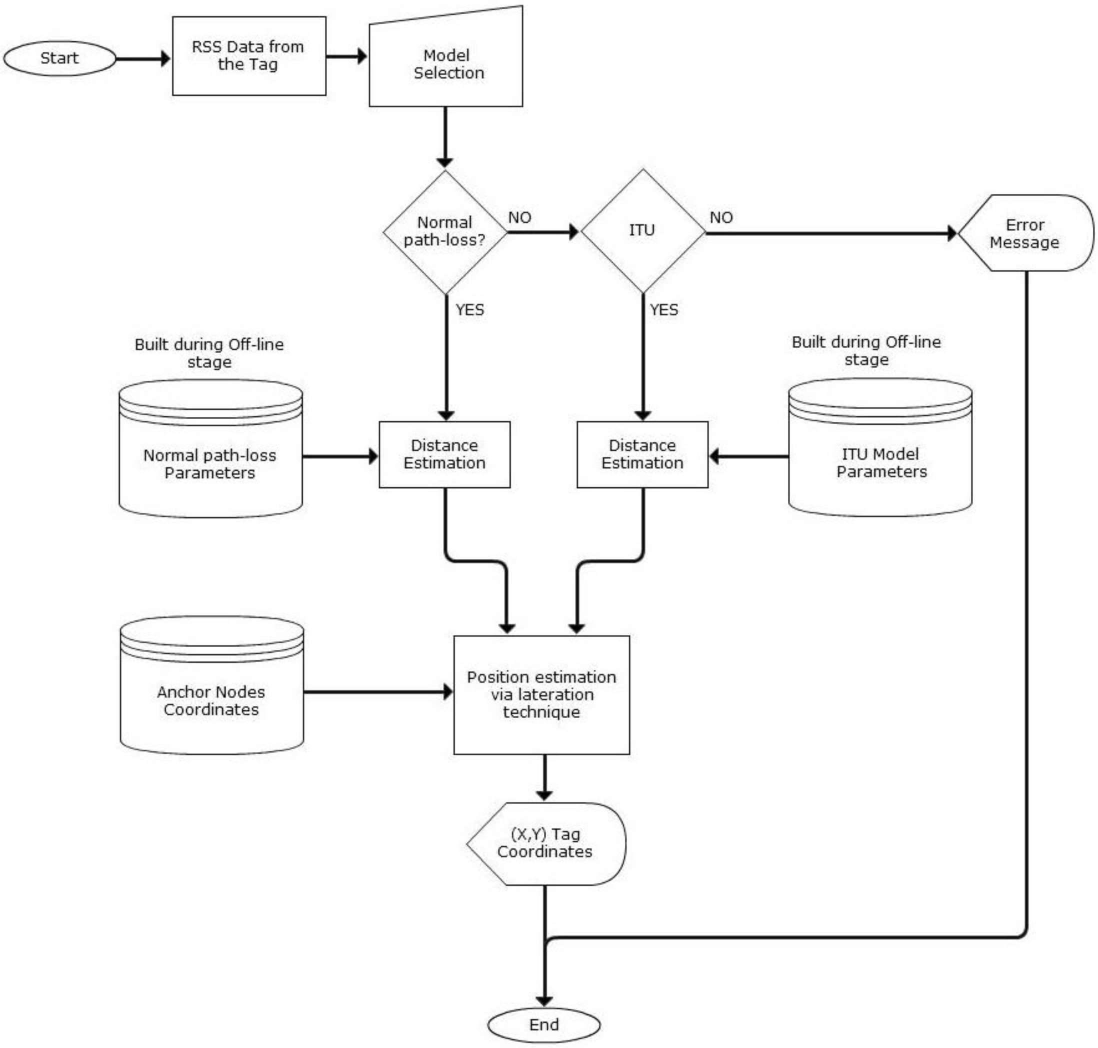


Figure 3.7 Run-time stage of the RSS-based position estimation algorithm using Lateration technique.

According to the proposed algorithm, a node with the unknown position should record the RSS measurements of the data packets exchanged between it and a number of reference nodes whose position is well-known. Afterwards, these measurements must be used to estimate the distance between the node with unknown position and each reference point. This estimation ought to be computed by using one propagation model. Therefore, the model must be selected among two proposed options.

The next step after computing the distances between the mentioned nodes is to estimate the unknown position of the node. As the method states, this estimation should be done via the lateration technique using the well-known coordinates of the reference nodes and the resulting distance estimation data as input information. Therefore, the final result can be obtained by solving the Equation (2) presented in Section 2.3.2.

3.2.2 Fingerprint using k-Nearest Neighbor Position Estimation.

Likewise the lateration technique based on RSS range measurements, the fingerprinting technique involves two stages: off-line and run-time stages. Nevertheless, the fingerprinting does not rely on a propagation model to estimate the position of a wireless node. Instead, it performs the pattern recognition of a set of RSS measurements between the node, whose position is going to be estimated, and a number of reference points whose position is predefined. Therefore, the RSS measurements can be compared against RSS values stored in a database in order to determine the unknown position of the node.

The off-line stage consists in the creation of the database. This involves the recording of a number of RSS samples taken at predefined positions throughout the area of interest. These RSS samples correspond to the RSS of the packets exchanged between the nodes of interest. Once the data collection at each point has finished, a data base containing the valuable information can be created. This data base can be based on several criteria. For instance, raw data, the average values of the recorded samples, the mode values, the standard deviation, among others. However, two different criteria are proposed for this master thesis. The first one is the average value of the samples taken at each sampling point. The second one is the mode value (the most frequent value) of the recorded samples. It is important to notice that both, the average value as well as the mode value, converge to the same limit as the number of samples increases. However, there is a difference between them in practice since the sampling size is limited due to power consumption reasons. Therefore, the behavior of a position estimation tool depending on the selected estimation criteria (from these two options) can be analyzed.

As a result, for each position, the tool ought to create two vectors containing the average and the mode values with respect to each reference point. The Equation (8) shows an example of a proposed vector for its utilization during the off-line phase:

$$RSS_j = \left(s_1, s_2, \dots, s_{kk}, x_j, y_j\right) \tag{8}$$

where:

$\left(x_j, y_j\right)$ $Denotes\ the\ coordinates\ of\ given\ position.$
kk $Denotes\ the\ number\ of\ anchor\ nodes.$
j $Denotes\ the\ position\ index.$
s $Denotes\ either\ mean\ or\ mode\ values.$

RSS_j $\quad$ $Denotes\ the\ vector\ of\ either\ mean\ or\ mode\ values\ at\ position\ n.$

As mentioned before, the second stage of the algorithm is the run-time phase. An algorithm proposal for the run-time stage is illustrated in Figure 3.8. This algorithm suggests that the estimation of the unknown position of the node should be based on online RSS measurements. These measurements must be performed by the node of interest during the run-time stage with respect to all the reference nodes.

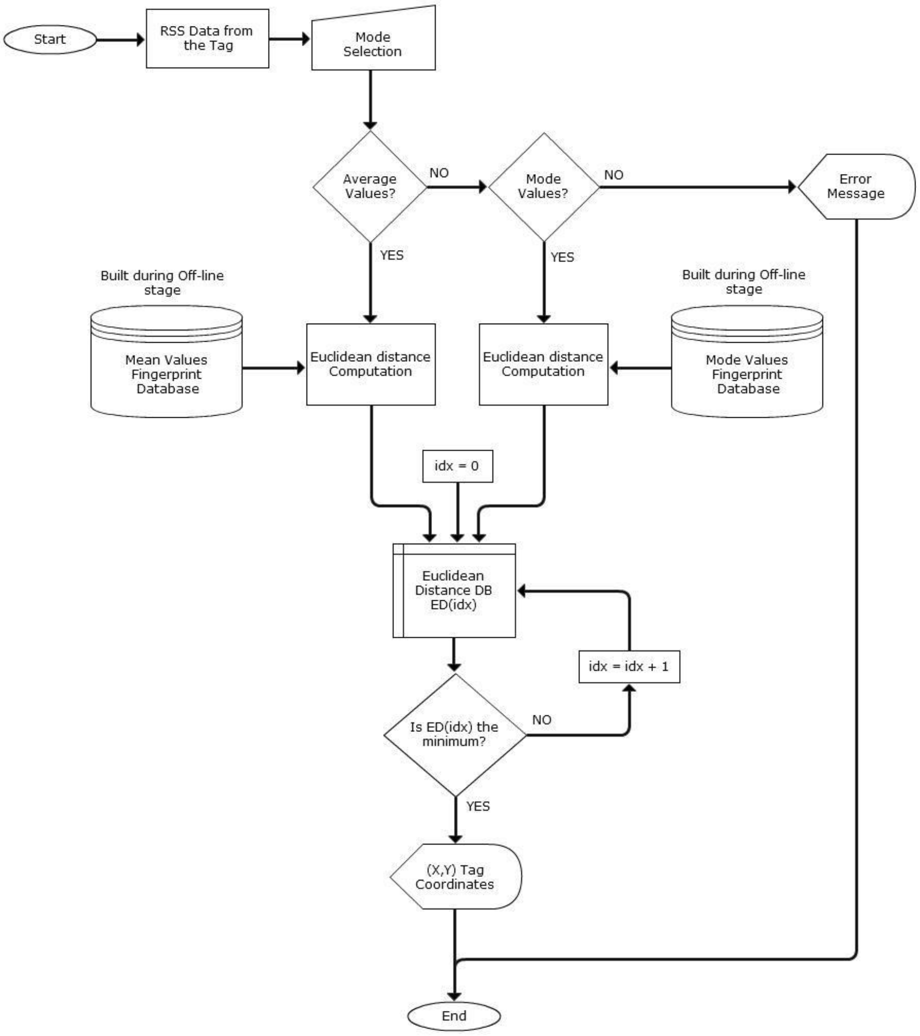


Figure 3.8 Run-time stage of the RSS-based position estimation algorithm using Fingerprinting technique

Once the measurements have been finished, the algorithm allows the estimation of the position depending on the selected criteria. In this case, the average or mode values are eligible choices. Subsequently, the online RSS measurements should be matched with the Average Values Fingerprint Database or the Mode Values Fingerprint Database. However, a matching criterion must be implemented in order to differentiate between the different results. This criterion can be selected among a variety of possibilities such as simple error, the absolute value of the error, mean squared error, Euclidean distance, among others. Among the suitable choices to match the online RSS values against the database ones, the Euclidean distance is proposed in this algorithm. This distance can be computed via Equation (9):

$$D_j = \sqrt{\sum_{i=1}^{kk} \left(RSS_i - s_{i,j}\right)^2} \tag{9}$$

where:

D_j $Denotes\ the\ Euclidean\ distance\ at\ a\ given\ position.$

kk $Denotes\ the\ number\ of\ anchor\ nodes.$

j $Denotes\ the\ position\ index.$

$s_{i,j}$ $Denotes\ the\ database\ values\ of\ the\ i^{th} anchor\ node\ at\ position\ n.$

RSS_j $Denotes\ the\ onlineRSS\ measurement\ vector$

The next step should create a new database with the resulting computations of the Euclidean distance. This new database should be used to estimate the unknown position of the node. For this purpose, the proposed approach is to find the minimum Euclidean distance in the database. Therefore the position matching the minimum value must be selected as the estimated position of a given node.

Notwithstanding the fingerprinting technique does not use the propagation model to estimate the position; it is important to notice that the database is applicable only for the particular scenario where it is created. Thus, changes in the environment may affect the position estimation results, leading to estimation errors. These changes may be produced by the small movements of the tag and movements of objects in the propagation paths such as people or machinery.

3.3 POSITION ESTIMATION ENGINE

In order to solve the position estimation of the asset problem and supports interoperability between different technologies, a position estimation engine that exploits the 6LoWPAN communication protocol characteristics is needed. Hence, it requires the utilization of IPv6 datagrams transmitted over IEEE 802.15.4 frames to communicate among the wireless network. Moreover, this engine should take advantage of the routing mechanisms implemented by the IPv6 protocol as well as the ICMPv6 mechanisms.

According to [Martinez and Lastra 2011], the topology of the network is not controlled by the routing mechanisms implemented by the 6LoWPAN protocol communication. Therefore, it cannot guarantee the achievement of a direct link between IPv6 wireless nodes. This direct link is required in order to measure the physical parameter from nodes that are interacting directly without intervention of third parties. Furthermore, the uncertainty of a direct links among the nodes may lead to errors in the position estimation results. Consequently, the engine should implement verification mechanism in order to ensure the direct link between the nodes involved in the position estimation process.

The referred position estimation engine is the core of the position estimation application independently of the algorithm used. This is because it should rule the role of the applications involved in the position estimation process and the decision making process. In this regard, a proposal for a position estimation engine is presented in Figure 3.9 as the core of the solution intended for this master thesis work. This engine considers three main components for its implementation. The first component is the targeted node whose position should be determined. The second is a number of the reference nodes with well-known positions. The last component consists of a host computer that runs a centralized position estimation application. Therefore the position estimation of the targeted node should be performed in an indirect manner according to the classifications presented in Section 2.3.2.

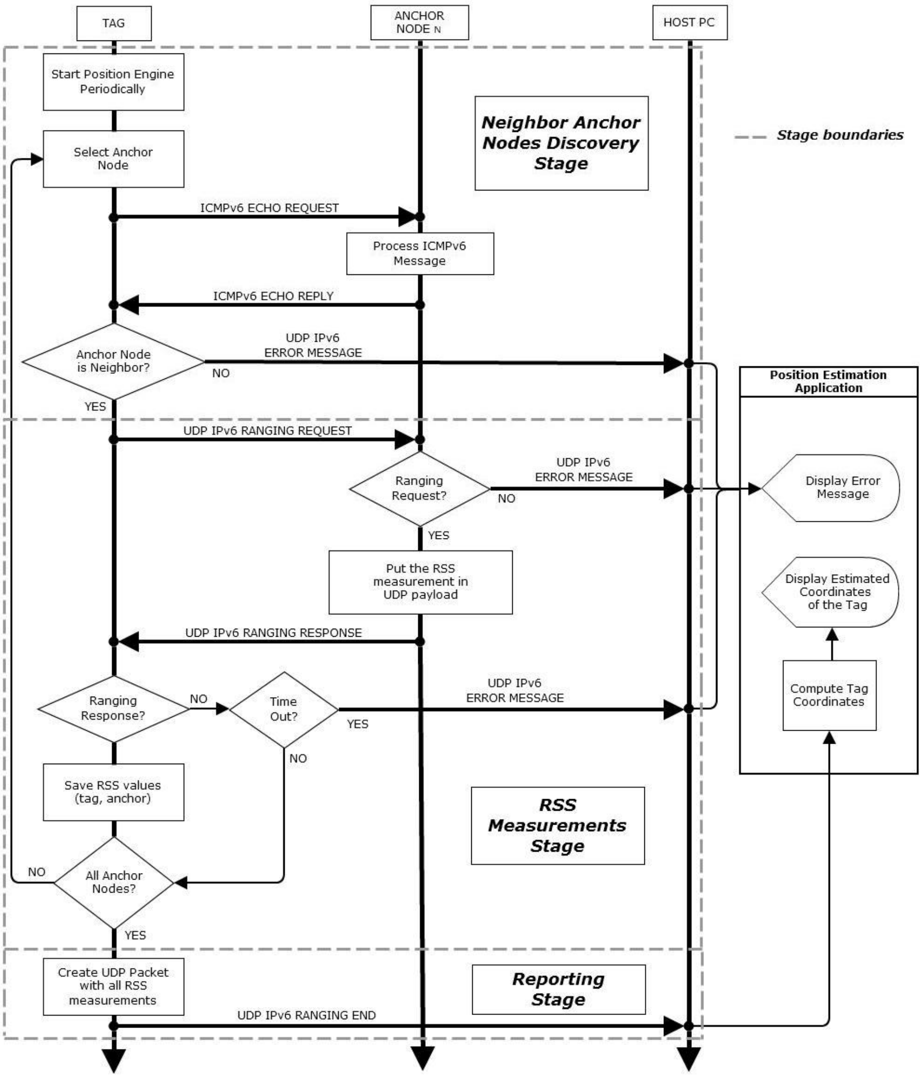


Figure 3.9 Position Estimation Engine

A key characteristic of the proposed engine is that the node, whose position needs to be estimated, is in charge of initiating the position estimation process. Endowing the targeted node with this functionality, instead of the reference nodes, helps in the minimization of the traffic throughout these reference nodes. Additionally, it simplifies the process and allows the total control of the process to the targeted node. As a result, the proposal considers an engine comprised by three different stages which must be executed sequentially.

The first stage should implement the discovery of the neighbor reference nodes via ICMPv6 messages. The key function of this phase must be the determination of the direct link between the targeted node and a given reference one. Therefore, as mentioned before, the targeted node should commence the communication by sending an ICMPv6 Echo Request datagram to a selected reference node and must wait for a response. Upon the reception of the ICMPv6 Reply message, the targeted node ought to verify that the source address of the received packet is contained on its neighbor table. This neighbor table is built as part of the implementation of the uIPv6 communication protocol stack. Hence, if the address matches any of the contents of this table, a direct link between the nodes should be considered. The achievement of this direct link is important to the positioning goal since all the measurements should be taken between two nodes without the intervention of a third party. A communication engagement of a third party might result in measurements that do not correspond to the values obtained without its intervention. Therefore, it might lead to hidden errors in the position estimation results. Once the direct link is verified, the position estimation engine can continue to the next phase. On the contrary, the engine should send an UDP IPv6 error message to the position application and the process should select a different reference node from a predetermined list. This must lead to the restarting of the first stage.

The second stage is the core of the proposed position estimation engine. During this phase, the RSS measurements should take place. A key characteristic on this stage is that the suggested design for the position estimation engine works as a double-sided measurement approach. Therefore, both, the targeted and the reference nodes RSS measurements ought to be performed on a single communication cycle. Thus, the first step during the RSS measurements stage should be the transmission of an UDP IPv6 packet from the targeted node to the selected reference one. This UDP datagram has to trigger an application in the reference node. This application is required to identify the payload of the received UDP datagram. Hence, if the payload content matches the ranging request message identifier, the application has to create a new UDP datagram. This new datagram must contain the RSS measured upon the reception of the requesting message. Afterwards a reply message should be sent back to the targeted node.

Once the reception of the raging request response is finished, the targeted node should parse the payload of the received UDP datagram. Subsequently, it has to perform a matching process of the payload content against the ranging response identifier. If the obtained result is positive, the reference node RSS measurement contained in the received message and the RSS measured by the targeted node at the reception of the response ought to be allocated in a memory space handled by the application running on the node. The last step of the second stage should implement the verification of the completeness of the ranging measurements. Therefore, the application is required to check if all the RSS measurements of an intended number of reference nodes have been completed. In case of a negative result, the engine must repeat the first and second stages while keeps storing the RSS measurements until it finishes. Otherwise, the proposed engine can continue to its last stage.

The last stage should report the resulting measurements to the centralized position estimation application running on the host PC. This must be accomplished by sending a new UDP IPv6 datagram. This datagram should contain, in its payload, the measured values as well as a string message identifier. After finishing the third stage, the position estimation engine must wait a predefined time before it can start running the whole process again. Additionally, the engine should be able to perform completely the first and second stages for a determined number of times before the values are reported to the position estimation application. In this case, the RSS values must be added among them and stored. When the cycle is finished, the reporting stage must be executed including an identifier of the number of iterations performed. This can help in the reduction of the communication traffic to the host PC if multiple measurement cycles among the targeted and the reference nodes are desired.

4 IMPLEMENTATION

Till this moment, several positioning systems for indoor environments were implemented for different applications as was reported on Chapter 2. The implementations of these positioning systems have been carried out by utilizing different wireless technologies aiming to accurately estimate the position of an asset in the network. Nevertheless, the accuracy by itself does not guarantee the efficiency and viability of a positioning system utilizing a wireless technology. Previous implementations have tried to satisfy the compromise between the designing goals and the challenges imposed by the application itself.

Though, as stated in Section 1.2.1, this thesis work focuses on realization of an indoor real time position tool addressing the problem of the positioning of manufacturing assets by utilizing a low-cost wireless technology with enhanced interoperability capabilities. Additionally, based on the information shown in Table 2.10, the most used radio technology in Industrial Automation, with usage of 49.10%, is the one compliant with the IEEE 802.15.4 standardization. This technology is widely used in the deployment of industrial WSN for different applications. The main reason for the widespread usage of this radio technology is that it operates in a license free frequency band. Furthermore, the hardware requirements of this technology result in cheaper solutions in comparison with the other ones.

Additionally, the interoperability has been a designing key in the past few years. The trends in WSNs in the industrial manufacturing aim towards the systems integration and the creation of a smart grid. This means the integration of smart embedded devices in the industrial networks able to achieve end-to-end communication and provide valuable information for the processes in real-time. As a result, the manufacturing techniques can be improved in order to overcome the challenges imposed by the current market. This interoperability can be achieved by endowing the WSN with IP capabilities. For this purpose, the implementation of the uIPv6 stack, discussed in Section 3.1, is required. This protocol stack runs on top of the open source Contiki OS. Therefore, the proposed position estimation engine detailed in the previous Chapter can be implemented in the wireless nodes in order to realize the position estimation tool.

The deployment of an IP-based WSN permits the development of a centralized position estimation tool that communicates with the wireless network via IP datagrams. Thus, no additional hardware is required towards the realization of the position estimation tool. Moreover, if it is required, the deployed WSN can join the Internet without extra communication efforts or gateways.

The remaining sections of this Chapter provide a brief description of the WSN platform used in the development of this thesis work. Subsequently, the applications developed on the IPv6 Wireless nodes are detailed followed by the explanation of the architecture of the deployed wireless sensor network. Afterward, the experimental implementation is discussed. Finally, the graphical user interface is briefly depicted in the last section.

4.1 WIRELESS SENSOR NETWORK PLATFORM

The real-time indoor position estimation tool in this thesis work is based on the RZRAVEN development kit for the AT86RF230 2.4 GHz radio transceiver compliant with the IEEE 802.15.4 standard and Atmel MCUs. This platform allows the development and debugging of a wide range of low-power IEEE 802.15.4, 6LoWPAN and ZigBee wireless network applications in a versatile and professional manner. In addition, the achievable WSN range from point-to-point communications through a dense populated sensor networks running complex communication stacks [Atmel AVR2002].

The wireless sensor network deployed with the RZRAVEN development kit is comprised by two main hardware components in the RZRAVEN development kit which are the RZUSBSTICK module and the AVRRAVEN module shown in Figure 4.1 and Figure 4.2 respectively. Additionally, both modules have MCUs that belong to the AVR family. This AVR MCUs can be programmed using the development tool JTAGICE mkII from Atmel Corporation®.

Figure 4.1 The RZUSBSTICK module [Atmel AVR2016]

Figure 4.2 The AVRRAVEN module [Atmel AVR2016]

Each module is intended for specific purposes and has different characteristics with respect each other. However, they have the AT86RF230 2.4 GHz radio transceiver as a common component in order to achieve the wireless communication.

WSNs deployed by using this platform can be comprised by at least one up to several RZUSBSTICK module and one or several AVRRAVEN modules.

4.1.1 The RZUSBSTICK module

The hardware of the RZUSBSTICK module is based on an AT90USB1287 8-bit microcontroller unit with 128 Kbytes of Read-Only Memory (ROM) and 8 Kbytes of RAM and an AT86RF230 radio transceiver chip. The MCU manages the USB interface, the radio transceiver and the radio frequency communication protocol stack. This

AT90USB1287 MCU belongs to the AVR MCU family and contains a low and full speed macro with the device, host and on-the-go capabilities [Atmel AVR2016]. The power supply for the module is provided via the USB interface. An overview of the RZUSBSTICK module is depicted in Figure 4.3.

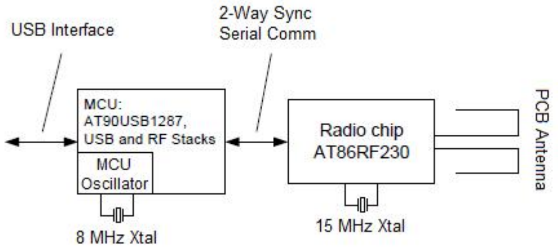


Figure 4.3 Overview of the RZUSBSTICK module [Atmel AVR2016]

The radio transceiver is low power consumption RF solution compliant with the IEEE 802.15.4 standard in 2.4 GHz ISM frequency band. It supports automatic acknowledge of packets, address filtering and automatic channel access and applications running on an enhanced layer of functionality on top of the basic radio transceiver layer. Moreover it can be tailored for a wide range of wireless applications. This makes it a viable choice for different types of networking devices. Additionally, the RZUSBSTICK has a miniature folded dipole antenna which net peak gain is 0 dB.

4.1.2 The AVRRAVEN module

The hardware of the AVRRAVEN module is based on two 8-bit MCUs belonging to the AVR picoPower family and an AT86RF230 radio transceiver as depicted in Figure 4.4. The first one is the ATmega3290P MCU with 32 Kbytes of ROM and 2 Kbytes of RAM. This MCU manages the in-built temperature sensor and the user interface (joystick, audio and LCD). The second one is the ATmega1284P MCU with 128 Kbytes of ROM and 16 Kbytes of RAN. This MCU handles the radio transceiver and the radio frequency communication protocol stack. The communication between both MCUs and the radio transceiver is performed through serial interfaces [Atmel AVR2016].

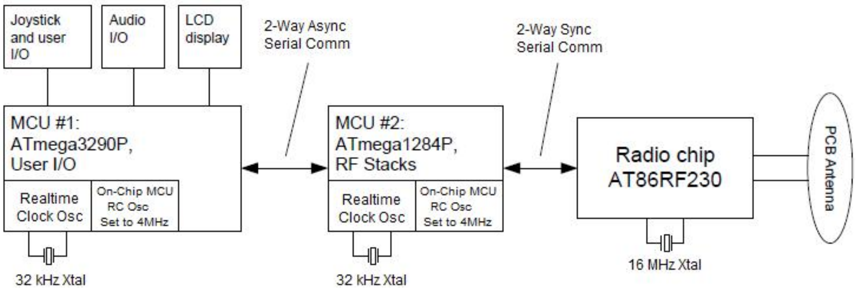


Figure 4.4 Overview of the AVRRAVEN module [Atmel AVR2016]

The radio transceiver is compliant with the IEEE 802.15.4 standard in 2.4 GHZ ISM frequency band. It is tailored for a wide range of applications running with a low power consumption profile. The radio transceiver works with 100 Ω loop antenna which has a net peak gain close to 5 dB.

Separate 32768 Hz clock crystals are connected to the asynchronous timer interfaces of MCUs as depicted in Figure 4.4. These crystals allow the implementation of real time clocks to manage the duration of the sleeping modes in order to enhance the power consumption efficiency. Additionally, the radio transceiver has a 16 MHz clock crystal connected that can be used as a real time clock for the system with a maximum resolution of 1 µs.

The module has an in-built Negative Temperature Coefficient (NTC) 100 kΩ thermistor that serves as temperature sensor. This sensor is connected to the Analog to Digital Converter (ADC) of the ATmega3290P MCU. Moreover the temperature lookup table can be modified in the firmware in order to perform corrections and calibrations.

Furthermore, the module has one 8 Ω speaker, one microphone and one LCD connected to the ATmega3290P MCU. These devices serve as user interface and can be used for debugging purposes that will help in the development phase. Additionally to the user interface devices the module has user inputs and outputs (I/O). These I/Os are: two relay coils, two analog inputs from 0-5 VDC and four digital I/Os.

The AVRRAVEN module can be powered by two 1.5 V LR44 battery cells or by an external power supply from 5 to 12 DC Volts. Therefore the power source can be selected via a jumper located in the front of the module close to the LCD.

4.2 IPV6 WIRELESS NODES APPLICATIONS

There are two types of IPv6 wireless sensors known as tag and anchor node respectively. The tag node refers to an IPv6 wireless node whose position is determined by using the real-time position estimation tool. The estimation process is executed according to the proposed engine described in Section 3.3. Furthermore, the estimation is executed by using a set of RSS measurements between the tag and the anchor nodes whose positions are well-known. Therefore, each type of node is intended for a specific purpose within the network in order to estimate the unknown position of the asset. Consequently, they run different applications contributing to the common goal. These applications depend on the role of the wireless node within the network.

4.2.1 Tag Node Applications

The tag node runs in parallel two main applications that contribute to the positioning goal. The first one is the heartbeat application and the second one is the RSS measurement application. Both applications run after the initialization of the tag. The flow chart diagram depicting these applications is illustrated in Figure 4.5.

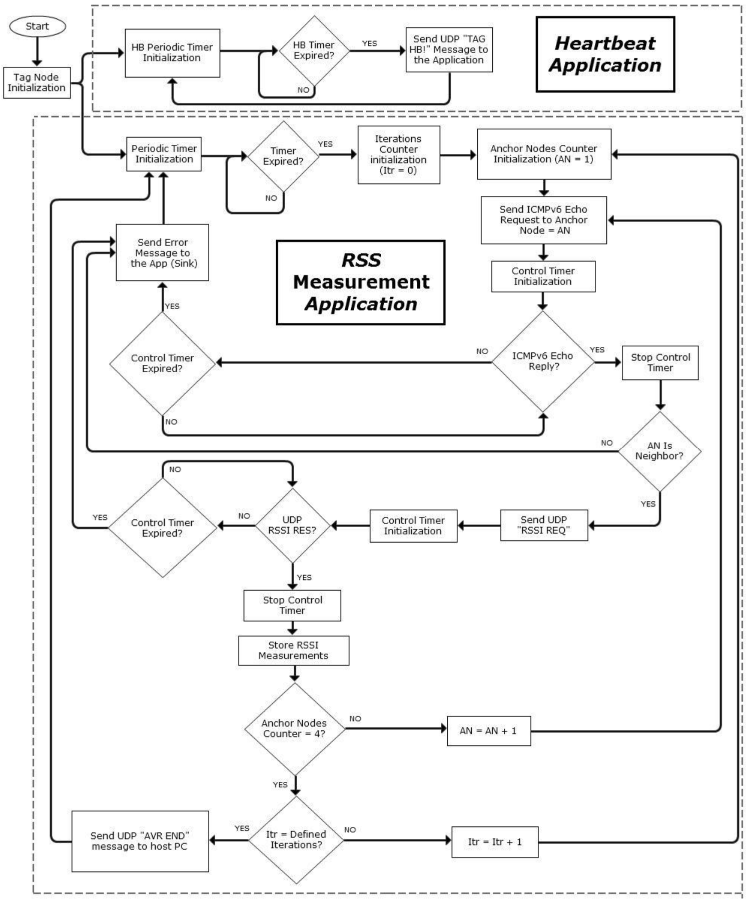


Figure 4.5 Flowchart diagram for the applications running on a tag node

The second application is the core of the position estimation tool. This application is in charge of triggering the RSS measurements needed to execute the position estimation algorithms. Subsequent to the initialization of the node, a periodic timer is set and initialized. Then the application remains waiting until the timer expiration. This timer triggers the discovery process of neighbor anchor nodes and initializes a counter up that keeps track of the accomplished measurement cycles. Therefore, the application selects a link local address from a table. This table contains the predefined addresses of the anchor nodes in ascending order. As a result, the tag node sends an ICMPv6 Echo Request message to the first anchor node and initializes a control timer. Thus, the application holds on until the reception of an ICMPv6 Echo Reply Message. In the case that the response is not received before the control timer expires, a timeout error is triggered. This timeout error is sent to the position estimation tool via an UDP IPv6 Message for informing purposes. Once the message is sent, the application resets the periodic timer initializing the application.

Upon the reception of the ICMPv6 Echo Reply message, the control timer is stopped. Moreover, the source address of the received data packet is matched against the addresses contained on the neighbors table of the node. The purpose of this verification is to ensure that there is a direct link connection between the tag and the intended anchor node. If the address does not match any of the contents of its neighbors table, the application produces an UDP IPv6 error message. This message informs the position estimation application that the anchor node is not reachable within a single hop distance. Therefore, the periodic timer is reset and the application starts over again. On the contrary, if the anchor node matches as a neighbor, the process continues. Hence, the RSS measurement stage is started.

The RSSI measurement stage involves the sending of the “RSSI REQ” message in an UDP datagram and the initialization of the control timer once more. Likewise the waiting process for the ICMPv6 Echo Reply message, the application waits for the UDP “RSSI RES” message. Therefore, if the control timer runs out the timeout error is sent to the position estimation application and the application goes back the periodic timer initialization step. Otherwise, the control timer is stopped and the information contained in the UDP “RSSI RES” is stored in a memory allocation handled by the application. Furthermore, the application checks if the RSS measurements from all the four anchor nodes have been recorded. If not, the index of the next anchor node is increased by one. Consequently, the ICMPv6 Echo Request is sent to the next anchor node and the process is repeated again from this point onwards.

Once the RSS measurement process is finished, the next step is to verify the completeness of the desired iterations. If the intended iterations have been executed, the application goes to the next stage, the reporting stage. Otherwise, the iteration index is increased by one. Besides, the index of the anchor node is set to one and the application repeats all over again starting from the selection of the anchor node onwards.

The reporting stage consists on sending the recorded RSS values to the position estimation application. Then, the “AVR END” UDP datagram is created containing the measurements. When the message is sent the entire cycle of the applications finishes and returns to the periodic timer initialization point. Thus, the process is repeated periodically. In addition, all the values of the used timers can be modified in the firmware if needed. Consequently, any change performed requires a new flashing of the wireless node.

4.2.2 Anchor Node Applications

Likewise the tag node, the anchor node runs in parallel two main applications. The first one is the heartbeat application. This application works in the same manner as in the tag node. It sends UPD IPv6 messages to the position estimation application periodically. After sending this heartbeat message, the application returns to the first step where the periodic timer is initialized. Moreover, this application is intended to serve as the target message for the discovery process of the anchor nodes running in the centralized position estimation application. The second application is the RSS measurement application. This application is the complement of the application with the same name run by the tag node. Both applications start running after the initialization of the anchor node as illustrated in the flowchart shown in Figure 4.6.

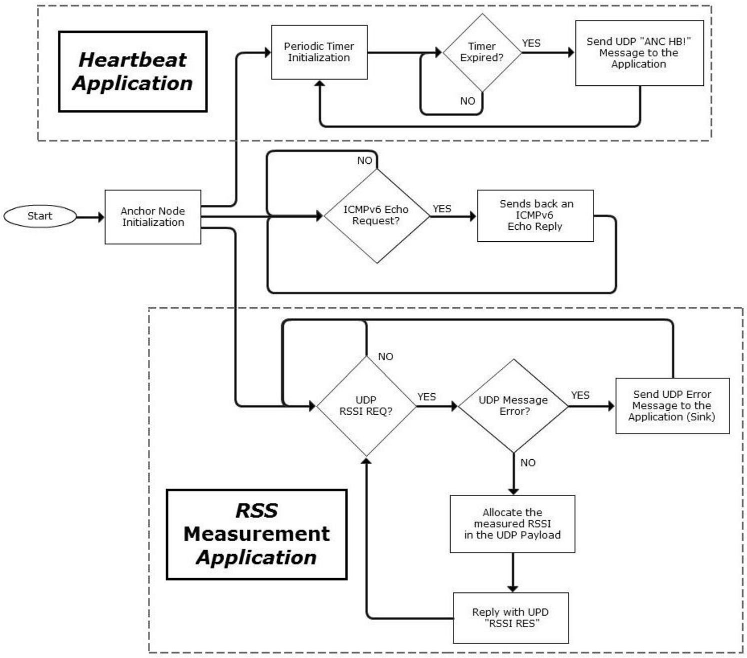


Figure 4.6 Flowchart diagram for the applications running on an anchor node

The RSS measurement application is in charge of replying the “RSSI REQ” messages sent by the anchor node. As a result, when one of these messages is received, the message is parsed and the content is verified searching for errors in the payload. These errors can be of different types, for instance, corruption on the message identifier or in the length of the payload. Hence, if an error is detected, a reporting UDP message is sent to the position estimation application identifying the cause of the error. Then, the anchor node stays waiting for the next “RSSI REQ” message before continuing the process. Otherwise, a new UDP IPv6 message is created. This message is the “RSSI RES” message that is sent back to the tag node that requested the measurement. Furthermore, this message contains the RSS value measured by the anchor node upon the reception of the requesting message. When the anchor node sends the message, the application waits for the next requesting message to repeat the process.

An additional functionality of the anchor node, besides the RSS measurement application, is required by the position estimation engine. This is the replying to the ICMPv6 Echo Request messages sent by a tag node. However, this functionality is accomplished by the uIPv6 protocol stack at the Network Layer. Therefore, no additional application is needed. Notwithstanding, this functionality is shown in Figure 4.6 for illustration purposes.

4.3 NETWORK ARCHITECTURE

The wireless sensor network deployed during the implementation of this thesis work is a fully connected ad-hoc wireless local area network. In addition, the routing mechanisms utilized are the route over mechanisms in a network with a maximum size of one hop distance. The basic network is comprised by at least seven elements which are: the host PC, 6LoWPAN adapter device and five IPv6 wireless nodes. Additionally, four out of five IPv6 wireless nodes work as reference nodes (anchor nodes) and the other one acts as the targeted node (the tag node). The basic network architecture is illustrated in Figure 4.7. The RZUSBSTICK module, presented in Section 4.1.1, is used as the 6LoWPAN adapter while the AVRRAVEN modules, described in Section 4.1.2, are used as the IPv6 wireless nodes.

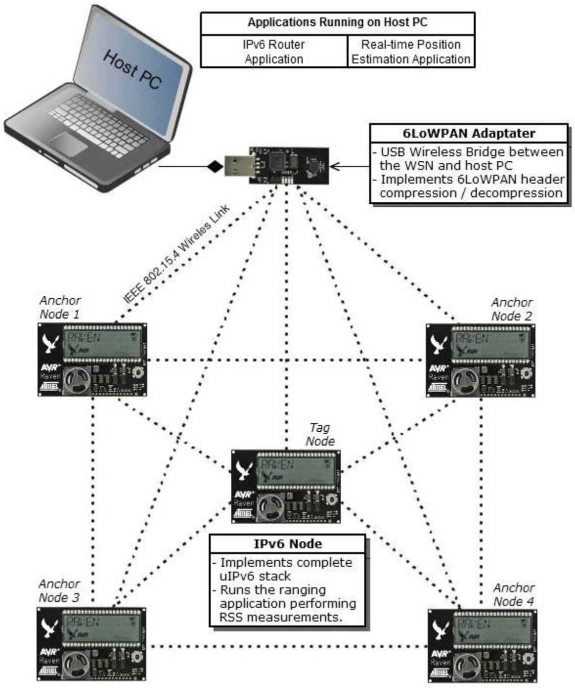


Figure 4.7 Wireless Network Architecture

The host PC plays a key role within the network. It hosts two applications: the real-time position estimation application and the Linux IPv6 Router Advertisement Daemon (radvd)[5]. The first one performs the position estimation algorithms by using the information received from a tag. Thus, the information is processed in order to estimate the position of the tag. The second application run in the host PC is in charge of managing the bootstrap of the network. Therefore, the radvd application sends Router Advertisement (RA) messages which are specified in RFC 4861 [Narten et. al. 2007]. These messages are transmitted either periodically to the entire wireless network or upon the reception of a Router Solicitation (RS) message from a wireless node.

The RA messages contain information regarding the type of router being used, the hop limit in the network, the MTU of the IPv6 packets, the prefix of the network, the lifetime and periodicity of the messages, among others. This information is needed in order to perform the IPv6 stateless address auto configuration process.

After initialize, the IPv6 wireless node sends RS message to the network. When it receives the RA message, the information contained in the message is used to configure

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[5] http://www.litech.org/radvd/

its address. This is done by merging the received prefix with its MAC address. Therefore it performs DAD process in order to verify if the address is not being used by another node within the network. Once the address has been resolved without conflict, the node can join the network and starts building its neighbor and routing table up. This process is performed by all the nodes joining the network. The given addresses of the devices involved in the deployed WSN, where the prefix "aaaa::" was used, are shown in Table 4.1.

Table 4.1 Addressing exemplification of the deployed ad-hoc Wireless Sensor Network

Wireless Node	MAC Address	Link Local IPv6 Address	Global IPv6 Address
6LoWPAN Adapter	02:12:13:FF:FE:14:15:16	FE80::12:13FF:FE14:1516	aaaa::1
Anchor Node 1	02:11:22:FF:FE:33:44:55	FE80::11:22FF:FE33:4455	aaaa::11:22FF:FE33:4455
Anchor Node 2	02:11:22:FF:FE:33:44:66	FE80::11:22FF:FE33:4466	aaaa::11:22FF:FE33:4466
Anchor Node 3	02:11:22:FF:FE:33:44:77	FE80::11:22FF:FE33:4477	aaaa::11:22FF:FE33:4477
Anchor Node 4	02:11:22:FF:FE:33:44:88	FE80::11:22FF:FE33:4488	aaaa::11:22FF:FE33:4488
Tag Node	02:11:22:FF:FE:33:55:86	FE80::11:22FF:FE33:5586	aaaa::11:22FF:FE33:5586

In addition, the IPv6 wireless nodes are endowed with IPv6 functionalities. These nodes implement the complete uIPv6 stack described in Section 3.1. Therefore, they run the applications needed to implement the position estimation tool depending on its role within the network (i.e. tag or anchor node). In order to execute the real-time position estimation tool there must be present four anchor nodes and at least one tag node.

However, unlike the radvd application, the communication within the wireless network utilizes the 6LoWPAN communication protocol. For this reason, the 6LoWPAN is needed between the WSN and the host PC. Thus, it acts as a bridge between the 6LoWPAN network and a fully IPv6 application. The main function of the 6LoWPAN adapter is to implement the adaptation layer between the Data Link Layer and the Network Layer. Consequently, this adapter is in charge of the compression / decompression of the IPv6 packets transmitted over IEEE 802.15.4 frames. Likewise, the communication between the host PC and the adapter is achieved via the serial interface.

4.4 EXPERIMENTAL IMPLEMENTATION

The main purpose of the experimental phase in this master thesis is to proof the concept of position estimation of manufacturing assets using a wireless technology. For these reason, the position estimation engine presented in Section 3.3 has been implemented in the selected wireless sensor platform. Furthermore, in order to accomplish the execution of this engine, the aforementioned applications (Section 4.2) have been implemented on the IPv6 wireless nodes and along with a centralized position estimation application running on the host PC. All the communications and wireless applications are accomplished by using the tailored uIPv6 stack which implements the 6LoWPAN communication protocol. The uIPv6 stack is customized according to the discussion presented in Section 3.1. Additionally, the testing process is executed on a Flexlink Dynamic Assembly System (DAS) located inside of an office building. Furthermore, for experimental purposes, the application running on this system is the circulation of pallets around the line. These pallets carry the tag nodes which serve as the manufacturing assets. Therefore, their positions must be estimated by the position estimation tool. This tool implements the proposed algorithms described in Section 3.2 to estimate the position of the manufacturing asset. Thus, the experimental process is carried out in two different stages sequentially, the offline and run-time stage respectively.

4.4.1 Test bed

The Flexlink DAS modular system that can be used for industrial appliances, for instance, light assembly processes, inspection, testing and repairing operations, packing solutions, among others. Additionally, different standard modules can be integrated into the Flexlink DAS (e.g. workstations, robot cells, conveyors, buffers and lifters) in order to expand its capabilities. The Flexlink DAS, used in the experimentation phase, is a two layered system comprised by three sections: start, middle and end sections, respectively. At the same time, each section is formed by modules. The start section consists of four modules. These modules are: the start lifter, main line conveyor segment, one work station and one robot cell. Similarly, the second section is comprised by four modules: the middle lifter, two work stations and one main line conveyor segment. Finally, the end section is formed by three modules. These modules are: the end lifter, one workstation and one main line conveyor segment. An illustration of Flexlink DAS is presented in Figure 4.8.

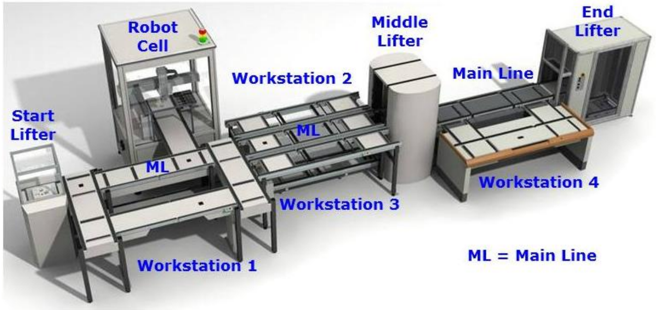
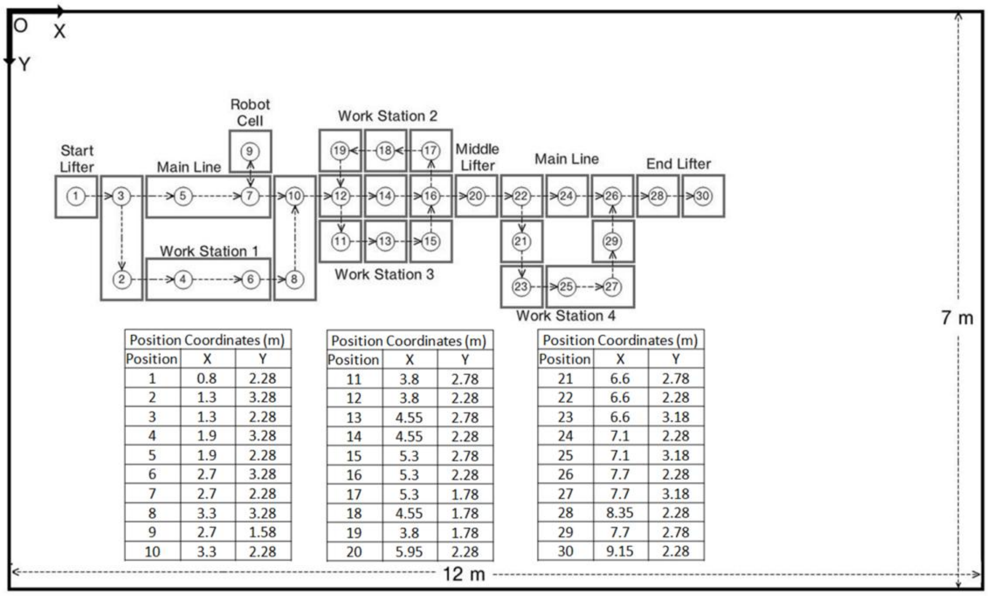


Figure 4.8 Flexlink Dynamic Assembly System

As previously mentioned, the light assembly system is located in an indoor environment. The corresponding environment is the room L209 situated on the first floor of the Rakennustalo building at the Tampere University of Technology. The dimensions of this space are twelve meters long and seven meters wide. Besides the assembly line in the room, there are office desks, bookshelves, lightning equipment, and ventilation and water pipes. Furthermore, the experiment is performed on the top of the assembly line. As a result, the returning path of the pallets throughout the lower level of the line is not considered. Additionally, it is considered that the upper level of the line can allocate the pallets in thirty different positions all over the line. Each position is identified by a number and its two-dimensional coordinates. The testing room dimensions along with the Flexlink upper layer positions, where a pallet can be allocated, and their coordinates are shown in Figure 4.9.



Position Coordinates (m)		
Position	X	Y
1	0.8	2.28
2	1.3	3.28
3	1.3	2.28
4	1.9	3.28
5	1.9	2.28
6	2.7	3.28
7	2.7	2.28
8	3.3	3.28
9	2.7	1.58
10	3.3	2.28

Position Coordinates (m)		
Position	X	Y
11	3.8	2.78
12	3.8	2.28
13	4.55	2.78
14	4.55	2.28
15	5.3	2.78
16	5.3	2.28
17	5.3	1.78
18	4.55	1.78
19	3.8	1.78
20	5.95	2.28

Position Coordinates (m)		
Position	X	Y
21	6.6	2.78
22	6.6	2.28
23	6.6	3.18
24	7.1	2.28
25	7.1	3.18
26	7.7	2.28
27	7.7	3.18
28	8.35	2.28
29	7.7	2.78
30	9.15	2.28

Figure 4.9 Testing room dimensions and Flexlink DAS upper layer positions coordinates

The implementation of the position estimation tool considers a totally automated pallet transfer process. Besides, no human intervention is considered in the manufacturing process.

4.4.2 Experimental Set Up

The testing process of the implemented real-time position estimation tool for pallets running on top of the Flexlink DAS requires four anchor nodes. These anchor nodes must be positioned at fixed well-known locations. Furthermore, the orientation of these anchor nodes must not vary during the entire experiment. Besides, the position of the anchor nodes should have a height around two meters and must be at least half a meter separated from the walls and corners of the room. These requirements aim to help in the improvement of the indoor signal propagation phenomenon while attempting to decrease the multipath effect. Therefore, the height of the anchor nodes has been fixed at 2.10 meters while their locations and orientations inside the room are illustrated at Figure 4.10.

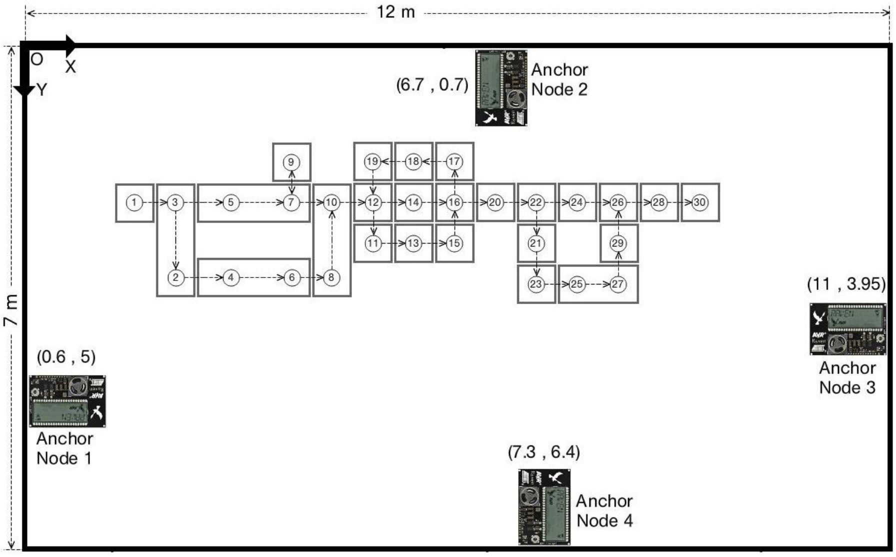


Figure 4.10 Anchor nodes distribution

The manufacturing asset to be positioned is comprised by a pallet equipped with an IPv6 wireless node used as tag. This node is located centered on top of the pallet. In addition, the orientation of the node is aligned with the axial axis of the main line from the start segment towards the end segment. The location and position of the tag node on the pallet are shown in Figure 4.11.

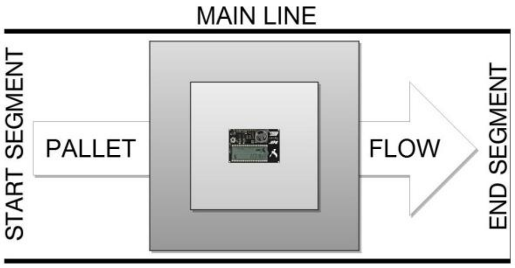


Figure 4.11 Tag location and orientation on the pallet

All the IPv6 wireless nodes are powered by two AA alkaline batteries of 1.5 volts each connected to the external power supply pins of the AVRRAVEN modules.

4.4.3 Off-line Stage

The first phase to be accomplished during the experimental process is the offline stage. The tasks to be performed during this stage depend on the used position estimation algorithm. Therefore two different processes are executed. The first one aims at the determination of the signal propagation models used by the lateration methodology. Likewise, the second one attempts to build-up the required databases for the fingerprinting methodology.

In order to establish the relationship between the distance traveled by the RF signal and the RSS value measured between two wireless nodes, a set of samples is recorded at different distances between them. One of the nodes must remain still while the other one should be moved along a straight line in steps of half a meter each. The measurements are performed along the longest dimension of the room. Moreover, the size of the recorded data at each point is 100 samples with a sampling frequency of eight milliseconds per sample. Afterwards, the complete recorded data should serve as input data to the curve fitting model for both cases, the ITU model for indoor environments and the path-loss model, described in Section 3.2.1. The curve fitting tool used during this thesis work is implemented in MATLAB. The resulting parameters of both models are introduced to the position estimation application via a comma separated values file for their further utilization during the run-time stage.

Regarding the offline process for the fingerprinting methodology, a set of 100 samples are recorded from each of the upper layer positions of Flexilink DAS. As a result, the recorded information is processed by the application in order to construct the required databases. Thus, two data bases are built-up utilizing the computed average and mode values at each position respectively. Both databases are generated according to the discussion presented in Section 3.2.2. The resulting values are stored in a memory allocation managed by the position estimation application and in a comma separated values file for further utilization during the run-time stage.

4.4.4 Run-time Stage

The second part of the experimental process is the run-time stage. During this stage, the estimation of the position of the asset is performed. This estimation is done by using the selected methodology, either lateration or fingerprinting algorithm. In addition, for each algorithm, there are two different options. Therefore, four tests are performed during the experimental process in order to evaluate the position estimation tool. This evaluation is based on the tests listed before:

- Lateration Methodology:
    - ITU Model for indoor environments.
    - Path-loss Model.
- Fingerprinting Methodology:
    - Average values database.
    - Mode values database.

In addition, the evaluation parameter used to measure the performance of the tool is the acquired accuracy. In the case of the lateration methodology, this accuracy is computed based on the Euclidean distance between the actual and the estimated position of the tag. Unlike the lateration methodology, the fingerprinting algorithm position estimation is performed in a discrete manner. Therefore, the set of possible results is equal to the length of the fingerprinting databases. As a result, the accuracy of the system is based on the number of times that the tool estimates the actual position of the pallet allocated on any of the possible solutions correctly.

In order to implement the run-time stage, besides the parameters of the models and the databases, additional data is needed. This information is comprised by the coordinates of the anchor nodes. These coordinates can be introduced to the application either manually (on-the-flight) or via a comma separated values file during the initialization of the application.

4.5 GRAPHICAL USER INTERFACE

The graphical user interface (GUI) designed to interact with the real-time position estimation tool via UDP IPv6 datagrams is developed in Java programming language. This interface opens a UPD socket on port 61630 to receive the datagrams sent by the IPv6 wireless nodes. Afterwards, the information received in the payload of the data packets is parsed and processed in order to execute the position estimation of manufacturing assets.

The position estimation application generates two separate tables corresponding for the anchor nodes and the tag nodes respectively. After the initialization of the tool, these tables are empty. However, they are filled during the discovery process.

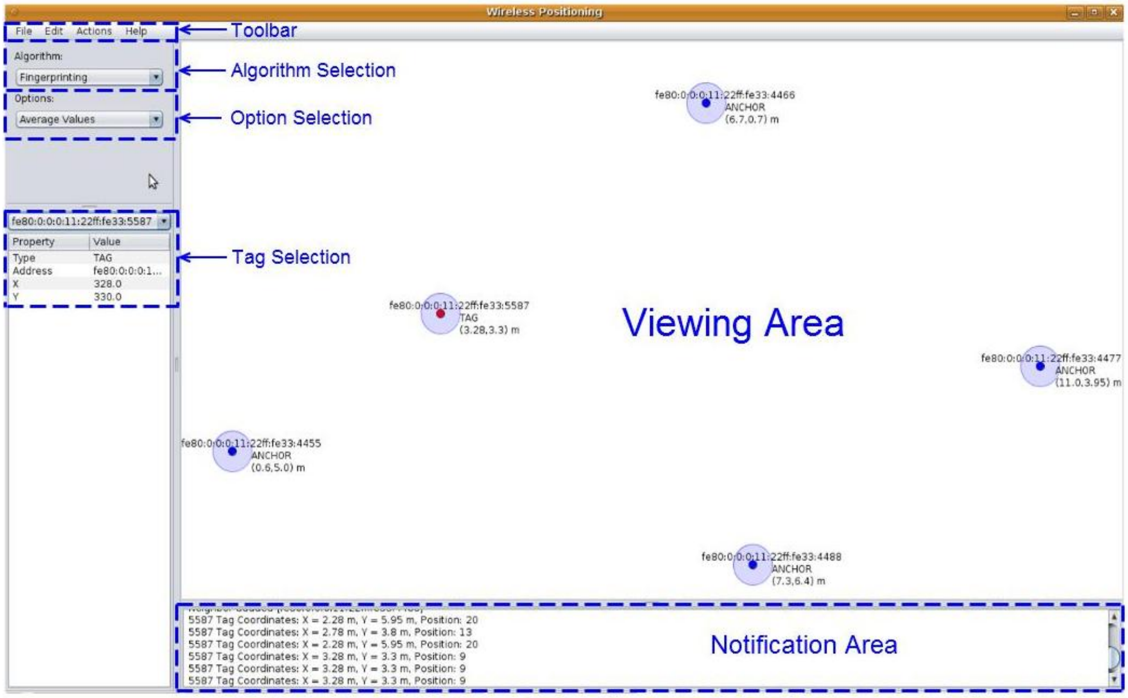
During its initialization phase, the position estimation tool reads different Comma Separated Values (CSV) files. The first two CSV corresponds to the Average and Mode Values Databases used in the position estimation process utilizing the Fingerprinting Methodology, respectively. After reading and loading the fingerprinting databases, the tool reads two more CSV files. These files contain the parameter values for both models used with the position estimation based on the Lateration Methodology. Therefore, the CSV containing the ITU model parameters is read. Subsequently the Path-loss model parameters are load into the tool.

Once the four files are loaded into the tool, it requests for the number of anchor nodes involved in the position estimation engine. Furthermore, the tool inquires about the method for feeding in the anchor nodes coordinates. Thus, two different manners are available, manual and automatic. The manual way requires that the user provides the X and Y coordinates for each anchor node via an input device. Otherwise, the automatic mode triggers the reading process of the anchor nodes coordinates from a CSV file. This implementation considers fixed addresses for the anchor nodes in an ascending numbering whose penultimate byte is equal to “44”. Therefore, each anchor node has fixed position associated to it which is retrieved from the information acquired during the initialization process. Once this process finishes, the initialization process is completed. Thus, the tool is ready to start the position estimation process starting by the discovery of the anchor and tag nodes comprising in the network.

The discovery process is done by receiving UDP packets from the wireless nodes. In the case of the anchor nodes, these packets are usually the periodical heart beat messages sent from each anchor node to the centralized application. Whereas in the case of the tag nodes, the packets correspond to the reporting messages containing the RSS measurements. Therefore, the application verifies if the source address of the datagram corresponds to an anchor or a tag node. In order to identify the different types of wireless nodes the tool matches the penultimate byte of the address. If this byte is equal to “44” the node is the type of an anchor node. Otherwise the node is a tag.

The nodes discovered by the tool are stored along with their properties such as address, coordinates and RSS measured values. These properties can be retrieved by the tool for further processing and computations in order to estimate the position of the tag nodes. Before performing the position estimation process, the number of the discovered anchor nodes must be equal to the number of anchor nodes declared during the initialization of the tool. Once this quote is accomplished the position estimation process can take place. Furthermore, the tool uses the values contained in the map tables to create a graphical representation of the wireless nodes and their positions displayed in the GUI.

The GUI has six main components which are the toolbar, the algorithm selection combo box, the option selection combo box, the tag selection combo box, the notification area and the viewing area. An illustration of the mentioned GUI is shown in Figure 4.12.



Algorithm: Fingerprinting

Options: Average Values

fe80:0:0:0:11:22ff:fe33:5587

Property	Value
Type	TAG
Address	fe80:0:0:0:1...
X	328.0
Y	330.0

```
5587 Tag Coordinates: X = 2.28 m, Y = 5.95 m, Position: 20
5587 Tag Coordinates: X = 2.78 m, Y = 3.8 m, Position: 13
5587 Tag Coordinates: X = 2.28 m, Y = 5.95 m, Position: 20
5587 Tag Coordinates: X = 3.28 m, Y = 3.3 m, Position: 9
5587 Tag Coordinates: X = 3.28 m, Y = 3.3 m, Position: 9
5587 Tag Coordinates: X = 3.28 m, Y = 3.3 m, Position: 9
```

Figure 4.12 Graphical User Interface

Within the toolbar options, the most important functionalities are the one related with the action and help button. The action button allows the creation of the databases required to implement the fingerprinting algorithm. Additionally, it offers an option to save the recorded data into a comma separated values (CSV) file in a matrix form. This function is useful for the offline process of the lateration algorithm implementation. The CSV format is compatible with MATLAB software facilitating the curve fitting process. On the other hand, the help button displays a webpage containing relevant information about the tool.

The next two components are the algorithm selection and the option selection combo boxes. The algorithm selection, as its name suggests, allows the selection of the desired position estimation algorithm. This choice can be made between the fingerprinting and the lateration. Besides, depending on the choice selected, it enables the available alternatives in the option selection combo box. Therefore, the option selection offers four alternatives: Average Values, Mode Values, Path-loss model and ITU Model. The first two options are enabled where the fingerprinting algorithm is selected in the algorithm selection option whereas the last pair is enabled upon the selection of the lateration algorithm as the position estimation methodology.

The notification area displays messages intended to inform the user about the events occurred in the tool. These events can be, for instance, the addition of an anchor or tag node to the network, the completeness of an estimation position cycle, the reception of error messages, among others.

The viewing area is meant to show the graphical representation of the position of the wireless nodes inside the room. In this area, the nodes are represented as two concentric circles of a given color depending on the type, either tag or anchor node. Additionally, the address of each node, its type and its coordinates are shown next to the node representation. The information is updated upon the reception and processing of the UDP datagrams.

Finally, the tag selection combo box allows the selection of a given anchor node that has been discovered by the tool. Upon the selection of a tag, its properties, stored in the memory map table, are displayed.

5 RESULTS

The results of the performance tests implemented during the experimental phase of this thesis work to the real-time position estimation tool are detailed along this chapter. Additionally, the propagation models and databases obtained during the testing process are exposed.

The remaining of this Chapter presents the experimental results for the position estimation based on Lateration methodology. On the other hand, the final section discusses the position estimation results obtained by utilizing the Fingerprinting Methodology.

5.1 POSITION ESTIMATION BASED ON LATERATION METHODOLOGY

The position estimation of an asset based on lateration methodology is achieved by utilizing the estimated distance between a pair of IPv6 wireless nodes. This distance estimation is obtained via signal propagation models. For this purpose, two different propagation models have been implemented. The first one is the path-loss model whereas the second one is the ITU model for indoor environments. Furthermore, both models have been determined during the offline process by measuring the RSS between two nodes along a straight line at different distances. These samples have been taken from one to ten meters of separation using one meter steps between sampling positions. Additionally, the size of the recorded samples at each position is five hundred measurements. Besides, the orientation of the tag node with respect to the anchor node is changed at each sampling position. Therefore, three different orientations have been considered 0, 90 and 180 degrees. The different antenna orientations used to perform the measurements are illustrated on Figure 5.1. The model used for each pair of nodes depends on the orientation of their antennas. Moreover, as previously stated, the antenna orientation of the tag does not change along the test; neither does the antenna of the anchor node.

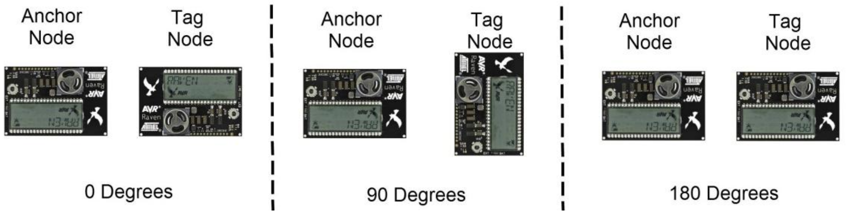


Figure 5.1 Anchor Node - Tag Antenna Orientation

The sampled data is processed in MATLAB in order to perform the curve fitting process to obtain the parameters of the different model approximations.

5.1.1 Path-loss Model Results

The recorded data during the offline stage is processed in MATLAB in order to approximate the curve depicted by Equation (6) in Section 2.3.2. Therefore three different approximations of the model are obtained. Each approximation corresponds to the different antenna orientation. The resulting approximation parameters for the path-loss model are presented in Table 5.1.

Table 5.1 Path-loss Model approximation parameters

Model Parameter	0 Degrees	90 Degrees	180 Degrees
A	-45.22	-45.22	-45.22
n	1.81	2.34	1.51
$X\sigma$	90.15	89.31	95.43

The parameters obtained via curve fitting utilizing least square approximation method are fed into the real-time position estimation tool. These parameters are used by the tool during the run-time stage in order to estimate the position of the asset.

In order to evaluate the performance of the position estimation tool, an evaluation test was run over the Flexlink DAS line. The pallet was allocated at each position and five hundred samples were recorded. Therefore, the tool was run in order to estimate the position of the asset for each sample. The resulting estimation coordinates were compared against the coordinates of the actual position via the Euclidean distance. The minimum position estimation errors at each position are illustrated in Figure 2.1.

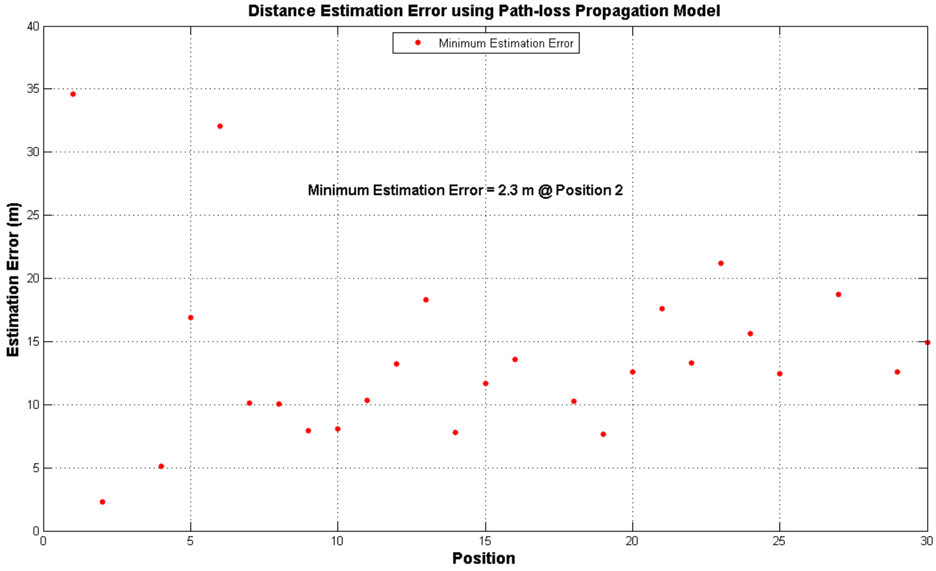


Figure 5.2 Distance estimation error using Path-loss propagation model

As it can be noticed from Figure 5.2, the best case accuracy achieved during the experiment occurs at position two. At this position, the distance estimation error is 2.3 meters. This is achieved when the path-loss propagation model is used to estimate the distance between nodes along with the lateration methodology.

Additionally, Table 5.2 presents the summarized information regarding the frequency of occurrence of a distance estimation error within a certain interval.

Moreover, these intervals start at the best case accuracy up to ten meters for each position with a step change of one meter among them.

Table 5.2 Position Estimation Error < 10 m using the Path-loss Model

Position	Distance Estimation Error							
	< 3 m	< 4 m	< 5 m	< 6 m	< 7 m	< 8 m	< 9 m	< 10 m
1	-	-	-	-	-	-	-	-
2	58%	99%	100%	100%	100%	100%	100%	100%
3	-	-	-	-	-	-	-	-
4	-	-	-	100%	100%	100%	100%	100%
5 -8	-	-	-	-	-	-	-	-
9	-	-	-	-	-	-	12%	47%
10	-	-	-	-	-	-	66%	100%
11 - 13	-	-	-	-	-	-	-	-
14	-	-	-	-	-	92%	99%	100%
15 - 18	-	-	-	-	-	-	-	-
19	-	-	-	-	-	-	32%	88%
20 - 30	-	-	-	-	-	-	-	-

The best overall accuracies observed range from a couple of meters up to tens of meters. Furthermore, only six positions, out of thirty, present accuracies less than ten meters. In addition, not all the positions were estimated within the coverage range about 30 meters. The position estimation errors less than 10, 20 and 30 meters all over the testing area are summarized in Table 5.3.

Table 5.3 Position Estimation Error < 10, 20 and 30 m using the Path-loss Model

Position	Dist. Est. Error			Position	Dist. Est. Error		
	< 15 m	< 20 m	< 30 m		< 15 m	< 20 m	< 30 m
1	-	-	-	18 - 20	100%	100%	100%
2	100%	100%	100%	21	-	43%	100%
3	-	-	-	22	100%	100%	100%
4	100%	100%	100%	23	-	-	86%
5	-	16%	100%	24		100%	100%
6	-	-	-	25	100%	100%	100%
7 - 12	100%	100%	100%	26	-	-	-
13	-	33%	100%	27	-	30%	100%
14 - 15	100%	100%	100%	28	-	-	-
16	69%	100%	100%	29	0.20%	99%	100%
17	-	-	-	30	26%	100%	100%

The best results obtained during the test occurred at position two where the accuracies less than 3 meters were achieved in the 58% of the sampled values. Moreover, accuracies within 4 m were achieved in the 99% of the cases. However, this behavior is not shown in all the positions. The estimation results vary strongly from one position to another resulting most of the time in distances greater than the dimensions of the testing room. Furthermore, those positions showing accuracies within the 10 m error range have a common characteristic. In these positions, the line of sight between the tag and the anchor nodes is achieved.

5.1.2 ITU Model Results

The ITU model for indoor environments is expressed in Equation (7) presented in Section 2.3.2. The sampling data collected during the offline stage served to perform the curve fitting process. This process allows obtaining the model parameters for the evaluation scenario. Furthermore, the model approximation process is executed for each one of the different antenna orientations. The obtained approximation parameters for the ITU model are presented in Table 5.4.

Table 5.4 ITU Model approximation parameters

Model Parameter	0 Degrees	90 Degrees	180 Degrees
f (MHz)	2450	2450	2450
N	24.60	28.81	28.24

Likewise for the path-loss model, the parameters resulting from the approximation process for the ITU model are fed into the position estimation tool. This information is used for further calculations during the run-time stage in order to estimate the position of the asset. Furthermore, the data recorded for the experiment presented in the previous section is also used to perform the evaluation of the tool using the ITU propagation model. Therefore, the utilization of the same information allows having a common ground in order to compare the performance of both approaches.

The results of the performance test using the ITU model are shown in Figure 2.1, where the minimum Euclidean distance computed for each position is illustrated. This Euclidean distance is the measure for the position estimation error which is computed using the estimated and the actual position of the asset.

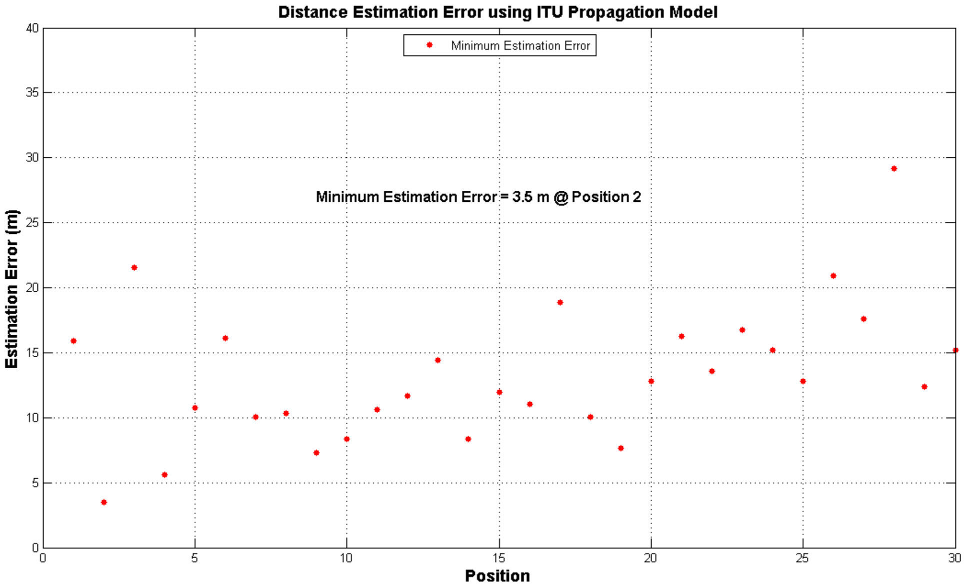


Figure 5.3 Distance estimation error using ITU propagation model

Moreover, Table 5.5 presents the summarized information regarding the position estimation error occurring within a range of ten meters. This range starts at the best case accuracy observed during the test all over the testing area with interval steps of one meter.

Table 5.5 Position Estimation Error < 10 m using the ITU Model

Position	Distance Estimation Error							
	< 3 m	< 4 m	< 5 m	< 6 m	< 7 m	< 8 m	< 9 m	< 10 m
1	-	-	-	-	-	-	-	-
2	-	22%	95%	100%	100%	100%	100%	100%
3	-	-	-	-	-	-	-	-
4	-	-	-	37%	100%	100%	100%	100%
5 - 8	-	-	-	-	-	-	-	-
9	-	-	-	-	-	18%	93%	100%
10	-	-	-	-	-	-	46%	100%
11 - 13	-	-	-	-	-	-	-	-
14	-	-	-	-	-	-	93%	100%
15 - 18	-	-	-	-	-	-	-	-
19	-	-	-	-	-	29%	100%	100%
20 - 30	-	-	-	-	-	-	-	-

During the performance test the ITU model was able to estimate the position of the asset within a range of 30 m at least once. This can be noticed from Table 5.6, where the position estimation errors less than 10, 20 and 30 meters all over the testing area are summarized.

Table 5.6 Position Estimation Error < 10, 20 and 30 m using ITU Model

Position	Pos. Est. Error			Position	Pos. Est. Error		
	< 15 m	< 20 m	< 30 m		< 15 m	< 20 m	< 30 m
1	-	75%	100%	18 - 20	100%	100%	100%
2	100%	100%	100%	21	0%	100%	100%
3	-	-	100%	22	100%	100%	100%
4 – 5	100%	100%	100%	23	0%	93%	100%
6	-	90%	100%	24	0%	100%	100%
7	100%	100%	100%	25	100%	100%	100%
8	99%	99%	99%	26	-	-	100%
9 - 11	100%	100%	100%	27	-	101%	101%
12	99%	99%	99%	28	-	-	0%
13	33%	101%	101%	29	64%	100%	100%
14 - 16	100%	100%	100%	30	-	100%	100%
17	-	3%	99%				

The ITU model approach presents its best case accuracy of 3.51 meters at position two performing poorer than the path-loss model. Furthermore, only this position shows accuracy less than five meters whereas six out of thirty positions show accuracies less than ten meters. Conversely, the ITU model behaves in a steadier manner than the path-loss model by positioning the asset within 30 meters at least once. In addition, likewise to the path-loss model, the influence of the line of sight among the nodes influences the accuracy results. Those positions that achieve the line of sight between the IPv6 wireless nodes result in the positions that show better accuracies.

5.2 POSITION ESTIMATION BASED ON FINGERPRINTING METHODOLOGY

The position estimation of an asset based on the fingerprinting methodology involves the creation of a database during the offline process. This database contains the RSS values of each position of interest within the coverage area. Hence, during this thesis work, the required database is built by recording and processing five hundred RSS samples at each position over the Flexlink DAS line. In addition, the sampling data is used to construct two different databases. Therefore, one is created by calculating the average values of the sampling data on each position whereas the other one uses their mode values. These databases serve to perform the evaluation test of the position estimation tool on the run-time stage.

5.2.1 Fingerprinting using Average Values Database

The position estimation engine works as a double-sided measurement system. Therefore, on a single cycle both RSS values are measured (i.e. on the tag side and on the anchor node side). This characteristic of the engine allows the creation of a database containing eight measurements for each position. Furthermore, the measurements are arranged in pairs of columns on the same row according to the anchor node involved in the measurement process. Hence, the first column pair corresponds to the measurements between the tag and the first anchor node and continuing in a subsequent manner. As a result, the building process of the database can be split into two parts. The first one corresponds to measurements packets received by the tag from each anchor node whereas the second part corresponds to the measurement in the opposite direction. The values stored in the database corresponding to its first part are plotted in Figure 5.4 while the values corresponding to the second part are shown in Figure 5.5. Additionally, the database contains as many rows as positions of interest exist.

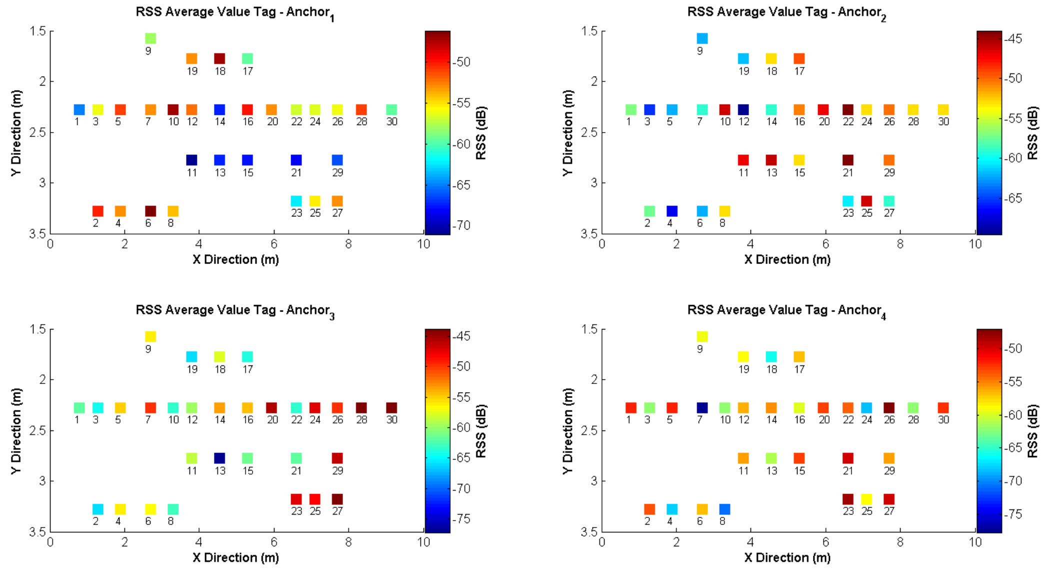


Figure 5.4 Tag – Anchor Node$_N$ RSS Average Database Values

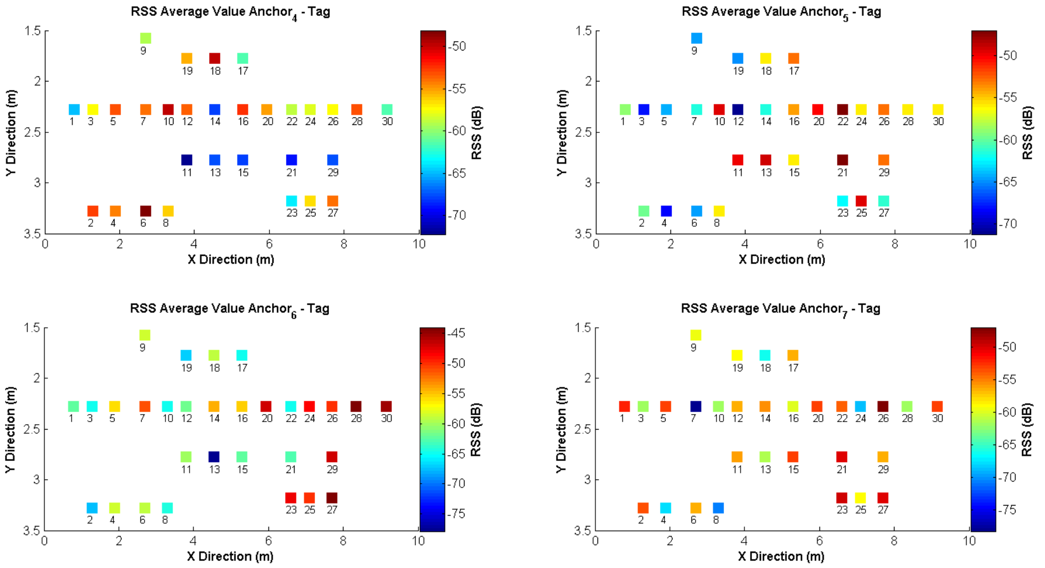


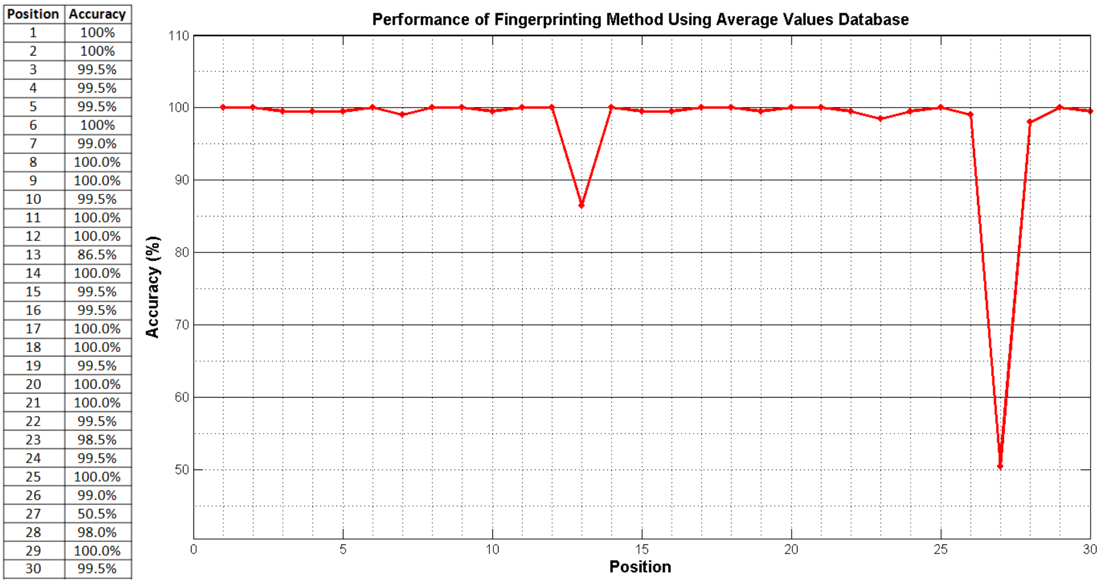
Figure 5.5 Anchor Node$_N$ – Tag RSS Average Database Values

From the information illustrated in Figure 5.4 and Figure 5.5, it can be noticed that it is difficult to distinguish clearly between some positions with similar RSS values by using only a single pair of nodes. Hence, by increasing the number of anchor nodes involved in the measurements it is possible to increase the ability to discriminate among different positions with similar RSS values. This characteristic is exploited by the fingerprinting methodology in order to estimate the position of the asset in a proper manner.

Once the database is created, the performance test is completed using the position estimation tool to estimate the position of a pallet on the assembly line. For that reason, the pallet is allocated all over the predefined positions on Flexlink DAS. Then, at each position, 200 samples are recorded and processed by the tool. Finally, the position estimation results are displayed on the GUI and stored in a CSV file. As a result, the position estimation accuracy can be computed as the number of times that the tool estimates the position of the pallet correctly.

The tool is able to estimate the position of the pallet on any allocation correctly at least 50 % of the times. In addition, in 28 out of 30 positions the tool estimates the position of the asset with accuracies at least equal to 98 %.

The position that shows the worst accuracy during the test is position 27. At this position 101 out of 200 times the tool estimated the position correctly. However, the rest of the times the estimated position of the pallet corresponds to the allocation 20. This position presents similar RSS values as the position 27. Likewise to position 27, the rest of the positions have their own Most Conflicting Positions (MCP). This MCP corresponds to the allocation that has the closest RSS values to the actual position where the pallet is allocated.



Position	Accuracy
1	100%
2	100%
3	99.5%
4	99.5%
5	99.5%
6	100%
7	99.0%
8	100.0%
9	100.0%
10	99.5%
11	100.0%
12	100.0%
13	86.5%
14	100.0%
15	99.5%
16	99.5%
17	100.0%
18	100.0%
19	99.5%
20	100.0%
21	100.0%
22	99.5%
23	98.5%
24	99.5%
25	100.0%
26	99.0%
27	50.5%
28	98.0%
29	100.0%
30	99.5%

Figure 5.6 Performance test results using Average Values Database

The MCP and the 2nd MCP for each defined position on Flexlink DAS are summarized in Table 5.7.

Table 5.7 MCP at each allocation during performance test using Average Values Database

Position	MCP	2nd MCP	Position	MCP	2nd MCP
1	15	17	16	28	18
2	19	6	17	22	15
3	6	19	18	16	8
4	6	3	19	22	3
5	6	12	20	26	25
6	5	12	21	11	15
7	26	25	22	20	17
8	18	16	23	27	20
9	3	19	24	18	28
10	28	18	25	20	16
11	21	15	26	6	30
12	5	9	27	20	25
13	17	15	28	27	20
14	1	29	29	30	14
15	21	1	30	6	29

5.2.2 Fingerprinting using Mode Values Database

Correspondingly to the average value database, the mode value database can be split into two parts. Additionally, the sampling universe used during the creation of the average database is also used to build the mode database up. The resulting mode values at each position contained in the database are illustrated in Figure 5.7 and Figure 5.8 for the first and the second part respectively.

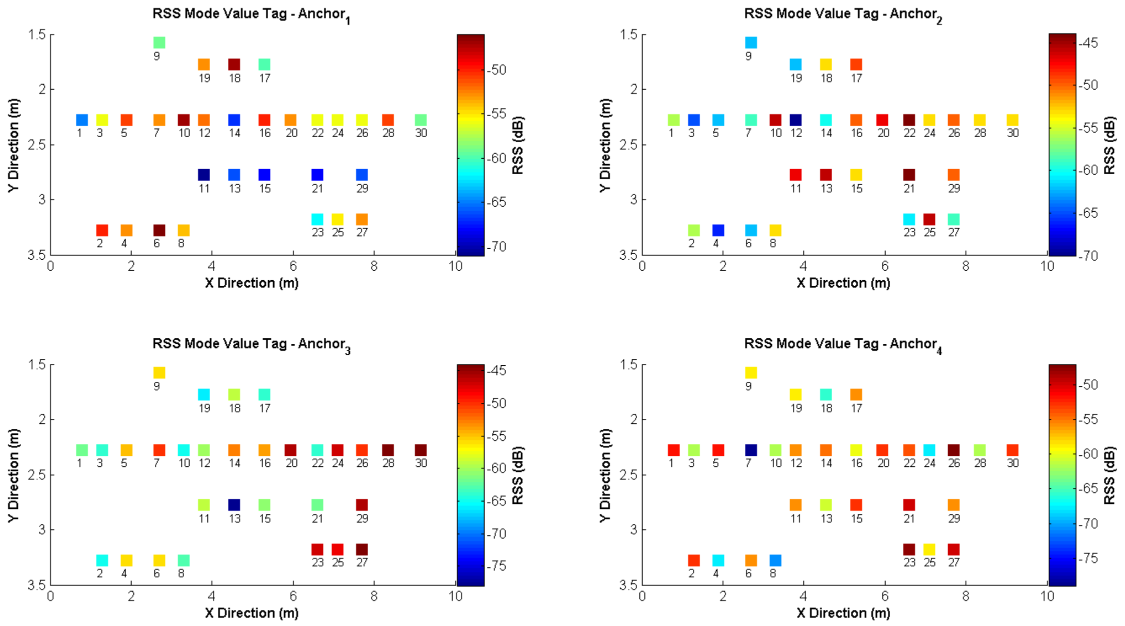


Figure 5.7 Tag – Anchor Node$_N$ RSS Mode Database Values

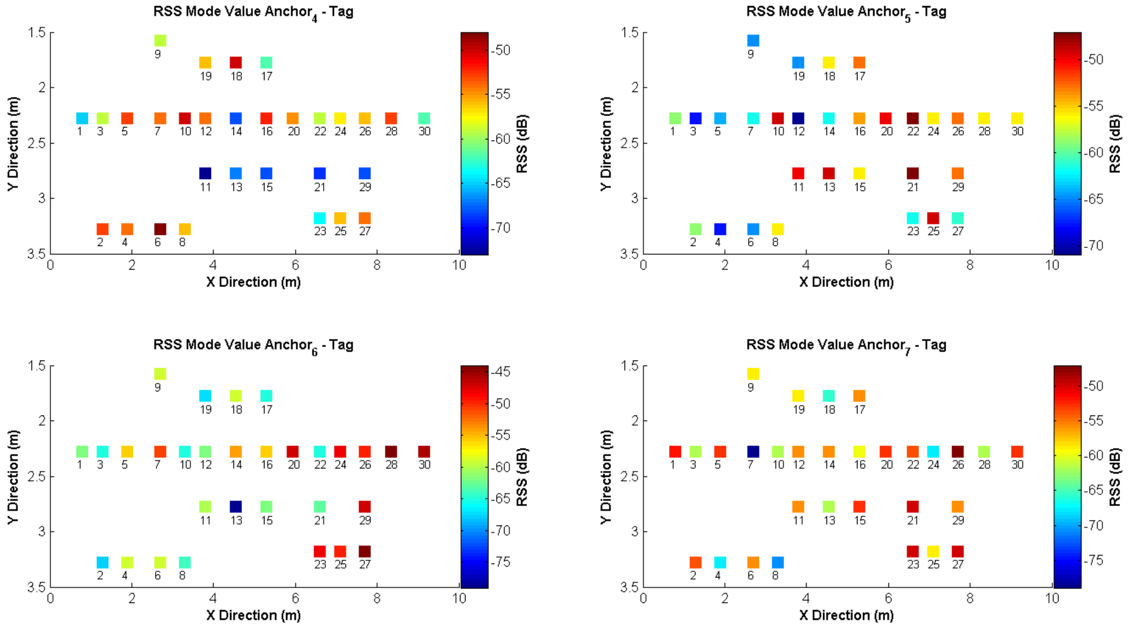
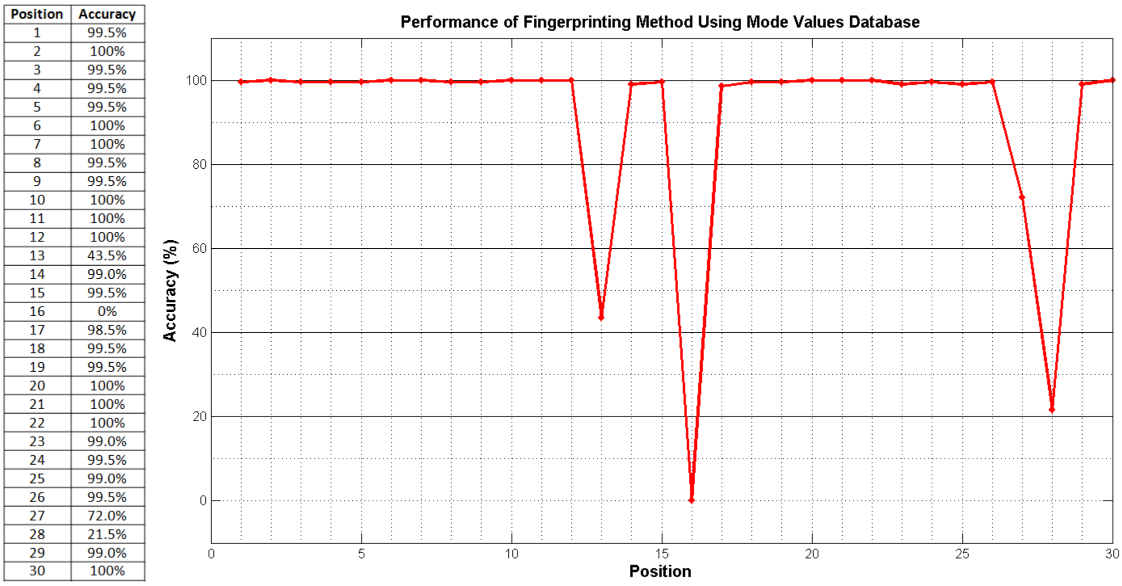


Figure 5.8 Anchor Node$_N$ – Tag RSS Mode Database Values

The utilization of four anchor nodes in the position estimation process helps to discriminate between different positions that cannot be distinguished if a single anchor node is used. Therefore, the obtained mode database values are loaded into the position estimation tool for further computations during the estimation process.

Subsequently to the offline process, the run-time stage takes place. Therefore, by matching the run-time RSS samples against the mode values stored in the database the position of the asset can be estimated by the tool. Thus, in order to evaluate the performance of the real-time position estimation tool the pallet is allocated in each one of the thirty predefined positions of Flexlink DAS. Moreover, at each one of these positions, 200 samples are recorded and processed by the tool. After processing the measuring data, the position estimation result is displayed in the GUI and stored in a CSV file. Based on these results, the accuracy of the tool can be calculated in the same way as in Section 5.2.1 and the performance can be evaluated. The accuracy results obtained from the performance test are depicted in Figure 5.9.



Position	Accuracy
1	99.5%
2	100%
3	99.5%
4	99.5%
5	99.5%
6	100%
7	100%
8	99.5%
9	99.5%
10	100%
11	100%
12	100%
13	43.5%
14	99.0%
15	99.5%
16	0%
17	98.5%
18	99.5%
19	99.5%
20	100%
21	100%
22	100%
23	99.0%
24	99.5%
25	99.0%
26	99.5%
27	72.0%
28	21.5%
29	99.0%
30	100%

Figure 5.9 Performance test results using Mode Values Database

Accordingly to the obtained results during the test, the position estimation tool performs with accuracies greater than 99 % in most of the positions but in four allocations with accuracies of 43.5%, 0%, 72% and 21.5% respectively. However, there is a position that could not be resolved correctly by the tool. This worst accuracy case occurs at position 16, where the position estimated by the tool corresponds to the MCP at allocation 16. The MCP and 2nd MCP for each allocation on the assembly line are summarized in Table 5.8.

Table 5.8 MCP at each allocation during performance test using Mode Values Database

Position	MCP	2nd MCP	Position	MCP	2nd MCP
1	26	15	16	14	30
2	19	6	17	28	30
3	10	19	18	10	16
4	6	3	19	2	3
5	26	6	20	26	25
6	5	12	21	11	15
7	24	4	22	17	21
8	28	18	23	27	6
9	23	3	24	26	28
10	18	16	25	16	26
11	21	15	26	21	30
12	5	9	27	20	20
13	17	10	28	27	28
14	30	9	29	28	30
15	21	1	30	29	23

6 CONCLUSION

This Chapter drowns the concluding remarks about the ideas and discussions provided along this thesis work. Furthermore, the results obtained from the performance test completed on the real-time position estimation tool are discussed. In addition, the proposed further development work and new suggested directions, from this point onwards, are also presented.

6.1 FINAL RESULTS AND SHORT ASSESSMENT OF THE REAL-TIME POSITION ESTIMATION TOOL

In order to evaluate the performance of the real-time position estimation tool, four different performance tests were implemented. These tests utilize different methodologies and algorithms in order to estimate the position of the asset based on the RSS estimation parameter. The outcome of these performance tests is shown in Chapter 5 whereas the discussion about it is presented in this Section followed by an overall evaluation of the position estimation tool.

6.1.1 Performance Test Results

Based on the evaluation performed on the real-time position estimation tool, where four different approaches were analyzed, there is an implementation that overcomes the performance of the rest ones. This implementation is the position estimation based on the Fingerprinting Methodology that utilizes the database comprised by the RSS average values at each position of interest.

The position estimation based on the Fingerprinting Methodology that uses the mode values is unable to resolve one of the positions over the testing area. However, most of the rest positions were accurately estimated by the tool. Nevertheless, the performance exerted by the tool was poorer than when RSS average values are used. Unlike the mode values database approach, by using the average values database approach with the Fingerprinting Methodology, the tool is able to estimate the position of the pallet on any allocation at least 50 % of the times correctly. In addition, in 28 out of 30 positions the tool performs with accuracies at least equal to 98 % whereas one out of 30 it performs with the worst case accuracy of 50.5 %.

Regarding the position estimation based on lateration methodology, the position estimation tool shows a limited performance. This poor performance was observed no matter which propagation model is implemented, either the path-loss or the ITU propagation model for indoor environments. In both study cases, the best accuracy is greater than two meters which is not sufficient to distinguish among different allocations for the pallet on the assembly line. Furthermore, only six out of the total positions were achieved with accuracies less than ten meters. Additionally, it was observed that the estimation results via lateration methodology vary strongly from one position to another. These variations lead to estimations of positions outside the testing room. Based on the observations done during the testing process, the main influence of these errors is caused by obstructions in the line of sight between the tag and the anchor nodes.

On the other hand, notwithstanding the position estimation methodology used in the implementation of the tool, the utilization of four anchor nodes in the position estimation process helps to discriminate between different positions with similar RSS fingerprint values more accurately. Otherwise, it is more difficult for the tool distinguishing among them if a single anchor node is used.

It is important to notice that the performance tests were run in an indoor environment where the traffic of people or machinery is reduced. Additionally, it is considered that the assembly process runs in an automatic way without the intervention of the human being. Therefore at the moment of running the tests, only the tester was present in the room. Moreover, it must be considered that the fingerprinting methodology works properly specifically for those environments where the database was created and under the conditions at the moment of its creation. Therefore, the changes experienced in the environment affect directly the position estimation results. The changes that affect the most the outcome of the position estimation process are obstructions in the line of sight between the wireless nodes. Especially those not present at the moment of the fingerprinting offline stage execution. Also the changes in the orientation of the antenna of the nodes lead to estimation errors regardless the position estimation approach implemented.

An additional remark affecting the position estimation result is the exact position of the asset. It has to coincide with the position whose values are stored in the fingerprinting database. Otherwise, slight misplacements produce errors in the estimation process.

6.1.2 Overall Performance

The overall performance of the real-time position estimation tool developed during this thesis work fulfills the requirements presented in Section 1.3.1. This tool utilizes a wireless sensor network that implements the 6LoWPAN communication protocol stack. As a result, IP packets can be transmitted over IEEE 802.15.4 PHY media while utilizing IPv6 protocol as the networking protocol. This characteristic allows the interoperation of the tool with different technologies.

A proof of this interoperation is the development of a GUI that interacts with the tool. The communication between the WSN and the position estimation application takes place by using UDP IPv6 messages without necessity for using tailored communication protocols. Additionally, this GUI permits the visualization of the position estimation results performed by the tool while managing multiple tag nodes (assets).

However, the advantage of using the IPv6 protocol comes along with limitations. The most important is the hardware limitation. Since the current implementations of 6LoWPAN protocol stack at the moment of this work, only supports a few WSN platforms. Moreover, these platforms are based on RF technologies whose characteristics do not allow the implementation of time-based position estimation methodologies. These time-based approaches have shown better performances than other approaches according to the literature reviewed along this thesis work. As a result, the implementation of the position estimation tool was limited to the RSS-based methodologies.

Regardless the limitations imposed by the selected technology, the implementation of a position estimation tool was realized during this thesis work. Furthermore, as discussed in the previous section, its performance is very good in most of the testing positions. These results support the statement that the designed position estimation engine for the tool was appropriate for the application. Likewise the implemented position estimation algorithm showed to perform in a good manner allowing the estimation of the position of a pallet on the assembly line at periods as fast as the WSN platform allows it (8 ms).

6.2 FUTURE WORK

The research developed represents one of the first attempts aimed to accomplish the positioning of manufacturing assets by utilizing wireless sensor networks working implementing the 6LoWPAN communication protocol stack. In this work, an ad-hoc IEEE 802.15.4 WPAN is deployed. However, in order to exploit the advantages offered by the IPv6 protocol as the networking protocol, the WPAN should be integrated into the Internet. For this purpose, the utilization of a border router is required.

Regarding the position estimation approach, a different technology with higher capabilities should be explored, for instance, the UWB technology which is one of the most promising technologies regarding positioning applications in WSN. Therefore, the utilization of an UWB radio chip allows the utilization of time-based algorithms to perform position estimations. This UWB radio chip can work together with an RF radio technology supported by the current 6LoWPAN implementations in order to handle the communication part. This tailored solution can help in the achievement of a position estimation tool more robust.

An additional functionality is the integration of web services into the WSN. Nowadays the IETF is working on communications protocols addressed to cope with constrained devices. However, a first approach for testing purposes can be the binding of the position estimation tool as a web service via the host PC, taking advantage from the fact that a full capability PC is running the position estimation application developed in Java programming language. Additional improvements to the actual tool can be the utilization of omnidirectional antennas in the wireless nodes in order to reduce the effects due to changes of the orientation of the antenna. Moreover, the fact that the IPv6 wireless nodes should keep the radio tuned on all the time, it is important to consider powering the anchor nodes with a power supply different from batteries.

Currently, the tool has shown to perform satisfactory in most of the test cases. However, a heuristic approach can be considered to combine additional data sources (e.g. RFID readers, historical information) to complement wireless technology and make further increment of accuracy.

As mentioned in Section 1.3.3, the work developed was intended for positioning of manufacturing assets in a 2-D plane. However, the functionality of the tool can be extended to perform 3-D positioning. In order to achieve accuracies similar to the obtained during this work it is necessary to increase the number of anchor nodes. Besides, additional modifications are needed in the source code of the tool in order to achieve the 3-D positioning functionality using the lateration methodology.

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