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A Supporting Infrastructure for Wireless Sensor Networks in Critical Industrial Environments

Thesis submitted as partial fulfillment of the requirements of the Doctoral Program on Information Science and Technology in the University of Coimbra, for the award of Doctor in the domain of Telematics Networking and Communications under the supervision of Professor Doctor Jorge Miguel Sá Silva.

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The whole of science is nothing more than a refinement of everyday thinking.

Albert Einstein

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Resumo

As Redes de Sensores Sem Fios (RSSFs) têm uma aplicabilidade muito elevada nas mais diversas áreas, como na indústria, nos sistemas militares, na saúde e nas casas inteligentes. No entanto, continuam a existir várias limitações que impedem que esta tecnologia tenha uma utilização extensiva. A fiabilidade é uma destas principais limitações que tem atrasado a adopção das RSSFs em ambientes industriais, principalmente quando sujeitos a elevadas interferências e ruídos. Por outro lado, a interoperabilidade é também um dos principais requisitos a cumprir nomeadamente com o avanço para o paradigma da *Internet of Things*.

A determinação da localização dos nós, principalmente dos nós móveis, é, também ele, um requisito crítico em muitas aplicações. Esta tese de doutoramento propõe novas soluções para a integração e para a localização de RSSFs que operem em ambientes industriais e críticos.

Como os nós sensores são, na maioria das vezes, instalados e deixados sem intervenção humana durante longos períodos de tempo, isto é, meses ou mesmo anos, é muito importante oferecer processos de comunicação fiável. No entanto, muitos problemas ocorrem durante a transmissão dos pacotes, nomeadamente devido a ruídos, interferências e perda de potência do sinal. A razão das interferências deve-se à existência de mais do que uma rede ou ao espalhamento espectral que ocorre em determinadas frequências. Este tipo de problemas é mais severo em ambientes dinâmicos nos quais novas fontes de ruído pode ser introduzidas em qualquer instante de tempo, nomeadamente com a chegadas de novos dispositivos ao meio. Consequentemente, é necessário que as RSSFs tenham a capacidade de lidar com as limitações e as falhas nos processos de comunicação. O protocolo Dynamic MAC (DunMAC) proposto nesta dissertação utiliza técnicas de rádio cognitivo (CR) para que a RSSF se adapte, de forma dinâmica, a ambientes instáveis e ruidosos através da selecção automática do melhor canal durante o período de operação.

As RSSFs não podem operar em isolação completa do meio, e necessitam de ser monitoradas e controladas por aplicações externas. Apesar de ser possível adicionar a pilha protocolar IP aos nós sensores, este procedimento não é adequado para muitas aplicações. Para estes casos, os modelos baseados em *gateway* ou *proxies* continuam a apresentar-se preferíveis para o processo de integração. Um dos desafios existentes para estes processos de integração é a sua adaptabilidade, isto é, a capacidade da *gateway* ou do *proxy* poder ser reutilizado sem alterações por outras aplicações. A razão desta limitação deve-se aos consumidores finais dos dados serem aplicações e não seres humanos. Logo, é difícil ou mesmo impossível criar normas para as estruturas de dados dada a infinidade de diferentes formatos. É então desejável encontrar uma solução que permita uma integração transparente de diferentes RSSFs e aplicações. A linguagem Sensor Traffic Description Language (STDL) proposta nesta dissertação propõe uma solução para esta integração através de *gateways* e *proxies* flexíveis e adaptados à diversidade de aplicações, e sem recorrer à reprogramação.

O conhecimento da posição dos nós sensores é, também ele, crítico em muitas aplicações industriais como no controlo da deslocação dos objectos ou trabalhadores. Para além do mais, a maioria dos valores recolhidos dos sensores só são úteis quando acompanhados pelo conhecimento do local onde esses valores foram recolhidos. O *Global Positioning Systems* (GPS) é a mais conhecida solução para a determinação da localização. No entanto, o recurso ao GPS em cada nó sensor continua a ser energeticamente ineficiente e impraticável devido aos custos associados. Para além disso, os sistemas GPS não são apropriados para ambientes *in-door*.

Este trabalho de doutoramento propõe-se actuar nestas áreas. Em particular, é proposto, implementado e avaliado o protocolo DynMAC para oferecer fiabilidade às RSSFs. Para a segunda temática, a linguagem STDL e o seu motor são propostos para suportar a integração de ambientes heterogéneos de RSSFs e aplicações. As soluções propostas não requerem reprogramação e suportam também serviços de localização nas RSSFs. Diferentes métodos de localização foram avaliados para estimar a localização dos nós. Assim, com estes métodos as RSSFs podem ser usadas como componentes para integrar e suportar a Futura Internet.

Todas as soluções propostas nesta tese foram implementadas e validadas tanto em simulação com em plataformas práticas, laboratoriais e industriais.

Abstract

The Wireless Sensor Network (WSN) has a countless number of applications in almost all of the fields including military, industrial, healthcare, and smart home environments. However, there are several problems that prevent the widespread of sensor networks in real situations. Among them, the reliability of communication especially in noisy industrial environments is difficult to guarantee. In addition, interoperability between the sensor networks and external applications is also a challenge. Moreover, determining the position of nodes, particularly mobile nodes, is a critical requirement in many types of applications. My original contributions in this thesis include reliable communication, integration, localization solutions for WSNs operating in industrial and critical environments.

Because sensor nodes are usually deployed and kept unattended without human intervention for a long duration, e.g. months or even years, it is a crucial requirement to provide the reliable communication for the WSNs. However, many problems arise during packet transmission and are related to the transmission medium (e.g. signal path-loss, noise and interference). Interference happens due to the existence of more than one network or by the spectral spread that happens in some frequencies. This type of problem is more severe in dynamic environments in which noise sources can be introduced at any time or new networks and devices that interfere with the existing one may be added. Consequently, it is necessary for the WSNs to have the ability to deal with the communication failures. The Dynamic MAC (DynMAC) protocol proposed in this thesis employs the Cognitive Radio (CR) techniques to allow the WSNs to adapt to the dynamic noisy environments by automatically selecting the best channel during its operation time.

The WSN usually cannot operate in complete isolation, but it needs to be monitored, controlled and visualized by external applications. Although it is possible to add an IP protocol stack to sensor nodes, this approach is not appropriate for many types of WSNs. Consequently, the proxy and gateway approach is still a preferred method for integrating sensor networks with external networks and applications. The problem of the current integration solutions for WSNs is the adaptability, i.e., the ability of the gateway or proxy developed for one sensor network to be reused, unchanged, for others which have different types of applications and data frames. One reason behind this problem is that it is difficult or even impossible to create a standard for the structure of data inside the frame because there are such a huge number of possible formats. Consequently, it is necessary to have an adaptable solution for easily and transparently integrating WSNs and application environments. In this thesis, the Sensor Traffic Description Language (STDL) was proposed for describing the structure of the sensor networks' data frames, allowing the framework to be adapted to a diversity of protocols and applications without reprogramming.

The positions of sensor nodes are critical in many types of industrial applications such as object tracking, location-aware services, worker or patient tracking, etc. In addition, the sensed data is meaningless without the knowledge of where it is obtained. Perhaps the most well-known location-sensing system is the Global Positioning System (GPS). However, equipping GPS sensor for each sensor node is inefficient or unfeasible for most of the cases because of its energy consumption and cost. In addition, GPS is not appropriate in some environments, e.g., indoors. Similar to the original concept of WSNs, the localization solution should also be cheap and with low power consumption.

This thesis aims to deal with the above problems. In particular, in order to add the reliability for WSN, DynMAC protocol was proposed, implemented and evaluated. This protocol adds a mechanism to automatically deal with the noisy and changeable environments. For the second problem, the STDL and its engine provide the adaptable capability to the framework for interoperation between sensor networks and external applications. The proposed framework requires no reprogramming when deploying it for new applications and protocols of WSNs. Moreover, the framework also supports localization services for positioning the unknown position sensor nodes in WSNs. The different localization methods are employed to estimate the location of mobile nodes. With the proposed framework, WSNs can be used as plug and play components for integrating with the Future Internet. All the proposed solutions were implemented and validated using simulation and real testbeds in both the laboratory and industrial environments.

Foreword

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Table of Content

List of Figures

List of Tables

List of Acronyms

AAA	Authentication, Authorization and Auditing
ABC	Assumption Based Coordinates
AEA	Adaptive Election Algorithm
AFL	Anchor-Free distributed Localization
ANN	Artificial Neural Network
AOA	Angle-of-Arrival
AP	Access Point
APIT	Approximate PIT Test
APS	Ad-hoc Positioning System
ASK	Amplitude Shift Keying
B-MAC	Berkeley Media Access Control
BPSK	Binary Phase Shift Keying
BPS-MAC	Backoff Preamble Sequential
CA	Coexistence Assurance
CCA	Clear Channel Assessment
CDMA	Code Division Multiple Access
CF	Cost Function
CM	Control Message
CR	Cognitive Radio
CRSN	Cognitive Radio Sensor Networks
CSMA	Carrier Sense Multiple Access
CTS	Clear-To-Send
DM	Data Message
DSA	Dynamic Spectrum Access

DSAP	Dynamic Spectrum Access Protocol
DTD	Document Type Definition
DynMAC	Dynamic Media Access Control Protocol
EBNF	Extended Backus-Naur Form
ECN	Explicit Contention Notification
EHTTP	Embedded Binary HTTP
FB	FaceBook
FDMA	Frequency Division Multiple Access
FHSS	Frequency Hopping Spread Spectrum
FRTS	Future Request-To-Send
GinMAC	Ginseng MAC
GML	Maximum-Likelihood
GPS	Global Positioning System
GSN	Global Sensor Networks
GTS	Guaranteed Time Slot
HTTP	Hypertext Transfer Protocol
ICMP	Internet Control Message Protocol
ID	Identification
IoT	Internet of Things
IP	Internet Protocol
IR	Infrared
ISM	Industrial, Scientific and Medical
JSON	JavaScript Object Notation
KNN	K-Nearest Neighbors
LE	Localization Engine
LMAC	Lightweight Medium Access Control
LoS	Line-of-Sight
LPL	Low Power Listening

LQI	Link Quality Indicator
MAC	Media Access Control
MACA	Multiple Access with Collision Avoidance
MACAW	Multiple Access with Collision Avoidance for Wireless
MDS	Multidimensional Scaling
MH-MAC	Mobility Adaptive Hybrid MAC
MLMAC	Mobile LMAC
NCR	Neighborhood-aware Contention Resolution
NLoS	Non-Line of Sight
NP	Neighbor Protocol
O&M	Observations and Measurements
OGC	Open Geospatial Consortium
O-QPSK	Orthogonal Quadrature Phase Shift Keying
OSA	Opportunistic Spectrum Allocation
PAMAS	Power Aware Multi-Access with Signaling
PDM	Proximity Distance Map
PEDAMACS	Power Efficient and Delay Aware Medium Access Protocol for Sensor Networks
PER	Packet Error Rate
PETF	Pattern Exchange Time Frame
PIT	Point-In-Triangle Test
PMAC	Pattern-MAC
QoS	Quality of Service
REST	Representation State Transfer
RF	Radio Frequency
RSSI	Received Signal Strength Indicator
RTLS	Real Time Location System
RTS	Request-to-Send

SAL	Simulated Annealing Localization
SCADA	Supervisory Control and Data Acquisition
SCP-MAC	Scheduled channel polling MAC
SDR	Software Defined Radio
SensorML	Sensor Model Language
SEP	Schedule Exchange Protocol
SHARP	Simple Hybrid Absolute Relative Positioning
SL	Second Life
S-MAC	Sensor MAC
SOAP	Simple Object Access Protocol
SOS	Sensor Observation Service
SPS	Sensor Planning Service
SQL	Structured Query Language
SQP	Sequential Quadratic programming
STDL	Sensor Traffic Description Language
SVD	Singular Value Decomposition
SVM	Support Vector Machine
SWE	Sensor Web Enablement
TCP	Transmission Control Protocol
TDMA	Time Division Multiple Access
TEDS	Transducer Electronic Data Sheets
TERRAIN	Triangulation via Extended Range and Redundant Association of Intermediate Nodes
T-MAC	Timeout-MAC
ToA	Time-of-Arrival
TRAMA	Traffic-Adaptive Medium Access
UDP	User Datagram Protocol
uIP	micro IP

UWB	Ultra-wide band
VBLM	Verification-Based Localization Method
WLAN	Wireless Local Area Network
WoT	Web of Things
WPAN	Wireless Personal Area Network
WSN	Wireless Sensor Networks
XML	eXtensible Markup Language
XDR	XML-Data Reduced
XSD	XML schema
Z-MAC	Zebra MAC

1 Introduction

Summary

This thesis deals with the problem of reliable communication, localization, and integration infrastructure for Wireless Sensor Networks in critical and industrial environments. The first section of this chapter discusses the motivation behind the research and the problem statement. The objectives of the work in this thesis are presented in Section 1.2. Then, Section 1.3 summarizes the main contributions of the thesis. The final section outlines the structure of the document.

1.1 Motivation and problem Statement

Wireless Sensor Networks (WSNs) have been emerging as a promising system for monitoring and possibly actuating the physical world. With ability to sense, process, and disseminate the ambient conditions of the physical environment as well as to activate the physical things, WSNs have a diversity of applications in most of the areas including military strategy, security, transportation, industry, healthcare and smart home. In addition, the small size and self-organizing features of sensor nodes allow them to be deployed in places where it is difficult to monitor such as volcanic and biological or nuclear agents. However, because of the constraints of sensor nodes such as small size, low energy consumption, the limited memory and computation, and low cost, there are a lot of problems in designing, developing, and deploying WSNs. The following sections discuss the problems that are dealt with in the thesis.

1.1.1 Reliable Communication

One of the crucial questions in this research domain is how to guarantee the reliable communication for WSNs. This requirement is important especially in the noisy and interference environments. As WSNs operate on the same frequency band with other wireless networks and devices, e.g., Wireless Local Area Network (WLAN), Bluetooth, and microwave, it makes the problem more severe. A recent study in [1] showed that with the interference of IEEE 802.11 wireless networks the Packet Error Rate (PER) of IEEE 802.15.4 based sensor networks could be up to 95% when the interferer was in the distance of 1.5 meters. In the inverse, the throughput of IEEE 802.11 wireless network could reduce up to 30% in case of there was the present of IEEE 802.15.4 networks in a short distance [2]. Besides the interference, other noise sources, such as machineries and heating, also affect the reliability of the WSNs.

In order to tackle this problem, researchers have proposed a number of Media Access Control (MAC) protocols [3]. In addition, IEEE 802.15.2-2003 [4] recommended two approaches for coexistence between WLANs and Wireless Personal Area Networks (WPANs). The first mechanism is a collaborative approach which requires the exchange of the information between two wireless networks to mitigate the interference. However, the problem with this approach is that it is necessary to have a communication link between two networks, and to exchange information between the two totally different types of networks. Consequently, it is difficult to implement this mechanism. The second one is non-collaborative approach, which is intended to be used when there is no communication link between the WLAN and WPAN. The possible techniques that can be used in these approaches include scheduling the medium access, packet traffic arbitration, scheduling packet depending on the condition of channel, and channel hoping [4]. In addition, Cognitive Radio (CR) is a recent study which aims at a more flexible and efficient usage of the radio spectrum [5]. According to [6] technological advances in CR enable the application of Dynamic Spectrum Access (DSA) models to WSNs. That may permit the efficient use of the frequency spectrum and the coexistence of networks. Although it is a potential mechanism for coexisting problems for WSNs, the full CR may be too heavy for sensor nodes and thus it is inefficient when applied for WSNs. The problem with the proposed protocols and solutions is that they cannot deal well with the dynamical environments in which the new interference and noise may be introduced at any time after the sensor network has been deployed.

1.1.2 Integration

With the ability to interface with physical environments, WSNs are considered as a bridge between the physical with digital worlds. They are envisioned to be an integral part of our life, and an important component of the future Internet. However, in order to realize their usefulness and potential, WSNs cannot operate in complete isolation, but they need to somehow be interconnected with the external networks, e.g., Internet, and applications [7]. This is a crucial requirement because the sensed data need to be collected, processed, and visualized by applications to make them understandable by the users. In addition, the sensor nodes and networks should also need to be monitored and controlled by users through the external applications. When considering interconnecting with the Internet, the obvious solution that most people think of is to use Transmission Control Protocol / Internet Protocol (TCP/IP) protocol suit. However, the constraints of sensor nodes on memory, computation, communication and power consumption [8] and special characteristics of WSNs such as data-centric, data flow patterns, application-specific, and heterogeneous network platforms and protocols [7], [9], [10] make them more challenging. Consequently, in order to make sensor networks applicable for everyday usage, the interconnection and integration infrastructure must take these requirements into account.

There are currently two approaches for integrating WSNs with the external networks and applications: gateway-based and IP-based. In the first approach, one or more gateways are deployed between the sensor networks and external networks to translate and forward the traffic between them. On the other hand, the second approach tries to directly implement IP protocol stack and/or web services on the sensor nodes. There are several gateway-based methods for integrating WSNs with the Internet, and applications including [7], [10], [11], [12], [13]. The advantage of the gateway-based approach is that it makes the sensor networks transparent to external environments. In addition, the developers can use any protocols that are most suitable for sensor networks.

It was often assumed that TCP/IP protocol was unfeasible and inefficient to be directly deployed into sensor nodes. However, the studies in [14], [15], [16] have proven that it is feasible to deploy IP protocol suite into sensor nodes. In addition, it is also possible to implement the web services on the constraint sensor nodes as shown in [17], [18], [19], [20]. Although it is possible to deploy TCP/IP protocol stack on sensor nodes, there are still several problems with this approach including energy efficiency, security and applicability.

An important question that arises out of this problem is that which approach (Gateway-based or IP-based) should be used to integrate WSNs with external environments. There are no trivial answers for this question because it depends on the deployment environments and on other requirements. However, it is believed that both solutions should concurrently exist and complement with each other [21], [22]. Furthermore, in many cases, gateway-based solutions are more appropriate [10], [11], [12]. In fact, although the web service is directly implemented on the sensor nodes as shown in [17], [18], [19], [20], it cannot be accessed directly but still needs a gateway or a proxy. The problem is that the compression and other optimization mechanisms applying to the IP protocol stack and web services running on sensor nodes makes them incompatibility with their counterpart standards. Actually, the works in [17], [18], [19] combined both approaches, and the access to sensor nodes always went through the gateway or proxy even for the nodes on which the web services were implemented. As a matter of fact, gateway-based approach for interoperating between WSNs and external applications will continue to exist in the foreseeable future.

As the constraints and characteristics of WSNs, the gateway-based approach is still a preferred choice for integrating sensor networks with the Internet and applications. The problem with current gateway-based integration solutions is their adaptability, i.e., the ability of the gateway or proxy to be reused, unchanged, for other networks with different data frames. The main cause of this problem is that it is difficult or even impossible to create a standard for the structures of data inside the frames of sensor networks because there are so huge numbers of possible formats. The traditional mechanism for this problem is to modify or reprogram the gateway or proxy, e.g., adding software driver or analyzer, to make them adaptable to the change of the protocols and/or applications of sensor networks. Consequently, it is necessary to have a mechanism to deal with this problem, i.e., the gateway or proxy has the ability to adapt to different types of protocols and data formats of sensor networks without reprogramming

1.1.3 Localization

Localization, i.e., determining the position of sensor nodes, is critical for many applications of WSNs because data are meaningless without knowing the location in which the data was obtained. In addition, locations of mobile nodes plays an important role in many types of sensor networks due to the nature of applications such as healthcare, patients' monitoring, monitoring of workers within hazardous environments, tracking children in a smart home, etc. The localization problem was studied since 1960s resulting in the most success location system that is widely in use today, i.e., Global Positioning System (GPS) [23]. However, because of the constraints of sensor nodes, localization in WSNs using GPS is inefficient in most of the cases. Firstly, cost and energy consumption constraints prevent equipping GPS sensors for every node. In addition, there are some cases in which GPS is not feasible such as indoor or places with a lot of obstacles. Moreover, the accuracy of civil GPS, in some cases, does not satisfy the requirements of the applications. The work in [24] tried to reduce energy consumption of GPS for sensor nodes by offloading the processing to the cloud. However, the accuracy of this work is still low (35m) [24]. Accordingly, it is necessary to have alternative solutions for localization in WSNs.

The localization in WSNs can be divided into two broad classes: one for ad-hoc sensor networks, and the other for infrastructure-based or controlled sensor networks. The former is based on the assumption that WSNs are randomly deployed into the field and after deployment nodes are rarely moved. The latter is applied for the sensor networks that are carefully designed, using engineering methods. In addition, the nodes in the controlled sensor network are divided into two groups: infrastructure which comprises nodes with the fixed known position; and mobile nodes, which are attached to people, vehicle or other movable things. In this thesis, we focus our work on the controlled sensor networks as we are particularly interested in applying the proposed solutions for critical and industrial environments.

There are numerous approaches and systems proposed for locating the position of mobile nodes in infrastructure-based sensor networks. Active Badge [25], Cricket [26] and Identec [27] are examples of the simple localization systems that are based on the closest anchor principle. This means that the location of mobile node is that of the nearest beacon based on some measurement, e.g., Received Signal Strength Indication (RSSI). The advantage of this method is that it is very easy to implement. However, this method only provides relative locations such as in which room a node resides. Another simple method is centroid algorithm [28], which estimates the position of a mobile node by computing the arithmetic mean of the coordinates of all the beacons that are in range of it. This method returns the same position for nodes that are in the range of the same group of beacons. A more complex method is called lateration that expresses the localization problem as a system of *n* equations (e.g., circles or spheres) and estimates them using the linear or non-linear least square method [29], [30] or Extended Kalman filter [31], [32], [33]. The most well-known public localization service employs this method is GPS [23]. In addition, Bat [34] is the example of the multi-lateration based location system for sensor networks. The advantage of this method is that it is more accurate than the first two. However, its accuracy depends on the accuracy of the distance measurement or estimation.

Another approach for localization in WSNs is to employ algorithms in machine learning field. The localization methods in this group are also known as pattern matching, learning-based, fingerprinting, or scene analysis methods. There are several algorithms in this approach including K-Nearest Neighbors (KNN) [35], [36], [37], [38]; probability-based [39], [40], [41]; Artificial Neural Networks (ANN) [42]; and Support Vector Machine (SVM) [43], [44]. The advantage of these localization methods is that they produce a higher accuracy than other methods. However, they are more complex to implement and require high memory and computation demand. In addition, it takes time to sample the environment in which the WSN was deployed to get the data to train the algorithms.

It is important to note that the critical problem in localization is the accuracy and the stability of the measurement methods and not the localization algorithms themselves. In WSNs, it is difficult to find an appropriate method for measuring the distance from the unknown node to the anchors, considering the hardware and software restrictions, and the requirements of accuracy, feasibility and cost. This problem is even more severe in critical and industrial environments with high degree of noise and interferences. Consequently, it is necessary to have a scalable, near real-time, and low cost localization system that can produce an acceptable accuracy using the commonly available measurements for controlled WSNs.

1.2 Objectives

The aim of this thesis is to propose a supporting infrastructure for facilitating the development, deployment, and maintenance of WSNs in critical and industrial environments. In particular, it covers three main important areas for WSNs: reliable communication, integration, and localization. To realize this aim, the following specific objectives need to be satisfied.

Firstly, it is necessary to have the mechanisms allowing WSNs to operate reliably in noisy and interference environments. This means that the deployed sensor network can somehow automatically avoid the existing noise and interferences. In addition, it can also be adaptable to new noise or interference occurring during its operation.

Secondly, the proposed integration infrastructure should be easily adaptable to different protocols and applications of sensor networks. This means that integration framework can be used for existing or new sensor networks without preprogramming. In addition, it should allow external environments seamlessly to interoperate with the sensor nodes and networks. Moreover, it is also easy to integrate other services for WSNs such as localization and security to the framework. In short, the infrastructure for integrating WSNs with the Internet and external environments should be interoperable, reusable, scalable and extensible.

Finally, as the increasing importance of positioning mobile nodes in WSNs, the infrastructure for them should also include the localization service. One important requirement is that the localization method should be scalable to apply for large sensor networks while producing an acceptable accuracy using the existing measurement methods.

1.3 Contributions

The aim of this dissertation is to design and implement the supporting infrastructure for sensor networks targeting at critical and industrial environments. The relevant contributions of the work in this thesis are:

The mechanisms for supporting reliable communication in WSNs.

The work in this thesis proposed and implemented the mechanisms to allow the WSNs to reliably operate in noisy and interference environments. Moreover, during its operation time the sensor network can be resilient to normal work without user intervention when there are new sources of noise and/or interference. In particular, Dynamic MAC (DynMAC) protocol is designed, implemented, and evaluated with both simulation and real testbed.

An interoperable, reusable, scalable and extensible framework for interoperating between sensor networks and external environments.

The proposed integration framework can be adaptable to the new protocols and applications of WSNs. This means that the framework can be reused for a multitude sensor networks with different types of applications and data frames without reprogramming. In addition, it makes the sensor network and external applications transparently to each other. Thus, it allows the programmers to develop client applications that can consume and control sensors even without knowledge of WSNs. The main component which served as the key for realizing the adaptable requirement of the framework is the Sensor Traffic Description Language (STDL).

A near real time localization engine for controlled sensor networks

The main purpose of the proposed localization methods is to provide an acceptable accuracy in estimating the locations of unknown position nodes. One critical requirement is that the localization method is fast and scalable for estimating the location for sensor network with a large number of mobile sensor nodes.

Prototyping and evaluating the proposed models in real environments

All the proposed models and framework are implemented and validated in real sensor networks. More important, the localization service was tested with testbeds both in laboratory and critical industrial environments.

1.4 Outline of the Thesis

The remainder of the thesis is divided into five chapters and organized as follows.

Chapter 2 provides background information about WSNs. It presents most relevant and recent research on Media Access Control, Cognitive Radio, integration, and localization for WSNs. This chapter also discusses the gaps in the current research that are addressed in this thesis.

Chapter 3 consists of two main parts. The first part dedicates to an empirical study of the quality of different channels of IEEE 802.15.4 compliant WSNs. The second one presents our proposed approach for providing the reliable communication for sensor networks. In particular, it describes the DynMAC protocol and its prototype. In addition, it also presents the experimental results and evaluation of DynMAC using both simulation and testbed.

Chapter 4 presents the proposed framework for interoperating between sensor networks and external applications. The most important component of this framework is the Sensor Traffic Description Language (STDL), which makes the integration framework adaptable to different types of protocols and data frames of sensor networks. This chapter also presents a prototype of this framework and some illustrated applications.

Chapter 5 focuses on the solutions for determining the unknown position nodes in controlled WSNs. It details model and localization methods implemented in the project. More important, it presents the experimental results with different testbeds both in laboratory and industrial environments.

Chapter 6 summarizes the main achievements of this thesis as well as describes some future work.

2 Literature Review

Summary

This chapter is devoted to the background on the Wireless Sensor Network (WSN) and the relevant works related to the problems tackled in this thesis. The first part of the chapter presents an overview of WSNs including the concept, potential applications, challenges, requirements, and supporting services. In the second part, the research related to reliable communication for sensor network is discussed. Then, the current approaches for integrating sensor networks with external environments are reviewed. The fourth part is dedicated to the current localization services for WSN. The fifth introduces some international research projects related to the topics presented in the thesis. The final part summarizes the chapter and set the scene for the work in this thesis.

2.1 Overview

2.1.1 Wireless Sensor Networks

A Wireless Sensor Network (WSN) is originally defined as a network that consists of a large number of small sensor nodes which are densely deployed inside or close to the phenomenon [8]. One example of such a network is that the sensor nodes are randomly scattered into the destination environment. However, the current research and deployments have considered several types of WSNs. Concerning the size, a sensor network may vary from a small network with several nodes to a very large one with thousands of nodes. In addition, they can also be categorized as structured or unstructured [45]. The structured, also called infrastructure-based, WSNs refer to the sensor networks in which the positions of a portion of sensor nodes are pre-planned. On the other hand, the unstructured WSN is similar to its original definition one, i.e., the positions of all or most of sensor nodes are unknown. The type of sensor network that is employed depends on the environments and on the requirements of the applications.

The core element of a WSN is the sensor node, which has computation and communication capabilities. What makes the WSNs distinct from other types of networks is that the sensor nodes have ability to sense (i.e., measure some properties of) the ambient environment. In addition, it may also include the ability to activate things such as appliances, pumps, etc. This means that the sensor nodes can interface with the physical environment to gather data from it as well as to send instructions to physical things. These capabilities of sensor nodes bring innumerable potential applications for sensor networks in most of the fields.

In addition to the sensor nodes, a sensor network also consists of one or more sink nodes, which also called base stations. Sinks act as the intermediate nodes between the sensor nodes and the controlling and monitoring applications. They receive sensed data from the sensor nodes and forward it to the application. In addition, they also forward the commands or instructions from the controlling application to the sensor nodes.

A typical model of sensor networks is follows: the sensor nodes measure ambient conditions at different spatial and temporal positions or targets, process the measured data, and transmit (active or passive) them to the sinks via a set of intermediate nodes. This is the information gathering paradigm of sensor networks which is based on the cooperation of a multitude of sensor nodes to obtain needed data. In addition to sensing capability, the sensor nodes can also be used to actuate other devices or appliances based on the commands from external monitoring and controlling systems.

With these abilities, WSNs are emerging as the promising tools for bridging the gap between virtual world and physical world. Consequently, WSNs have unlimited useful and important applications in most of the areas including military, industrial, environment, healthcare, and civilization [8], [45]. They offer potential tools to explore the ambient conditions of the physical environments for variety purposes such as monitoring environment conditions (e.g., temperature, humidity, pressure, radiation, etc.), monitoring and tracking people (e.g., workers, patients, etc), etc.

However, the constraints on size and cost cause the limitations of the sensor nodes on memory, storage, processing and communication. Most of the sensor nodes currently available on the market have a 8-bit or 16-bit processor, 1 to 512 KB of RAM, and 8 to 256 KB of program flash memory [46], [47]. In addition, the communication range of sensor nodes is around 10 meters [48]. Moreover, because sensor nodes are usually powered by battery, the energy is also a scarce resource. Consequently, these limitations have significant impact on the designing and developing of the sensor networks and applications.

2.1.2 Challenges

With these above concepts, constraints and limitations, there are numerous challenges when designing, developing and deploying WSNs. The following paragraphs discuss these important challenges and their implications.

Limited memory and computation: The obvious problem in a sensor network is the limitation of memory and computing resources of the sensor nodes. This implies that the sensor nodes cannot host and run large and complex protocol and programs. This means that the operating systems, protocol stacks, and applications running on normal computers or other devices cannot be used for sensor nodes. Consequently, it is necessary to have specific operating systems, protocol stacks and applications for WSNs.

Limited energy sources: Because the sensor nodes are mainly powered by batteries, the energy is the scarcest resource in sensor networks. In order to be able to operate unattendedly for months even years, the critical requirement for WSNs is low energy consumption [8]. Therefore, the protocols and applications for WSNs must take into account this problem to prolong the operation time of sensor nodes, and thus the lifetime of WSNs.

High bit-error rate: The bit error rate in communication in WSNs is very high in the range of 5% to 10% or even more [49]. Therefore, it is difficult to control error as well as to provide reliability in WSNs while considering the energy efficiency.

Limited bandwidth and small frame size**:** IEEE 802.15.4 [48], a standard for low power, low cost, short range and small size devices, is currently supported by most of the common sensor devices. In this standard the maximum data rate is 250 Kbps and the maximum frame size is 127 bytes. These limitations impact the design of protocols and applications for WSNs.

Large number of sensor nodes: A sensor network may consist of hundreds or even thousands of sensor nodes [8], [45]. This leads to several problems that need to take into account when designing, developing, deploying and managing WSNs including energy efficiency, multi-hop communication, routing, delay and reliability.

Node failures: The nodes in a sensor network may fail because of energy drain or other factors. This leads to the problem of coverage and topology changes and affects the normal operations of the sensor networks.

Data-centric routing: A common type of applications of WSNs is data gathering and processing. In this new paradigm, the data at sensor nodes is usually named using attribute-value pairs, and the routing protocols may be likely based on this named data and not based on the addresses [8], [45].

Data flow pattern: The common data flow pattern in most TCP/IP networks is one-to-one, i.e., the client requests the data or service on another computer by using a specific IP address. However, in WSNs the common data flow is one-to-many and many-to-one [9]. For instance, when an application needs data from a WSN, it will send the request to the sink, which in turn broadcasts the request to all sensor nodes, i.e., one-to-many pattern. In the reversed direction, the data flow pattern is usually many-to-one because multiple sensor nodes may have data satisfied the client's request.

Positioning: The locations of sensor nodes are crucial information for many applications because the collected data are meaningless without knowing the places in which they are obtained. Although the localization in WSNs attracted a numerous researchers in both academia and industrial [45], [50], it is still to be a hard problem especially for the sensor networks that comprise mobile nodes.

Security: Similar to other networks, WSNs are also exposed to security threats and risks such as eavesdrop, attacks to the integrity of the messages, or injection of fake messages [45]. However, the risks of sensor networks are more severe than other traditional networks because the hardware constraints of the sensor nodes. In addition, the nodes can be captured, modified or destroyed by adversaries.

Interconnection and integration: The data collected by sensors finally need to be processed, analyzed and visualized by suitable tools or applications for making them meaningful. However, because of the limitation of sensor nodes, the existing interconnecting and integrating solutions for other networks are not appropriate or efficient to be used for sensor networks.

2.1.3 Requirements

In order for WSNs become wildly used in a real environment, the following requirements should be taken into account when designing and developing the protocols and applications for them.

Small code footprint: In order to fit to the sensor nodes, which have limited memory and computing capability [8], the codes for protocols and applications must be simple, small and optimized.

Energy efficiency: As battery is the primary power source of sensor nodes, the energy is a scarce resource. Therefore, energy efficiency is the main concern when designing the protocols for WSNs. In addition, because the component that consumes most energy is the radio communication [8], [51], in order to save energy it has to be minimized.

Fault-tolerance: The nodes in a WSN could be failed due to the drain of energy or other factors. In addition, the positions of sensor nodes can be intentionally or accidently moved because of human beings or other causes such as wind. These factors cause the change of the network topology, and affect the normal operations of the sensor networks. Therefore, the protocols and applications designed for WSNs should have a mechanism to deal with these changes. This means that the sensor network should continue to work normally in case there are some failed nodes or in case the topology has changed [8].

Routing: The routing protocols for WSNs have to be reliable delivery, energy efficiency, and able to deal with the changes of topology [45].

Self-organizing: As mentioned in [45], the self-organizing refers to the ability of sensor nodes to organize themselves to form a network as well as the ability to control and manage themselves efficiently. In addition, the protocols of sensor network should also include the capability to detect communication failures and to adjust to them.

Scalability: A sensor network can have up to thousands of sensor nodes [8], [45]. Therefore, the protocols designed for it should be able to work efficiently with such a large network.

Support data flow patterns: The protocols and applications should support all kind of data flow patterns of sensor networks. It should also support the data-centric feature of sensor network efficiently.

Security: Secured data transmission is an essential requirement of numerous sensor networks especially in critical environment. In addition, detecting other malicious attacks, e.g., jamming or replay is also an important requirement. Security solutions have to take into account the constraints of sensor nodes while providing an acceptable performance.

Coverage: One of the main functionalities of the sensor nodes is to gather the data surrounding them. Therefore, sensor networks and protocols designed for them have to ensure the acceptable coverage to produce the reliable results [45]. This means that the nodes in a sensor network cooperate to sense and transmit data so that any instance of the collected data cover the expected area.

2.1.4 Supporting Services

Besides the core requirements as discussed in previous section, it is necessary to support other requirements such as mobility, localization, and integration to bring the sensor networks into real life.

Mobility: Movement is a natural activity of most of the living objects, and it is an important feature of communication systems. In wireless network, mobility is the ability of devices such as laptop and smart phones to move freely but remaining connected. Such devices can switch from one network to another automatically. In WSNs, mobility can be classified in two main different fields: Mobility of the Sink, Mobility of the Node. Wang et al. [52], among others, introduces the mobility of sinks in which the sinks (base stations or data collectors) move across the networks to provide the communication or collecting data. In mobility of node, the mote itself has the ability to move [53] or is attached to a movable body. Mobility plays an important role in WSNs especially in maintaining coverage, connectivity and in increasing the lifetime of the sensor networks

[54]. In fact, supporting mobility for WSNs is an essential requirement for many applications.

Localization: Localization is the process or method for determining the location of unknown position objects. It plays an important role in WSNs, and it has been identified as one of the fundamental systems services that are essential for proper functioning of many types of sensor networks [55]. The positioning systems can be used for monitoring the location of patients in health care applications, monitoring workers in hazardous working environments, tracking the children in smart home, etc.

Integration: In order for WSNs becomes an integral part of our life as well as an important component of future Internet, interoperating WSNs with the IP network and external applications is desirable. By interoperating with the IP-based networks, WSNs are considered as an integral part of the Internet of Things (IoT) because they provide a digital interface to the physical world. Furthermore, the sensed data from WSNs can be processed, analyzed, and visualized by external applications such as Supervisory Control and Data Acquisition (SCADA), enterprise applications, Web 2.0, etc.

2.2 Medium Access Control protocol (MAC) for WSNs

In WSNs, besides energy efficiency, the reliable communication, i.e., the ability to successfully deliver packets to their destinations in a reasonable time, is also a desirable requirement. There are several factors that affect the reliability of sensor networks including noise, interference, multipath fading, and poor hardware. The mechanism for providing reliable communication can be done at data link layer or span all layers of a communication protocol stack. This section reviews recent research on the Medium Access Control protocol (MAC) for WSNs.

Because the wireless medium is shared by multiple wireless devices, it is necessary to have a mechanism to regulate the access to it. This is where the MAC protocol comes to take its role. The main function of MAC protocol is to decide when a node can access the medium and to resolve the collision between competing nodes when it happens. Moreover, it also provides the reliable transmission by error detection and retransmission. In order to provide this, two most common problems that most MAC protocols for wireless networks try to solve are hidden terminal and exposed terminal [56], [57].

The traditional MAC protocols can be divided into two main categories: contention-free and contention-based. The contention-free protocols avoid collisions by allocating resources to devices such that each device can exclusively use the allocated resource during the given time. Frequency Division Multiple Access (FDMA), Time Division Multiple Access (TDMA), Code Division Multiple Access (CDMA) [56] are examples of the mechanisms used in the contention-free protocols. On the other hand, the contention-based protocols allow multiple nodes to access the medium concurrently, but to provide mechanisms for nodes to minimize and to deal with the collisions. The common mechanisms used in wireless network are Carrier Sense Multiple Access (CSMA) [56], Multiple Access with Collision Avoidance (MACA), and Multiple Access with Collision Avoidance for Wireless (MACAW) [57].

Because of the special characteristics of sensor networks, e.g., large number of nodes, and limited capability of nodes, the primary concern of MAC protocols is energy efficiency. There are several sources causing energy wastage in WSNs including [58]:

- **Collisions**: This happens when two or more nodes within transmission range are simultaneously transmitting. The effect of collisions is that the collided packets are corrupted.
- **Overhearing**: In this case, a node wastes energy for getting packets that are not destined for it but for its neighbor.
- **Idle listening**: The nodes listen when there is no traffic on the channel.
- **Overhead**: There are two types of overheads: packet header and the control packets. The former refers to the header part of the frame or packet. The latter are the control packets that are sent and received by the protocol for synchronizing among the nodes before sending the data packet(s). These overheads cause energy wastage especially for transmitting short data packet.

Consequently, MAC protocols for WSNs try to reduce these waste energy sources. In addition to the energy saving concern, the MAC protocols for WSNs should also address the following problem: reliable communication, latency control (i.e., low and predictable), scalability, and adaptability (e.g., changes in topology). The existing MAC protocols for WSNs can be approximately divided into three categories: (1) contention-based, (2) schedule-based, and (3) hybrid as shown in Fig. 2.1. It is important to note that the schedule-based category is not always contention-free, i.e., some method is contention-free and some is not. In addition, most of schedule-based MAC protocols can also be hybrid because they employ both scheduled-based and contention-based mechanisms. The following sub-sections review the MAC protocols in these types.

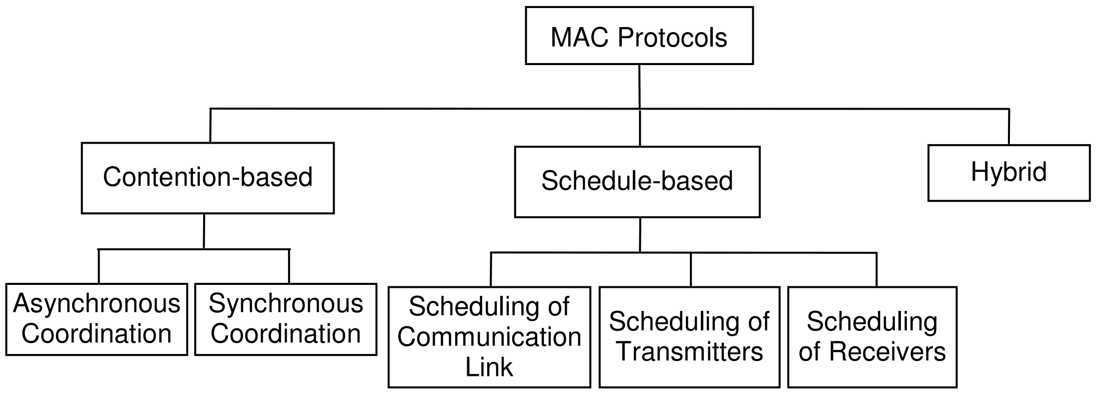


Fig. 2.1 A Category for MAC Protocols for WSNs

2.2.1 Contention-based MAC Protocols

In contention-based MAC protocols, the nodes have to compete with others to obtain the medium to send data. The advantage of the contention-based MAC protocols is their simplicity comparing with other methods. As a consequent, it is easy to adapt to the changes of the network such as topology or traffic pattern. However, it usually results in higher collision and energy consumption because of idle listening and overhearing [59]. In addition, it also faces with the problem of fairness because there may be some nodes obtaining the channel more often than others. The contention-based MAC protocols for WSNs can be divided further into two categories: synchronous and asynchronous coordination. The synchronous contention-based MAC protocols require neighboring nodes exchange their schedules in order for sender and receiver to wake up at the same time to transmit and receive the packets. On the other hand, the asynchronous contention-based MAC protocols do not require any cooperation between neighboring nodes.

2.2.1.1 Asynchronous Coordination Contention-based MAC Protocols

Perhaps one of the earliest contention-based MAC protocols that tried to reduce energy consumption by overhearing is Power Aware Multi-Access with Signaling (PAMAS) [60]. In this protocol, a node will turn off its radio when it cannot transmit or receive data. Therefore, the core function of PAMAS is to determine when a node cannot transmit or receive data. Similar to MACA, it uses Request-to-Send (RTS) and Clear-to-Send (CTS) control packets to reserve the channel before sending a packet. When a node overhears RTS packet not for it, it assumes that it may not receive the packets from other nodes because the arrival packets will be collided with the sending packets from its neighbors. Therefore, this node will turn off its radio if it has no packets to send. Similarly, when a node overhears CTS message, it will turn its radio off because it knows that it cannot send packets. The PAMAS can significantly reduce the energy consumption caused by idle listening and overhearing. However, it is costly to implement and inappropriate for WSNs because it uses two separate channels (radios): one for sending control messages, i.e., RTS and CTS and the other for data messages [60]. In addition, during receiving message time, the energy consumption of the receiver is almost double because it has to issue the busy tone on the control channel to blocking its neighboring nodes from initializing new transaction.

A more common approach for saving energy in WSNs is to use duty-cycle, i.e., the nodes turns off its radio as much time as possible and only turns on its radio when they have packets to transmit or to receive. For the asynchronous coordination MAC protocols, each node independently chooses its active/sleep schedule. Because neighboring nodes do not wake up at the same period, in order for a receiver to detect a transmission, a preamble is prepended to a data frame. When a node wakes up, it will sample the medium. If it detects a preamble, it will stay awake to receive the data, otherwise it goes back to sleep immediately. It is important that the preamble should be long enough for its intended receiver to wake up, detect it and receive the data. This type of protocols is also called channel polling or Low Power Listening (LPL).

Berkeley Media Access Control (B-MAC) [61] is a preamble sample MAC protocol in which the preamble is slightly longer than the sleep interval of the receiver to assure that the receiver will wake up and receive the packet. To reduce the collision, B-MAC uses backoff mechanism. In addition, to improve the efficiency of the clear channel determination, it proposed a Clear Channel Assessment (CCA) method based on outlier [61]. Furthermore, the active/sleep interval of a node can be configured to adapt with the traffic load of the application. B-MAC significantly saves the energy wasted by the idle listening, and control overhead. However, this protocol suffers wastes energy caused by overhead of long preamble, and overhearing problem.

X-MAC [62] tries to reduce the overhearing problem of B-MAC by dividing the long preamble into a series of short preambles. In addition, each short preamble also includes the identification (ID) of the receiver. When a node detects that the incoming packet is for it, it will send an early acknowledgement to inform the sender that the receiver is awake and ready to receive the packet. As shown in Fig. 2.2, the early acknowledgement will stop the sender from sending more preambles and thus it saves energy. In addition, it also saves the energy from overhearing by using the ID of the receiver.

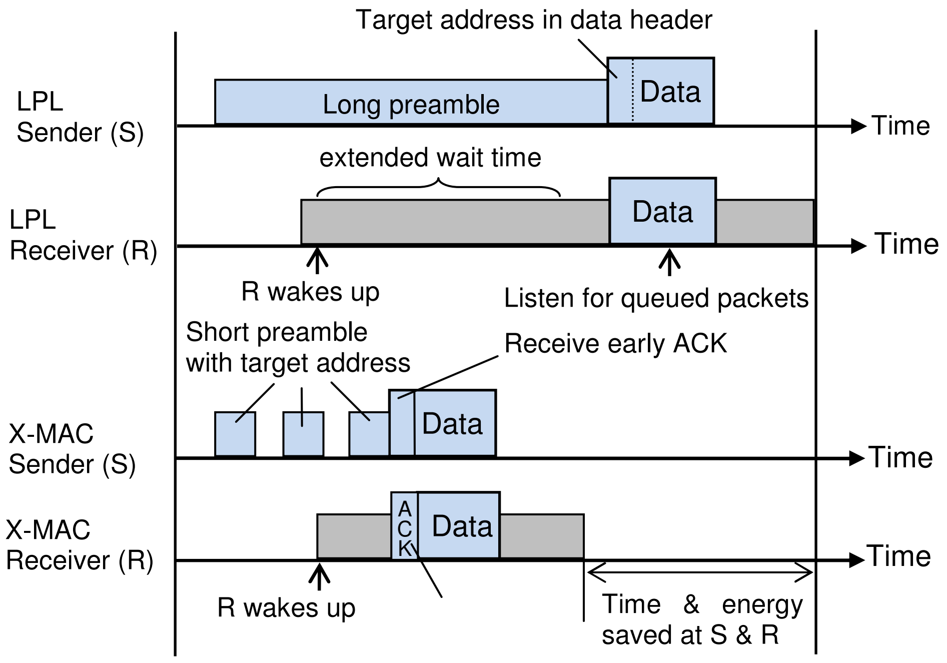


Fig. 2.2 Comparison of timelines between LPL's extended preamble and X-MAC's short preamble approach [62]

Another preamble sampling MAC protocol for WSNs is Backoff Preamble Sequential (BPS-MAC) [63], which uses a backoff preamble with variable length to reserve the access to the medium. The primary objective of this protocol is to provide reliably data exchange in dense WSNs. In this method, the interval during medium access is divided into very short slots whose duration is equal or larger than the CCA delay duration [63]. When a node wants to transmit a packet, it senses the medium for three slots. If the medium is free after the third slot, the node switches its transceiver from receive to transmit mode. Then, it randomly chooses a length of the backoff preamble, which is between one and the maximum backoff window, and transmits the preamble. After transmitting the preamble, the node switches from transmit to receive mode to sense the medium. If the medium is still free, the node switches its transceiver back to transmit mode and starts transmitting the data. Otherwise, it switches off its transceiver and waits for duration between two and the maximum backoff window before restarting the process. The use of preambles with variable lengths reduces the collision. However, the energy consumption of this protocol is very high because it does not use the duty-cycle.

2.2.1.2 Synchronous Coordination Contention-based MAC Protocols

In this approach, nodes also employ the duty-cycle method, i.e., the node periodically switches between active and sleep period, to save energy consumption. However, differing from asynchronous coordination protocols, this method requires neighboring nodes to be synchronized to wake up at the same time. Consequently, during the active period, the neighboring nodes compete to gain the access to medium to transmit the data.

Sensor MAC (S-MAC) [58] employs a fixed length active interval and a configurable sleep interval, defined by its duty-cycle parameter. The active interval is divided into two main portions: one for exchanging the SYNC packets and the other for transmitting the data packets [58]. Each sub interval is further divided into smaller slots. In order for the neighboring nodes to be able to communicate with each others, they have to wake up at the same periods, i.e., common active periods. S-MAC employs a distributed method for neighboring nodes to establish and synchronize their schedules. A node starts by listening on the medium for duration at least one active interval plus one sleep interval. If during this startup period, the node receives a SYNC packet, then it adopts the schedule carried in that packet. Otherwise, it forms a schedule for itself by randomly choosing a sleep interval. The node, then, broadcasts its schedule using the SYNC packet. To maintain the schedule synchronization, each node consists of a table of its neighbors' schedules, which are periodically broadcasted to the medium using SYNC packets [58].

In S-MAC, nodes transmit packets using the RTS/CTS handshake as used in MACAW [57]. In addition, to avoid overhearing, a node turn its radio off when it detects that it cannot neither transmit nor receive data as in PAMAS [60]. The packet of S-MAC includes a duration field to help the neighboring nodes to decide their sleep duration. Moreover, it also includes a mechanism that allows a node to reserve the medium for transmitting long message called message passing [58]. One limitation of this MAC protocol is that the schedule is decided beforehand, and it may be inefficient in real networks. In addition, because the listening period of S-MAC is fixed, it may waste energy if there is little or no traffic or it may be not enough when having heavy traffic. Furthermore, the energy wasted by the control packets, i.e., SYNC, RTS/CTS packets, is also high. Moreover, the collision is still high in dense WSNs.

A variation of S-MAC is Timeout-MAC (T-MAC) [64], which provides a mechanism to adapt with variable traffic load by using an adaptive duty-cycle. When a node wakes up, it listens for activity on the medium in a short duration and return to sleep mode when no communication is observed. In addition, it employs a flexible active period that let a node continue listening for a short interval after completing transmitting, receiving, or overhearing a message. This allows the node to receive or transmit multiple packets during its active interval. When a node has data to send but cannot transmit because the channel is busy, it continues waked up until the channel becomes idle. This leads to the early sleep problem, i.e., the intended receiver may return to sleep mode. T-MAC resolves this problem by using Future Request-To-Send (FRTS) message [64] to inform the intended receiver that there are incoming packets for it. This works as following: when seeing the CTS on the medium, the node, which has data to transmit but cannot do it, will send a FRTS message to request the intended receiver to stay awake. It is important to note that the FRTS message may collide with the data message of the neighbor transmitter. To solve this problem, after receiving CTS message the transmitter transmits another dummy message called Data-Send (DS) to delay the transmission of actual messages. However, this mechanism significantly increases idle listening and thus wastes energy.

2.2.2 Schedule-based MAC Protocols

The schedule-based approach requires coordination among neighboring or all nodes to reduce collision, idle listening and overhearing. Among the three common coordination techniques for traditional MAC protocols, i.e., TDMA, FDMA, and CDMA, the first is the highly used in WSNs. In addition, because their special characteristics, there are several variations of TDMA schedule-based MAC protocols for WSNs. The MAC protocols in this category can be divided into three groups: (1) Scheduling of communication link, (2) Scheduling the transmitter, and (3) Scheduling of the receiver.

2.2.2.1 Scheduling of Communication Link

This is the traditional approach in which the time is divided into frames which in turn are divided into slots. In each frame, each pair of neighboring nodes is assigned two slots: one for transmitting and the other for receiving. The advantage of this traditional method is that the internal collision can almost completely be avoided. In addition, the overhearing and idle listening are minimized. However, in multihop WSNs the collision may still happen because different paths may have different schedules. Another disadvantage of this type of MAC protocol is that it requires a high accuracy time synchronization, and thus increasing overhead. The scheduling mechanisms can be either centralized or distributed.

The Traffic-Adaptive Medium Access (TRAMA) [65] is a distributed election scheme to establish the schedules for nodes. In this protocol, each time frame is divided into random and scheduled access periods. The former period is used for synchronization and updating two-hop neighbour information while the latter one is used to contention-free exchange data between nodes. The Neighbor Protocol (NP) is used to gather and periodically update the two-hop neighbor information by using the signaling packets during the random access period. The nodes use Schedule Exchange Protocol (SEP) to exchange their schedules. For each time frame, every node computes number of slots it needed and employs the Adaptive Election Algorithm (AEA) to decide which time slots it can transmit. AEA computes the priority for a node at the time slot t using the pseudo-random hash on the time slot ID and the node's identification similar to that of used in Neighborhood-aware Contention Resolution (NCR) [66]. Each node computes this priority for all time slots for the node itself and all its two-hop neighbors, and it uses those time slots for which it has the highest priority. Based on the schedules exchanged using SEP protocol, nodes know when it should wake up to transmit and receive the packets and when it should go to sleep to save energy. The nodes without any data to send will give up the unused slots to its neighbors, thus, improving the channel utilization.

Besides saving energy, this protocol also scales well because the schedule is computed only based on the two-hop neighbors. In addition, it can also be easy to adapt to the addition and removal of nodes. Moreover, it allows node to give up the unused slots for other nodes and thus improving the throughput. However, the election algorithm is complex. In addition, the overhead caused by control packets was very high. Moreover, the delay of the packet may be long and unbounded. Furthermore, the fairness is also a problem of this protocol.

DMAC [67] is designed for the data-gathering tree pattern, i.e., the traffic flow is from the nodes to the sink. In this protocol, a "staggered wakeup schedule" is created for each route from a leaf node to the sink as follows. During its sending interval, a node sends a packet to the next hop on the route and waits for an acknowledgement. At the same time, the next hop node is in receiving state and immediately follows by a sending state to forward the packet to the next hop. This process is repeated until the packet reaches its destination. DMAC minimizes the energy wastage by idle listening and overhearing. In addition, it can guarantee a bounded delay. However, the collision between the nodes with different parents, i.e., different paths, is still happen. In addition, its traffic model is designed for sensor networks with static routes. Therefore, it cannot work well for arbitrary flow between source and destination or when the data flow is changed.

Power Efficient and Delay Aware Medium Access Protocol for Sensor Networks (PEDAMACS [68]) proposed a method for applying centralized TDMA for dealing with the unplanned sensor network. It consists of three phases: topology learning, topology collection and scheduling. In the first phase, each node collects information about its neighbors and decides its parent node based on the control packets sent by the sink. Then, the nodes send this information to the sink during the second phase. Based on the gathered information, the sink calculates the schedule for all nodes in the network such that in each time frame a node can transmit a packet to its parent without collision. After finishing computing, the sink broadcast the schedule to the nodes. It is important to note that the communication during the first two phases is contention-based and the schedule is only for the uplink, i.e., only including the path from nodes to sink.

PEDAMACS minimizes the collision, overhearing, and idle listening. In addition, it gives a bounded delay in a multi-hop network. However, besides the cost of control packets, the limitation of PEDAMACS is that it assumes the sink is powerful enough to reach all the nodes. This leads to the scalability problem. In addition, its performance is poor with a large sensor network.

Ginseng MAC (GinMAC) [69], [70] is another TDMA MAC protocol which guarantees reliable and timely data delivery while providing energy efficiency. It is used for multi-hop WSNs with a pre-dimensioned virtual tree topology and hierarchical addresses. The three main features of GinMAC are [69], [70]: off-line dimensioning, i.e., the network topology and traffic patterns are defined before deployment; exclusive TDMA, i.e., a slot used by one node cannot be re-used by other nodes in the network; Delay Conform Reliability Control, i.e., it supports delay bounds of time to send data to sink and time to send commands from the sink to actuators while achieving very high data transport reliability. Similar to traditional TDMA, with GinMAC the schedule is computed by the sink and broadcasted to the nodes. However, the topology and the maximum number of nodes of the sensor network must be defined in advance.

In GinMAC, each node is aware of its position in the tree and knows the slot numbers assigned to its child nodes and parent node, thus allowing it to transfer data in a collision-free mode. However, because the time slots are exclusively used it reduces the throughput. In addition, also has a problem with the scalability. Furthermore, if during its receiving slot the node does not has data to receive; it wastes the energy by idle listening.

2.2.2.2 Scheduling of Transmitters

The lightweight medium access control (LMAC) [71] is a TDMA-based protocol in which every node based on its two-hop neighborhood information to choose a time slot for itself. A node gets one slot in a frame to transmit packet, i.e., this method only creates the schedules for the transmitters. In order to indicate the intended receivers of each packet, a time slot is divided into control message (CM) and data message (DM). The former is used to send control message that includes ID of the intended receivers. When a node has data to send it waits until its allocated time slot and sends a control message during the CM period. Every other node has to listen at the beginning time slots of other nodes to check for incoming packets. If there is a packet for it, the node will wake up during the DM interval to get the packet; otherwise it will go to sleep mode. To establish the schedule at startup every node has to find a free time slot in its two-hop neighbors and then randomly choose one of them. It does this by listening for the CM from its neighbors, which contains a field named *occupied slots* indicating which slots are occupied. By combining the occupied slots in CMs from its neighbors, a node can find a list of free slot and randomly choose one of them. If there is a collision between nodes, the involved nodes will restart the process of choosing time slot. This process starts at the base station by randomly choosing a time slot and broadcasting it to the network.

Because scheduling only based on the information from two-hop neighborhood allows spatial reuse of the time slots, i.e., nodes whose distances are more than two-hops can use the same time slot. It provides fairness among nodes in the network. However, the nodes have to wake up at every time slot to check the destination of a packet, and thus it will increase the idle listening. In addition, the schedule is only calculated once, it does not adapt well to mobile sensor networks in which nodes regularly join and leave the network.

The Mobile LMAC (MLMAC) [72] is an improvement of LMAC by allowing nodes to update their schedules. In MLMAC, when two nodes are no longer receiving control messages from each others, they will remove them from their neighbor lists. On the other hand, when a node moves to new area, its old schedule might collide with a new neighbor. If this happens, at least one node in their neighbor will recognize the collision, and it will set the collision time slot as unused. This process forces the collision nodes to restart their scheduling process. Because both these MAC protocols use fixed allocation method, the bandwidth is not efficient used. In addition, control packet overhead also high.

2.2.2.3 Scheduling of Receivers

In contrast to the scheduling of transmitters, this type of MAC protocols creates the schedule for receivers, i.e., the node's schedule is the time slot in which it will listen for the incoming packets. It is important to note that scheduling of receivers is not collision-free because at any time there may be more than one node to transmit packets to a specific receiver. In this case, the transmitters have to contend to transmit the packets.

Pattern-MAC (P-MAC) [73] is contention-based and duty-cycle MAC protocol in which nodes use patterns to describe its tentative awake and sleep time. The pattern is a string of bits in the form 0^m1, where m=0,1,…,N-1, and N is the period or the frame length. The bits 0/1 represents the sleep and awake slot, respectively. For example, a pattern of 0001 and N=8 indicates that this node will wake up at the slots fourth and eighth of the period. This means that the pattern is repeated if its length is less than N. Nodes exchange their patterns during a time interval called the Pattern Exchange Time Frame (PETF) [73]. This pattern is only the tentative sleep-awake plan. The actual schedule of a node also depends on its current traffic and the patterns of receivers. A node always wakes up during bit 1 of its tentative plan to receive data. When a node has data to send, it will wake up and attempt to transmit at the time slot of the receiver. The node will go to sleep during other time slots. In order to save energy, during its time slot, a node only wakes up at the beginning of that time slot and listens for a certain period of time. If it hears nothing from its neighbors within that period, it goes to sleep again. Although P-MAC can adapt to the traffic changes in the network, it does not improve idle listening during active slots. In addition, the collision may be high when there is high contention during a slot. Moreover, its control header is also high because of the pattern synchronization.

O-MAC [74] is similar to P-MAC [73] in which each node independently selects its reception slot. During its reception slot, the node wakes up and senses the channel. If it detects a preamble then it remains active until it receives the whole packet [74]. In O-MAC, the nodes are scheduled to wake up so that the neighboring receivers do not interfere with each others. This protocol minimizes idle listening and overhearing but the collision and overhead is still high.

Y-MAC [75] is another TDMA-based protocol, but it uses a multiple channels. Each time frame is divided into broadcast period and unicast period. Each period contains a number of time slots which further are divided into two parts: (1) contention window and (2) message. Nodes wake up at the beginning of the broadcast period to exchange broadcast messages, e.g., control messages to synchronize the schedules among nodes. Each node is assigned a unicast slot to receive the data packets. When having a packet to transmit, during the contention window of the time slot of the receiver, the transmitter polls the base channel at a random time. If the channel is idle, it will occupy the channel by sending a preamble to the channel until the end of the contention window to suppress competing nodes. In order to further reduce idle listening, during its time slot a node only wakes up at the end of the contention window to checks whether there is any packet to receive.

In order to improve the performance (the throughput and delay), Y-MAC employs multiple channels and light-weight channel hopping mechanisms to hop between channels [75]. The advantage of this MAC protocol is that it can improve throughput and reduce deliver latency using multiple channels. In addition, scheduling receiver mechanism improves the energy efficiency. However, the overhead by control packets is high. In addition, it works poorly in the heavy traffic conditions.

2.2.3 Hybrid MAC Protocols

The hybrid MAC protocols combine the characteristics of both contention-based and schedule-based mechanisms. These protocols try to take the advantages of these types of protocols and try to eliminate their limitations.

Zebra MAC (Z-MAC) [76] is a MAC protocol that combines the TDMA and CSMA. As other distributed scheduling method, each node first collects information about its two-hop neighbor nodes. Then, each node employs DRAND schedule algorithm [77] to assign slots to every node in the network. DRAND ensures that no two nodes within two-hop neighborhood are assigned the same slot. Each time slot is large enough to transmit multiple frames. Z-MAC [76] has two operation modes depending on the contention level. In a low contention level mode, nodes compete in all slots with different priority. During its assigned slot, the owner has backoff time from 0 to T_0 and other nodes have backoff from T_0 to T_{n0}. After the backoff time, the nodes sense the channel to determine the channel conditions. In the high contention level mode, a node can use Explicit Contention Notification (ECN) [76] messages to notify all nodes within two-hops not to send during its time-slot.

Scheduled channel polling MAC (SCP-MAC) [78] is an ultra-low duty cycle which combines the strengths of scheduling and LPL, and other optimal mechanisms to save energy. Similar to other MACs, SCP-MAC also synchronizes the schedule with its two-hop neighbors. In addition, it avoids idle listening and overhearing within the active period through the sampling technique like that of used in X-MAC, i.e., including the address of the receiver in the preamble messages. Moreover, SCP-MAC can also be adapted to the traffic changes by additional wakeups that are added in the interval between two regular wakeups.

The Mobility Adaptive Hybrid MAC (MH-MAC) [79] protocol is another hybrid MAC protocol in which the scheduled–based approach is used for static nodes and contention-based approach is used for mobile nodes. A frame is divided into time slots which consist of two types: static slots and mobile slots. Each node estimates its mobility by using a mobility estimation algorithm based on received signal strength [79], and it uses a static or mobile slot depending on its mobility status. The nodes exchange its mobility during the contention time at that start of frame. MH-MAC uses the same mechanism as that of LMAC [71] to schedule static slots. For the mobile slots, the nodes contend for using the medium in a two-phase contention period by using the preamble sampling mechanism. Because all nodes have to wake up to sense the medium during the mobile slots, it increases the energy consumption. In addition, the overhead is also high because each frame includes first few slots for exchange mobility information of nodes.

It is important to note that besides the internal collisions, there are other factors that affect the communication in sensor networks including noise and interference from other devices and networks. In addition, in real environments, there is probable that other networks coexist with the sensor networks, which make it difficult to control the operations and reliability of the sensor network. One current research direction that tries to deal with these issues is Cognitive Radio (CR). The next section reviews current research in this field.

2.3 Wireless network Coexistence and Cognitive Radio (CR)

2.3.1 Wireless Network Coexistence

As the wireless networks and devices become ubiquitous and many of them operate on the same frequency band, interference happens almost everywhere. The interference affects the performance of the involved networks and devices. As an example, the IEEE 802.11b/g/n and IEEE 802.15.4 compliant networks use the same 2.4 GHz band and they may be deployed in the same area. The study in [1] showed that with the interference caused by IEEE 802.11 based network the Packet Error Rate (PER) of IEEE 802.15.4 was up to 95% when the interferer is in the distance of 1.5 meters.

Inversely, the throughput of IEEE 802.11 based network was reduced up to 30% when the IEEE 802.15.4 based network in a short distance [2].

Yuan et al. [80] presented a model based on power and timing to evaluate the coexistence of WLAN (IEEE 802.11b/g) and WSN (IEEE 802.15.4). In this work, the CSMA/CA was employed and the CCA mechanism was used by a node to decide whether or not to transmit a frame. Results from simulation showed that interference between the networks was related to the power of transmission and the distance between nodes and it severely affects the throughput of sensor networks. In addition, Toscano and Lo Bello [81], [82] showed that even in networks consisting only of WSN, interference still exists. Their test results on IEEE 802.15.4 based networks showed that interference depended on the transmission power, on the distance between nodes and on the duty-cycle. From these studies, it is important to note that interference is a hard problem in coexistence of wireless networks, and it is necessary to have mechanisms for different wireless networks to work reliable in the same area without affecting each others.

Interference in wireless networks can be divided into two different types: co-channel and adjacent channel. Co-channel interference is defined as the use of the same frequency by more than one network or devices in the same area [83]. This type of interference cannot be solved by increasing the signal power as that would increase the interference and the communication problems in other neighbor networks. On the other hand, adjacent channel interference occurs when consecutive channels are used by different devices which lead to the degradation of both signals. That is the reason why channels of a standard are separated in frequency to avoid interference. However, the separated mechanism may not be sufficient because the filters and transceivers used by devices are imperfect and they cannot cancel all the interference [83]. The effect may even be more severe when transmitters and receivers from different networks using adjacent channels are close to each other. To prevent this, better filters can be used in transceivers and non-adjacent channels should be selected.

In order to deal with the coexistence of different wireless networks in the same area, the IEEE 802.15.2-2003 work group [4] proposed a recommended practice for coexistence of Wireless Personal Area Networks (WPANs) with other wireless devices operating in unlicensed frequency bands, particularly wireless Local Area Networks (WLANs). This recommendation suggests two approaches for coexistence between WLANs and WPANs. The first approach requires the involved networks to collaboratively exchange the information about the traffic patterns to mitigate the interference. However, the problem with this approach is that it is necessary to have a communication link between two networks. In addition, it requires a central control system to synchronize to grant the access to the medium. The control mechanisms could be timing or on demand. Moreover, it is difficult to realize in real environments.

The second approach is to use non-collaborative mechanisms in which no common communication link between the two types of networks is required. The possible techniques that can be used in this approaches are adaptive packet selection and scheduling, signal processing, adjust packet size depending on the condition of channel, and channel hoping [4]. Recently, the IEEE 802.19 work group [84] was created to continue the previous recommendations and to develop a standard for coexistence between wireless devices operating in unlicensed band.

The work in [85] illustrated the utilization of the collaborative mechanism for allocating channels among WSNs. The network model in this study consists of a central entity and the WSN coordinators. It is assumed that all WSN coordinators have wireless and wired interfaces and that the communication to the central entity is made using an Ethernet network. Results showed that this mechanism could be used to allocate the resources (i.e., the channel) to sensor nodes and allow coexistence among WSNs. However, this mechanism is only validated with simulation. In addition, it only works for the same types of networks (i.e., WSNs). Consequently, it cannot deal with the interference from other wireless devices.

Zhou et al [86] experimentally demonstrated how electronic devices operating at 2.400 MHz can cause interference and even hinder the operation of the IEEE 802.15.4 based WSNs. To avoid this, the authors proposed a multi-channel approach for WSNs, which have multi-frequency radios. They also proposed a middleware between the physical and MAC layers in order to support multiple channels. However, this model was not validated.

Frequency Hopping Spread Spectrum (FHSS) can be used as an alternative solution to the coexistence of WSNs. According to [87], channel hopping can reduce interference and increase resilience between neighborhood networks. However, this mechanism uses a pseudo-random sequence to make the frequency hops and does not consider the quality of different channels. If interference exists in more than one channel, FHSS technique may result in loss of packets and intermittent disruptions.

2.3.2 Cognitive Radio (CR)

A more recent technique for flexible and efficient usage of radio spectrum is Cognitive Radio (CR) [88]. The objective of CR is to allow secondary devices to opportunistically access the radio channel without affecting the primary users. One of the main characteristics of CR is the ability to change the radio parameters (including frequency, power, modulation, bandwidth) depending on the radio environment, user's situation, network condition, etc [89]. Consequently, it is important to have such a kind of radio that enables dynamically reconfiguring these parameters by software; and this type of radio is called Software Defined Radios (SDR) [5], [89]. CR is based on Dynamic Spectrum Allocation (DSA), or Opportunistic Spectrum Allocation (OSA) scheme to improve the usage of the radio spectrum. The main functions of CR are sensing, management, mobility, and sharing the spectrum [5]. These functions help to indentify a best channel or available hole for devices or networks to use at current time

Dynamic Spectrum Access Protocol (DSAP) [90] is a collaborative protocol for coexistence with central coordination. It is designed to be used in limited geographical areas and aims to lower the congestion and interference between networks by adjusting the channels used by the nodes, according to information provided by the central coordinator. To accomplish this, management coordinators must have previous knowledge of the channels in use in the region. The coordinators use two interfaces, one to have a common channel to communicate with its client nodes and other to access the information about the channel usage in the region. Results show that the DSAP reduces interference and improves the throughput. However, a wrong choice of the common channel or the effects of noise in the communication environment may disrupt the communication between nodes.

The study in [6] showed that it is possible to apply DSA models for WSN to efficiently use frequency spectrum and to support the coexistence of the networks. To accomplish that, CR explores the frequency spectrum using an opportunistic mode, adjusting the transmission parameters (frequency, transmission power and/or codification) based on the information gathered from the environment. Other approaches using CR are discussed in [5], [88] and propose that CR, besides the programmable reconfiguration, may also learn to adapt to the surrounding environment by reconfiguring, in an intelligent way, all the transmission parameters.

A framework for employing CR for WSNs, named Cognitive Radio Sensor Networks (CRSN), was proposed in [91]. In this work, the authors developed two spectrum decision protocols for applying CR mechanism for WSNs. These protocols employ distributed mechanisms to select the best wireless channel based on the application's Quality of Service (QoS) requirements. Simulations of low, medium and high noise scenarios have shown that the protocols improve the delivery rate while keeping the delay and energy consumption unchanged. However, the works in [91] only validated using simulation, its applicability for real WSNs is a question and needs more efforts to realize. In addition, the proposed protocols are based on CSMA/CA whose response time is not deterministic and therefore are not suitable for critical environments.

Although cognitive radio is a potential mechanism for coexistence, the full CR may be too complicated for sensor networks. Therefore, it is necessary to have simpler mechanisms for WSNs to coexist with other wireless networks while providing an acceptably reliable communication. In addition, the coexisting solution should also take into account other noise sources such as machineries, engines, and turbulences.

2.4 Integrating Sensor networks With External Environments

Although there are numerous potentials, WSNs are useless if operating in isolation. It is clear that the sensed data must be collected, processed and visualized by some applications to make them meaningful to users. In addition, the sensed data could be mashed up with other data resources via web to create new applications. Moreover, the sensor nodes and networks can also be remotely monitored and controlled by users through front-end applications. Consequently, interoperability between sensor networks and external environments is an undeniable requirement. Realizing this requirement will make WSNs an important component of the future Internet and integral part of our lives. The following subsections reviews the current works on interconnection and integration approaches for WSNs as well as discusses their advantages and limitations.

In this thesis, the term external application refers to an application such as Supervisory Control and Data Acquisition (SCADA), enterprise application, or application platforms such as web 2.0. In addition, the term external network refers to the networks other than sensor network such as LAN or Internet. Moreover, the term external environment refers to both external application and network.

2.4.1 Internetworking

The approaches for interconnecting WSNs with external networks can be divided into two main categories: Gateway-based and IP-based.

2.4.1.1 Gateway-based Approach

As sensor networks are very different from the IP-based networks, the common approach to interconnect them is to deploy one or more gateways or proxies between the two dissimilar networks. Different gateway-based methods have been proposed for connecting WSNs with external networks.

2.4.1.1.1 Application-level Gateway

In this approach, the gateway or proxy translates and forwards the packets between two networks. The gateway or proxy can act as a relay or as a front-end [7]. In the relay mode, when receiving a message from sensor network, the gateway/proxy simply translates and relays it to the client applications on TCP/IP network. In order to know to destinations to forward the messages, the clients must register for the particular interest data with the gateway. On the other hand, in the front-end mode, the sensed data are collected and stored in the database on the gateway, and the clients then query it for the required information.

The main advantage of application-level gateway is that it completely decouples two types of networks. This makes them totally transparent to each other, i.e., the client applications can use the sensed data without knowing details about sensor networks. In addition, it is simple to implement. Furthermore, some security features such as authentication and authorization can be implemented with the front-end gateway approach. However, the application-level gateway is usually for specific tasks or a set of specific protocols, i.e., it requires a specific gateway or proxy for each sensor network [7]. In addition, conventional application-level gateway does not support direct access to individual sensor nodes. Furthermore, the gateway is the single-point of failure, i.e., if the gateway fails, then the communication between two networks becomes impossible.

In order to allow direct access to individual sensor nodes from the Internet using application-level gateway, Kim et al [11] proposed a scheme for assigning IPv6 addresses to sensor nodes. In this method, the gateway maintains a table of mapping between IP address and sensor node’s identification information such as network ID and sensor ID.

2.4.1.1.2 Low-level Gateway

Low-level gateway is another approach for interconnecting sensor networks with external networks. Differing from the application-level gateway, in this approach the gateway does not translate the content of the packets but it only translates the lower level header information of the packets between these two networks.

Shu et al. [12] proposed an approach for interconnecting several isolated heterogeneous WSNs with IP-based networks to form a virtual sensor network named VIP Bridge. VIP Bridge was based on the node-centric or location-centric communication paradigm to map node IDs to IPv6 addresses. Because the TCP/IP protocol stack was not implemented on the sensor nodes, the IP addresses of sensor nodes were stored on the VIP Bridge. Similar to the application-level gateway, the packets that comes from one side is translated into the corresponding format and sent to the other side by the VIP Bridge. However, VIP Bridge is not an application-level gateway but a low-level gateway, i.e., it does not translate the content of the packets but only makes a mapping between IPv6 addresses and sensor node IDs and routes the traffic between these two networks.

The main advantage of this approach is that Internet applications can directly access to the sensor node using IP addresses. This makes the sensor networks transparent to the Internet users, i.e., sensor nodes are viewed as normal IP hosts. In addition, the communication protocols in WSNs could freely be chosen. However, this approach has several limitations. First, it requires the sensor nodes to register their IDs or location addresses as well as the essential information with VIP bridges. In addition, the client applications are WSNs-specific, i.e., they must have the ability to understand and analyze the payload of the WSN packets. One more drawback is that the packet analysis and translation are based on a specific field to categorize the packets into operation or query commands (O/Q) or data or acknowledgement (D/A) [12]. As a result, the VIP Bridge regulates its own packet format for communication between WSNs and IP networks, i.e., this solution cannot be deployed for existing sensor networks and applications. Furthermore, creating and sending multiple packet to WSNs for a data query is not efficient.

Another low-level gateway that bases on the idea of VIP Bridge with some improvements was proposed in [10]. First, it does not require sensor nodes register their information to the gateway. Second, it does not use a specific field to identify the type of commands (operation or query). Therefore, it also does not require modification of user and sensor applications. In addition, it supports the data-centric WSNs by assigning a virtual IP address for a specific interest similar to multicast IP. Furthermore, it also provides two-way communication by assigning virtual sensor node IDs for IP hosts. However, this approach has several drawbacks. First, the low-level gateways assume that the application protocol is the same on both sides. This makes the sensor networks not totally transparent to Internet host. This also means that the low-level gateway approach requires that the user applications must have ability to analyze the packets from the WSNs to get the useful data. Furthermore, these frameworks are not well support for data-centric network, i.e., one-to-many and many-to-one data flow.

2.4.1.2 IP-enabled WSNs

Because of the resource-constraint of sensor nodes many researchers assumed that it was unfeasible or inefficient to deploy TCP/IP protocol stack directly into sensor nodes [8], [10], [12]. However, the micro IP (uIP) implemented in [14] proved that it is possible to implement the TCP/IP stack on the sensor nodes with limited memory and computation. In addition, Dunkels et al. [21] introduced some optimization mechanisms such as spatial IP address assignment, header compression, application overlay routing, and distributed TCP caching for adapting TCP/IP protocol stack for WSNs. These works laid groundwork for exploring the use of TCP/IP for WSNs.

In recent years, IPv6 for sensor nodes has attracted a lot of attention of the research community because of its huge number of addresses and its simplicity. In order to apply IPv6 for sensor networks, 6LoWPAN [15], [92], [93] proposed an adaptation layer between link layer and network layer to enable efficient IPv6 communication over IEEE 802.15.4 links. In addition, it also proposed a cross-layer optimization with three primary elements: hear compression, fragmentation and layer-two forwarding. Currently, both TinyOS [94] and Contiki [95], the two most common operating system for WSNs, include an implementation of the 6LowPAN [15].

Incorporating IP directly in sensor nodes makes the interconnection between sensor nodes and the Internet easier and more natural, i.e., the Internet host can directly communicate with the sensor nodes. It is the crucial step to realize the vision of Internet of Things (IoT). However, its efficiency in terms of energy and usefulness as well as its suitability and applicability for WSNs still needs more investigation. The most obvious issue with this approach is that it is not suitable for data-centric sensor networks, where the routing is based on the contents and not on the addresses of sensor nodes. In addition, security is also a big issue. Furthermore, adaptation layer and other optimal mechanisms make 6LoWPAN [15] incompatible with conventional IP network. Consequently, it still needs a bridge/router/gateway between WSNs and IP networks.

Although the studies have shown that it is possible to deploy TCP/IP protocol stack into sensor nodes, both approaches (gateway-based and IP-enabled) for interconnecting

WSNs with the external networks have been continue co-existing. In some case, IP-based approach is more appropriate but in others gateway-based must be used. Furthermore, the combination of gateway-based and IP-based approaches is also possible.

2.4.2 Integration

Interconnecting sensor networks with external networks opens the gate for realizing the IoT. However, because the primary functions of a WSN are to sense or gather the physical data and to activate things, it needs to be monitored and controlled by other applications. In order to allow a seamless interoperability between sensor networks and external applications, it is necessary to have another abstraction layer. This means that it needs an infrastructure for simplifying the data exchange between sensor networks and external applications.

The current work on integrating sensor networks with external applications can be approximately categorized into two groups: direct access and Indirect access. The following subsections review the research on these areas.

2.4.2.1 Direct Access Approach

One research direction on integrating sensor network with Internet and external applications is to treat the sensor nodes as the normal nodes of the IP based network. This means that each node has a unique IP address, a web server, and/or a Web service API. In this approach, each sensor node is treated as an information server [18], and it can be directly accessed from the Internet.

One of the early works on this approach was Tiny Web Services [17], which employed uIP [14] and Web services for sensor nodes. Because the standard implementation of Simple Object Access Protocol (SOAP)-based web services [96] is unlikely to be suitable for sensor nodes, Tiny Web Services employed numerous optimization mechanisms to reduce overhead and delay [17]. First, the TCP persistent connection was used to reduce the number of TCP messages in each call. In addition, TCP acknowledgements were disabled to reduce delay. Furthermore, to support end-to-end reliability, link layer retransmissions were employed instead of transport layer. Moreover, the low power mode between TCP messages could also be used to improve the energy efficiency. Notably, although, the Hypertext Transfer Protocol (HTTP) binding is used to remove the SOAP envelopes from the messages, the sizes of messages are still too large for constraint devices. Therefore, Tiny Web service [17] employed a context based compression method in which the method name was replaced by its compact tag, i.e., a number. For supporting duty cycled nodes the WS-Eventing [97] was implemented at the gateway. A prototype was implemented to prove that it was possible to use Web service for resource-constrained sensor nodes. However, despite the payload of the message being compressed, it was still very large when compared with the bare-bone protocol. In addition, because Tiny Web Services [17] employed the generic compression algorithms and supported cycled duty, it still required an HTTP proxy between the client applications and sensor nodes.

Another work that implemented an embedded IP stack and HTTP server on each node to make its sensors and actuators available through web service API was introduced in Web of Things (WoT) [19]. Different from Tiny Web Services [17], this work employed Representation State Transfer (REST) [98] based web service, i.e., it was built on top of HTTP and uses JavaScript Object Notation (JSON) [99] instead of eXtensible Markup Language (XML) [100] for formatting messages. Because the work in [19] did not employ any optimization mechanisms for reducing the overhead, it is possible for user applications to directly access sensors' data and functionalities. However, although RESTful web service [98], [101] is more compact then XML based web service, it is still inappropriate for many constraints sensor nodes. In addition, it is difficult and inefficient to implement both standard TCP/IP stack and traditional web services on sensor nodes. In fact, the current implementations of this work was not included the TCP/IP protocol stack. Consequently, a proxy and gateway is still needed to access the web service API implemented on the sensor.

A similar work to [19], which implemented RESTful web service on the sensor nodes, was sMAP [18]. However, sMAP targeted at the representation and transmission of the physical information. Particularly, it defined a hierarchical organization for the information. In addition, the web service on each node also provided the necessary information for interpreting the sensed data. Moreover, to make the message more compact for sensor nodes, sMAP employs the adaptations at different layers for running on constraint devices including 6LowPAN [15] at network layer, User Datagram Protocol (UDP) [102] at transport layer, Embedded Binary HTTP (EHTTP) [103] for web instead of HTTP, and packed JSON [18]. Similar to previous works, the proxy and/or gateway was still needed for the communication between the user applications and sensor networks.

2.4.2.2 Indirect Access Approach

This approach refers to the integration methods that comprise one or more gateways or proxies sitting between the sensor networks and the client applications. The gateway provides a set of web service API for the client applications to access the sensed data as well as to communicate the commands to the sensor networks.

Global Sensor Networks (GSN) [13] proposed an infrastructure for data integration from multiple sensor networks through the virtual sensor abstraction. The virtual sensor receives and processes the input data from the real sensors or other virtual sensors to produce a unique output. Which input data and how they are processed to create the output is described by the virtual sensor description. This way, the virtual sensor abstracts the details of access to the sensor data. The input and output data structure are described using XML, and Structured Query Language (SQL) syntax is used to describe how the input data are manipulated to produce output. Consequently, GSN [13] can help to integrate data from multiple sensor networks, and to hide the details of sensor networks from client applications. In addition, it also allows client applications to easily combine the sensed data as other traditional data sources. However, in order to feed the input data to GSN, a software wrapper is needed for each specific type of devices and for each data frame structure.

Inspired by the success of Web 2.0 paradigm, researchers have tried to leverage this model for integrating sensor networks with the applications. This means that the sensed data and sensor nodes can be treated as traditional data sources, i.e., they can be easily accessed by applications, e.g., via web service API or using a browser. SenseWeb [104] was such an approach which proposed an infrastructure for sharing sensor data in order for them to be consumed or mashed up with other applications. It provides a Web Services API for applications to access shared sensor data. In addition, to communicate with sensors, it comprises a gateway, called DataHub [104], and drivers to communicate with sensors. Moreover, it also includes mobile proxy for communicating with mobile devices such as mobile phone or sensor attached to vehicles. Furthermore, in order to add semantics to the data, it also consists of a set of transformers to convert raw data to suitable format as well as adding the description to it.

2.4.3 Comparison of the Integration Methods for WSNS

This section makes a comparison among the current approaches for integrating WSNs with the external environments. This comparison is mainly based on the features that an integration solution should provide. It is important to note that the 6LowPAN [15] is not included in this comparison because it is considered as the infrastructure for other higher layer integration solutions. In addition, the application level gateway in this context is the traditional gateway, i.e., it simply translates the messages between two different types of networks.

Table 2.1 Comparison of Different Approaches for Integrating WSNs and External Environments

	Application level gateway	VIP ridge [12]	Tiny Web Service [17]	WoT [19]	sMAP [18]	GSN [13] and SenseWeb [104]
Transparency	Yes	No	Yes	Yes	Yes	Yes
Interoperability	Potential	No	Yes	Yes	Yes	Yes
Freely choose optimal protocols for WSNs	Yes	Yes	No	No	No	Yes
Individual node access	Potential	Yes	Yes	Yes	Yes	Yes
Easy Integration	Potential	No	Yes	Yes	Yes	Yes
Data-Centric	Potential	No	No	Partial	Partial	Yes
Adaptability	Potential	No	Partial	Partial	Partial	Partial

In this comparison:

- "Potential" means that it is possible to provide such features but it was not considered or implemented in traditional methods.
- "Partial" means that the proposed solution does not fully support the feature.

The "*transparency*" feature in this context means that the details of sensor nodes and networks are hidden from the external applications. In addition, the changes inside the WSNs (e.g., adding new frame format, changing routing protocols, etc) should be hidden from the client applications. What the application needs to know is how to obtain required data or how to send command to the sensor network(s). VIP Bridge [12] only provided virtual IP address for sensor nodes, it did not hide the higher layers from applications. In addition, it required modifying the sensor node applications to register to the gateway.

The second feature, *interoperability*, means that the integration solution should follow a well-known encoding format for exchanging information. In addition, the contents presented in the message are correctly understood by the applications, i.e., semantics. Moreover, it should also provide a standard interface for accessing sensor networks. The Internet host's applications can interact with WSNs using the similar methods that are used to interact with other software components, e.g., using web services. The first two methods in Table 2.1only concentrate on interconnect the two types of networks, and it leaves the user applications to analyze and interpret the sensed data. On the other hand, the remaining solutions exposed the sensed data using web services. In addition, it could also include the semantics for the sensed data, as an example, sMAP [18] comprises description for the representation of data. Consequently, it is very easy for the user applications to interoperate with WSNs.

Because the sensor nodes have very limited resources, the integration solutions should maintain the optimization mechanisms for the sensor networks, i.e., the developers can freely choose protocols that best fit for the specific deployment. Because the Tiny Web service [17], WoT [19], and sMAP [18] directly deployed web services on sensor nodes, it limits that the optimization mechanisms can only be related to TCP/IP and web services. Therefore, it is difficult or impossible to choose the optimal protocols for WSNs. The other solutions do not intervene in the internal operations of sensor networks; therefore, they are free to choose the protocols to be used in WSNs.

In this section, "*individual node access*" means that Internet hosts can directly send commands to individual sensor nodes using some types of identification, e.g., IP address. This type of access is required for remotely manage purposes such as monitoring, reprogramming, reconfiguring nodes (e.g., control sensing and report functions) or actuating other systems. Among the current approaches, implementing web services on sensor nodes naturally provides access to individual sensor node. Similarly, low-level gateway [12], which assigns a global unique IP for every sensor node on the bridge, also allows to directly access to individual sensor node using its virtual IP address. Meanwhile, it is assumed that application-level gateway does not provide direct access to sensor nodes. However, it is possible to adopt this functionality into application-level gateway to provide access to individual sensor nodes.

One crucial requirement for integration solution is that it is easy for the applications to access and consume the sensed data. By exposing the sensed data using web service

API, e.g., Tiny web service [17], WoT [19], sMAP [18], and SenseWed [104] make the interoperability between sensor networks and applications easy. They allow the physical information available to be mashed up with other data source via web. Other solutions require the application to know how to analyze the message from the sensor networks. However, the application-level gateway could include the web services to expose the sensed data; and therefore, it can make the integration with external applications easier.

Data-centric, named data query, is one of the typical features of WSNs. It is also a challenge for integrating WSNs with IP-based networks. The approach embedding HTTP servers and web services into sensor nodes mainly focuses on providing access to individual sensor nodes, and do not dedicate much attention towards methods for querying sensor networks (data-centric). Although VIP Bridge [12] allows to send queries, it only allows to send individual sensor nodes. Additionally, it does not provide a mechanism for processing and aggregating the result data. The gateway-based approach, .e.g., GSN [13] and SenseWeb [104] can supports data-centric for WSNs.

Adaptability feature refers to the ability of the integration solution to be able to adapt to different types of protocols and data frame formats of sensor networks. It is an important requirement because there is a large number of protocols and a frame formats developed for WSNs, and the numbers have never stopped increasing. In addition, the sensed data is not consumed directly by end users but by other applications. This leads to a small change in data format could lead to totally different packet for the client applications. Because web service in sensor nodes sits on top the communication layer, this approach adapts well with the diversity of protocols and data formats of sensor networks. VIP Bridge [12] cannot adapt well with the changes in sensor networks because they needs to know the detail of the protocols to make the conversion. In order to add a new type of sensor, or data format frame, it is necessary for the gateway-based solution to have new modules or drivers to deal with this change.

From the analysis in this section, we recognize that in order to seamlessly integrate WSNs with external applications, the integration solution should take into account the requirements mentioned in Table 2.1. The integration infrastructure should be able to adapt to different data formats of WSNs without reprogramming. As adaptability is an important feature and it is not resolved by the current gateway-based, the integration framework in this thesis tries to propose a solution for this problem. In addition, the interoperability is also a primary focus.

2.5 Localization

Localization is the process of determining the positions of devices, objects, things or people within an area of interest. Localization in wireless networks (including WSNs) is an important area attracting considerable research and development both in academia and industry. It is especially important in WSNs because the measured data are meaningless without knowing the location from which the data are obtained. In addition, many important and useful applications, e.g., rescue, target tracking and monitoring, and health-care, need information about the place in which the events happened, i.e., the position of the objects involved in the events. Furthermore, the positions of nodes can be used in routing algorithms and for reducing power consumption mechanisms.

In order to estimate the position of unknown position objects (e.g., sensor nodes), the localization algorithms need some inter-sensor measurement, e.g., the signal strength, the angle, or the propagation time. In addition, in most cases, it is necessary to have the presence of a number of known position nodes called anchors, reference points or beacons. Based on different assumptions and applications, numerous localization algorithms have been proposed for WSNs. Although using different algorithms and having different requirements, the localization systems usually comprise two main phases: measurement and position estimation. In each phase, there may be one or more steps depending on the localization algorithm. During the measurement phase, data useful for the localization purpose are obtained from the network. The measured data are then used by the location algorithms to estimate the position of the object in second phase.

This section reviews the measurement techniques that are practically feasible in wireless networks and major localization algorithms that were proposed so far for determining the positions of nodes in WSNs.

2.5.1 Measurement Techniques

In order to determine the position of a device, it is necessary to have some measurement between nodes or between a node and several anchors in the network. The common measurement methods that can be used in estimating the position of a device in a wireless network are Received Signal Strength Indication (RSSI), Propagation time, and Angle-of-Arrival (AOA). This section reviews these measurement methods and discusses their strengths and limitations.

2.5.1.1 Received Signal Strength Indication (RSSI)

Perhaps the simplest and cheapest measurement method is RSSI because it is easy to measure and is available in almost every wireless network including WSNs. RSSI is the magnitude of the power of the signal received at the receiver. Theoretically, by using RSSI, the transmitted power, the gain of antennae at the transmitter and receiver, and the propagation model, it is possible to estimate the distance between the transmitter and receiver. However, because the propagation characteristics of the channel change from place to place and from time to time [105], it is very difficult to find a good propagation model for a specific environment. In addition, there are a number of factors that affect the quality of the received signal strength including pathloss (i.e., attenuation and the effects of the propagation channel), shadowing (e.g., absorption, reflection, scattering, and diffraction caused by obstacles between the transmitter and receiver) [106], interference, noise, and even the quality of the devices (e.g., anisotropy and the sensitivity of the antenna) themselves. These factors make the RSSI value be unstable and unreliable. As a result, it is high inaccurate to estimate the distance using RSSI value.

2.5.1.2 Propagation Time

Signal propagation time, also called time-of-flight, is the time taken by a signal to travel from the transmitter to the receiver. It is possible to use the propagation time to estimate the distance between two devices because the propagation speed of signal in the medium is usually known in advance. For instance, the sound signal travels at the speed of 344 meters per second in dry air at 21◦c; or radio signal travels at the speed of 299,792,458 meters per second [107]. There are several different techniques that can be used to measure the propagation time including Time-of-Arrival (ToA), Round-trip time-of-flight, combining radio signal and Ultra-sound, and Ultra-wide band (UWB).

Time-of-Arrival (ToA): ToA measures the difference between the time at which a signal is received (arrival) at the receiver and the time that signal was transmitted by the transmitter [108], [109]. In order to compute this time difference, it is required that the transmitter has to timestamp the frames when sending them. More importantly, the local time of transmitter and receiver must be very accurately synchronized. However, because the travel speed of radio signal is very fast and WSNs only communicate in a short distance, it demands that sensor nodes have a very high accurate clock and more complexity algorithms to have the high accurate synchronization, i.e., nanosecond (ns). Consequently, ToA is not a suitable measurement method for WSNs.

Round-trip time-of-flight: This method to measures the difference between the time a frame was sent by a node and the time that frame arrived back to it [108], [109], [110]. Although the time synchronization is not required, because the same clock is used, there are still several sources of errors. First, the waiting times at the transmitter and receiver, i.e., the duration that the frame is in queue because channel is busy. In addition, the processing time of MAC protocol and higher layers is usually difficult to compute. Moreover, the precision of hardware packet timestamp also contribute to the accuracy of this measurement method. Furthermore, other factors such as Non-Line of Sight (NLoS) also significantly affect the accuracy of measurement. Finally, because this method requires multiple frames to be exchanged between unknown position device and anchors, it is difficult to use in localization algorithms for highly mobile nodes.

Combination of Radio and Ultra-sound signals: A more accurate but more costly method for measuring propagation time without time synchronization is to combine Radio Frequency (RF) signal and Ultra-sound signal [26]. In this method, the transmitter sends both the RF signal and ultrasound pulse at the same time. Because the speed of RF signal is very fast comparing with that of Ultra-sound pulse and the communication in WSN is in very short range, the RF signal could be considered as instantaneously received at the receiver without any delay. Consequently, the propagation time can approximately be calculated as the difference between the arrival time of Ultra-sound pulse and that of RF signal. The advantage of this method is the accurate estimate of the propagation time. However, it requires the additional hardware which is costly and energy inefficient for WSNs. In addition, the Ultra-sound is severely affected by obstacles, multipath and other noise sources.

Ultra-wide band (UWB): A signal is considered as an UWB if its total bandwidth is more than 500 Mhz [111]. It is a new wireless technology for short-range high bandwidth communication with a low energy level. The characteristics of UWB signal can be exploited to improve the accuracy of the propagation time measurement. In addition, [112] proposed to use generalized maximum-likelihood (GML) estimation for detecting the direct path of the signal. The process of measurement of propagation time is the same as that of ToA or round-trip time of flight. Therefore, this method also has the same issues as those of these two techniques but it is more accurate.

2.5.1.3 Angle of Arrival

Angle of Arrival (AoA) technique measures the angle of the received signal at a measurement unit [113]. Based on the angles obtained from measurement units, the location of the devices can be estimated by localization algorithms. The AOA techniques can be divided into two subclasses: amplitude response and phase response [108]. The former uses the amplitude while the latter exploits the phase of the received signals to infer the angle. A common technique in both these approaches is to use an array of the antennae (at least 2 antennae).

The amplitude-based approach exploits the anisotropy in the reception pattern of antennae, i.e. the antenna is not uniform in all direction – the same transmitted signal has different strength if received by the different directions, to infer the direction and thus the angle of the transmitted signal. In [114], an array of antennae is used to measure the angle by comparing the received signal strengths received at different antennae and overlapping the reception patterns of the antennae.

Similar to amplitude-based approach, the phase-based approach also uses an array of antennae at the receiver but it measures the phases of the signals instead of the strengths of received signals at different antennae. Phase interferometry discussed in [115] uses an array of antennae separated by a uniform distance to measure the phases of the transmitted signal. The signals received at different antennae have different phases and this information is used to estimate the angle or direction of the transmitter.

The AOA could produce an angle measurement with an accuracy of up to 2 degrees. However, it requires an array of antennae, which is more expensive than the normal one. In addition, the accuracy of this method relies on the Line-of-Sight (LoS) path from the transmitter and receiver. Therefore, it is severely affected by shadowing, multipath and obstacles.

Having reviewed the potential measurement methods in WSN, the next section presents methods which can be used for estimating the positions of sensor nodes in WSNs.

2.5.2. Localization Methods

There are numerous ways to categorize the localization methods based on different criteria such as whether or not the algorithm requires the distance measurements (range-based and range-free); whether or not it needs the beacons (beacons and beaconless); whether or not it supports mobile nodes, etc. In this review the localization algorithms are divided into two main groups: one for ad-hoc sensor networks and the other for controlled ones. As shown in Fig. 2.3, in each main category, the algorithms are further divided into different types depending on mathematical model or algorithm type. It is important to note that some localization methods could apply to both types of sensor networks such as lateration, SVM, etc.

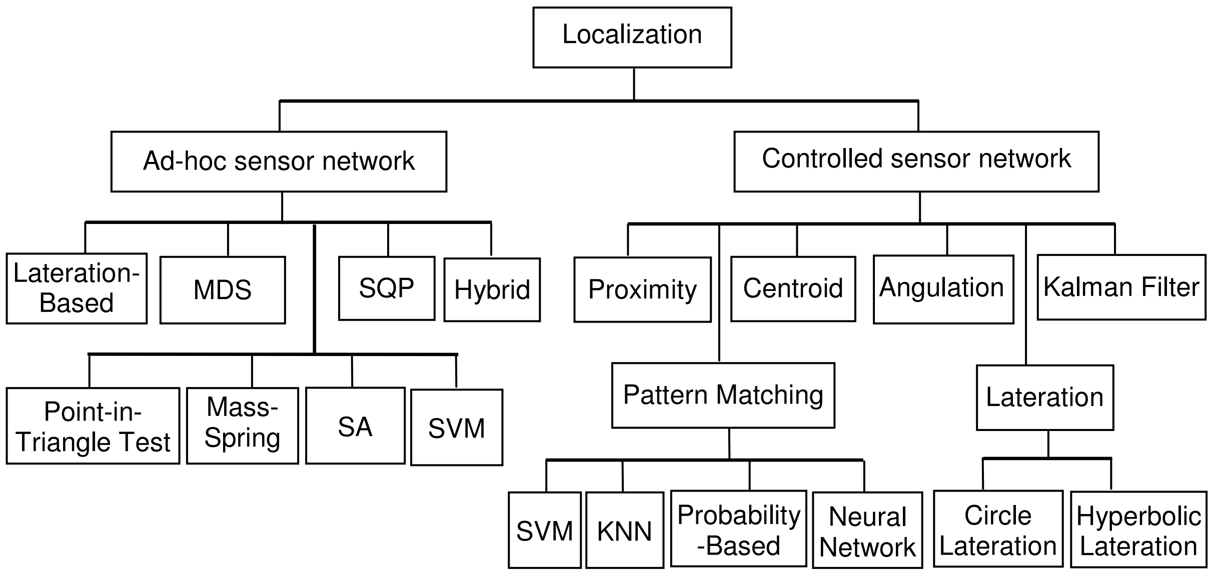


Fig. 2.3 Category of Localization Methods

Almost all of the localization algorithms assume that a proportion of nodes in the network have fixed known positions. These special nodes are called different names such as anchors, reference nodes, beacons or landmarks. In the following subsections these terms are used interchangeable.

2.5.2.1 Localization Methods for Ad-hoc Sensor Networks

Based on the original concept of WSNs, i.e., a large number of small and inexpensive sensor nodes are wirelessly connected together to form a network with the useful functions for monitoring and controlling the physical environments [116], one research direction targets localization problem with assumption that sensor networks are static or semi-static. This means that the sensor networks will be deployed by randomly scattering nodes on the area of interest (e.g., forest or battle field). In addition, after deployment the nodes rarely change their positions except some minor changes such as accidently moved, or dead. In such deployments, the positions of the sensor nodes are usually unknown; therefore, it is necessary to have a mechanism to determine their positions.

With the above-mentioned scenarios, a sensor network can be modeled as a graph whose vertices are the sensor nodes and whose edges are the direct connections between two nodes. With this view, finding positions of sensor nodes is equivalent to finding the best positions of vertices in the graph with the weights (e.g., distances) between them provided. In order to accurately determine the locations for nodes in a WSN, it is necessary to have some nodes with known position. The following sub-sections review algorithms and methods proposed for estimating the locations of nodes in such deployments.

2.5.2.1.1 Lateration-based Methods

Perhaps one of the early mathematical models applied for localization is lateration in which the location problem is expressed as a system of *n* equations (e.g., circles (2D) or spheres (3D)). In which *n* is the number of equations, and it is called trilateration when *n* equal to 3. In order to apply this method, it is necessary to have some reference points, i.e., anchors. In addition, it is required to have the distance measurement from a device to several anchors to estimate the position of the device. If the measurement between the unknown position node and the anchors is distance then a system of circles or spheres is formed. The measurements that could be used with this type of algorithms are RSSI, ToA or Ultra-sound. Because of the errors in measurements and distance conversion, the intersection of circles or spheres is often not a single point but an area as shown in Fig. 2.4 or no intersection at all. Consequently, instead of solving the system of equation, the linear or non-linear least square method [29], [30] is used to estimate the location of the node. The most well-known positioning system that employs lateration is Global Positioning System (GPS) [23].

Ad-hoc Positioning System (APS) [117] proposed a method to allow nodes to estimate its position in the multi-hop ad-hoc sensor network. Each node employs lateration method to estimate its position. The distances from a node to an anchor are estimated using the hop by hop propagation. After having the distance to three or more anchors, a node can estimate its position. APS proposed three propagation methods for estimate distance from a node to the anchor: DV-Hop, DV-Distance and Euclidian [117]. DV-Hop uses the number of hops to the landmarks to estimate the distance. The distance of a hop is computed by landmarks based on the number of hops between two landmarks and their corresponding Euclidian distance. Because there may be more than one value for the distance of a hop, each node only retains the first value it receives and uses it in the positioning process. On the other hand, DV-Distance propagation method uses the RSSI between neighboring nodes as the distance measurement (in meters) instead of hop count. Each node computes the accumulative distances from it to the anchors and forwards them to its neighbors. Similar to DV-distance, the Euclidian method also estimates distance using RSSI. However, it requires that each node has at least two neighbors that have distance estimates to the same anchor. This information allows the node to compute the distance from it to that anchor. The objective of these propagation methods is to allow nodes to obtain the distances from it to several landmarks. This information is then used for estimating the node's position using the lateration procedure. One important feature of APS is that it can support semi-static because each node maintained a table of the distance to the anchors and the estimation was done by the node itself. However, the accuracy of this method depends on the accuracy of the

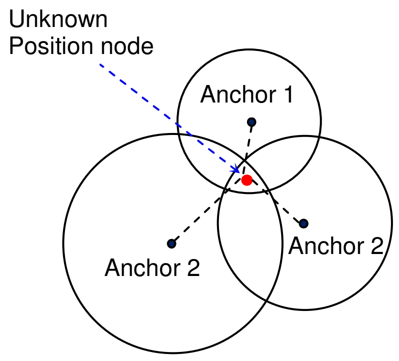


Fig. 2.4 Circle Lateration Localization Technique

distance measurement method.

Similar to DV-hop, the work in [118] proposed a gradient algorithm to find the shortest path (the minimum number of hops) from a node to an anchor by maintaining the minimum counter value received from each anchor. By ignoring messages containing larger counter values, it prevents the messages from travelling backwards. The distance from a node to an anchor is estimated based on hop count and based on a fixed distance ***r*** for each hop. After having the estimated distances from at least three anchors, a node computes its coordinates by minimizing the squared error between calculated distances and estimated distances. The advantage of this method is that all steps are calculated locally by sensor nodes and it is able to adapt to failures and addition of nodes. However, the estimated distance is based on the maximum range of the communication hop *r*, producing a high error.

Savarese et al. [119] proposed two lateration-based algorithms for estimating location of nodes using RSSI as ranging measurement: Assumption Based Coordinates (ABC) and Triangulation via Extended Range and Redundant Association of Intermediate Nodes (TERRAIN). The first algorithm was used by a node to estimate the relative positions of its neighboring nodes, one at a time, based on the order in which they established the communication with the node. Assuming that the ABC algorithm starts on the node n_0 with the coordinates (0,0,0). For the first few neighbors, it does not have enough information for forming lateration problem. ABC dealt with this issue as follows. When the first node communicated with n_0, it was considered this node as n_1 and its coordinates would be (r_{01},0,0). In which r_{01} is the distance between n_0 and n_1 based on the RSSI measurement. The location of the next node (i.e., n_2) communicating with n_0 was computed using the follow equations [119]:

$$x_2 = \frac{r_{01}^2 + r_{02}^2 + r_{12}^2}{2r_{01}};\ y_2 = \sqrt{(r_{02}^2 - x_2^2)};\ z_2 = 0$$

From the node n_i (i>=3), its coordinates are estimated using the standard lateration method (i.e., least square) on the following system of equations [119]:

$$x_i = \frac{r_{01}^2 + r_{0i}^2 + r_{1i}^2}{2r_{01}}; y_i = \frac{r_{0i}^2 - r_{(i-1)i}^2 + x_{i-1}^2 + y_{i-1}^2 + 2x_{i-1}x_i}{2y_{i-1}}; z_i = \sqrt{r_{0i}^2 - x_i^2 - y_i^2}$$

With ABC the locations of neighbor nodes were relative to that of the estimated node. Therefore, to determine the global positioning for an ad-hoc sensor network TERRAIN algorithm [119] was proposed as follows. First, the ABC algorithm was applied at the anchor nodes. The results computed at the anchor nodes were then forwarded to other nodes. The unknown nodes waited for the results from at least four independent anchor nodes to compute its own position using a lateration method. To improve the accuracy, after these steps the nodes could apply an iterative refinement process [119] which combines the most recently computed coordinates of its neighboring nodes and the ranging measurements to these neighbors to recompute its own position.

Collaborative multi-lateration proposed in [120] is another lateration based method that allows nodes to collaborate with each others to jointly estimate their locations in a multi-hop ad-hoc sensor network. This method comprises three main phases: (1) formation of collaborative subtrees, (2) computation of initial estimates, and (3) position refinement. In the first phase, each unknown position node finds a set of neighboring nodes (at least three) that satisfy the tentatively unique conditions proposed in [120]. To build the subtree, each unknown position node tests whether it has at least three neighbors with tentatively unique positions, i.e., they are anchors or their positions can be estimated using information from their neighbors. In the second phase, each node estimates its initial coordinates based on the locations of beacons and the distance measurements to these beacons using the bounding box method proposed in [120]. Finally, the position of node is refined using Kalman Filter [121], [122] based on the information about the subtree, its initial position, distance measurements to neighbors and location of neighbors. Although it was claimed that this method could be implemented in a distributed mode, it is inefficient or unfeasible to implement the Kalman filter on most of the current sensor nodes because of the heavy matrix and float number computation.

Proximity Distance Map (PDM) [123] proposed a method to deal with the anisotropic WSNs in which the nodes were distributed non-uniformly caused by geographic shapes of the region, different node densities, anisotropic radio patterns, etc. It proposed a mapping method between the proximity measurement, e.g., RSSI, and a geographic distance using the truncated singular value decomposition (SVD) pseudo-inverse technique [29]. To collect the information for this process, PDM employs the method similar to that of DV-hop [117] to collect the number of hops to the anchors. By applying the PDM on the hop counts and physical distance between anchors, more accurate distance estimations for hops are obtained and thus more accuracy in location estimation. Similar to APS, the node also employs lateration based method to estimate its position. The drawback of this method is that it requires a high ratio of beacons to produce the proximity map of anisotropy networks. In addition, SVD has a high computational complexity O(n^3).

2.5.2.1.2 Point-In-Triangle Test

He et al. [124] proposed a distributed localization method based on the Point-In-Triangle Test (PIT) principle named Approximate PIT (APIT). It consists of four main steps. First, each node obtains information about the positions of anchors and the signal strengths to these anchors, and exchanges this information with its neighbors. Then, the node runs the approximate PIT Test algorithm [124] to determine a set of triangles in which it resides. In the third step, APIT runs SCAN algorithm [124] to calculate the intersection of all the triangles determined in step 2. Finally, the coordinates of the node are the center of gravity of this intersection area. Because APIT runs on every node, it is totally distributed and it is thus very scalable. However, it requires that the anchors must have the high power transmitters to reach all the nodes in the network. In addition, the node density must be high (e.g., each node must have at least 6 neighbors) to obtain an acceptable accurate rate in the determination of whether a node is inside or outside a triangle. Furthermore, similar to GPS system, in order for this method to be applied, each unknown position node must be in range of at least 3 anchors.

2.5.2.1.3 Multidimensional Scaling (MDS)-based Methods

Multidimensional Scaling (MDS) is the search for a low dimensional space [125], and it is often used in reconstructing the maps, i.e., finding relative positions of points in the maps, given the distances between points. Consequently, MDS can be used in solving the relative locations of nodes in ad-hoc sensor networks.

One of the localization methods based on MDS is MDS-MAP [126] which accepts as its input the WSN's information in form of an undirected graph in which a set of vertices are the sensor nodes and the edges are measurements between nodes (e.g., signal strengths or distances). This method consists of three steps. In the first step, the weights of the edges are assigned based on the input information. If the measurement between neighboring nodes is the distance then it is also the weight of the corresponding edge, otherwise, the value one is assigned to all edges. Then, the shortest distances between all pairs of nodes are computed to construct the distance matrix for MDS. In the second step, the classical MDS [125] is applied on the distance matrix to construct a 2-D (or 3-D) relative map of the sensor network. The result from MDS is an arbitrarily rotated and flipped version of the original layout. Consequently, when there are a number of anchors exist, step 3 is applied to transform the relative map to an absolute map based on the position of anchors. This step includes scale, rotation and reflection to minimize the error of localization. The advantages of MDS-MAP are that it can be applied even if there are no anchors and the measurement is not the distance but the connectivity information.

A variant version of MDS-MAP to make it work in distributed mode is MDS-MAP(P) [127] which stands for MDS-MAP using patches of relative maps. MDS-MAP(P) comprises two main phases: (1) each individual node computes its own local map using its local information, and (2) the local maps are merged to form a global map. In the first phase, each node obtains the measurements of its nearby neighbor nodes within R_{lm} hops (R_{lm} was chosen in advanced). Then, it employs the first two steps of MDS-MAP algorithm to compute its local map. Finally, the node applies the least-square minimization to refine its local map. In the second phase, local maps are merged to create global map. First, one node is elected as core map in which the merging process starts. Then, the core map is grown by merging with the maps of its neighbor nodes. Each time a neighbor node with maximum number of common nodes is selected. This process is repeated until the core map covers the entire network. The MDS-MAP(P) [127] also comprises an optional step to refine the global map by applying least square minimization to the coordinates produced in previous step. The problem with this method is that it is too complex for sensor nodes.

2.5.2.1.4 Mass-spring based Optimization

Priyantha et al. [128] proposed a distributed localization method based on mass-spring optimization named anchor-free distributed localization (AFL). In this method each node is considered as a mass and the edge connects two nodes is considered as the spring between two masses. The spring is on the rest state when its length is equal to the measured distance between two nodes; otherwise, there is a force that pulls or pushes the nodes apart. With this view, localization can be seen as a mass-spring optimal process. AFL comprise two main phases [128]: (1) generating a fold-free configuration, and (2) mass-spring optimization. The objectives of the first phase are to avoid folds in the resulting graph, and to assign the initial coordinates for every node. It starts by nodes cooperatively electing 5 nodes to become reference nodes using the heuristic algorithm proposed in [128]. The reference nodes are elected such that four of them are on the periphery of the graph, and roughly perpendicular pairs; and the fifth node is on the centre of the graph. Then, every other node, n_i, computes its polar coordinates (p_i, θ_i) as follows:

$$p_i = h_{5,i} * R$$

$$\theta_i = \tanh^{-1}\frac{(h_{1,i} - h_{2,i})}{(h_{3,i} - h_{4,i})}$$

In which, R is the maximum radio range; and $h_{i,j}$ is the hop count from node i to node j

After calculating its polar coordinates, the node periodically broadcasts its position to its neighbors.

In second phase, every node uses its current coordinates, the coordinates of its neighbors, the measured distances from it to its neighbors to build the mass-spring model [128] and runs the optimization process on this model to minimize the errors.

One advantage of this method is that it is anchor-free and it can produce a good network topology. However, as other anchor-free methods, the resulting graph is usually translated, rotated or reflected. In addition, it requires distance measurement between neighboring nodes. Furthermore, it may be too complex for constraint devices.

2.5.2.1.5 Sequential Quadratic Programming

Sequential Quadratic programming (SQP) is a framework for solving the nonlinear optimization problems directly [129]. It was proposed to solve the localization problem of static/semi-static WSNs based on the RSSI as shown [130]. The proposed method comprises three stages [130]: (1) RF mapping of the network, (2) Creation of ranging model, and (3) Centralized localization algorithm. In the first stage, each node exchanges the short packets at different power levels in order to obtain RSSI values and then sends them to the centre server for further processing. In the second stage, the RSSI values obtained in the first phase are used to find the best values for parameters *a* and *b* of the model family $P_r = a + \frac{b}{r^k}$. In which, P_r is the received power of the signal; r is the distance, and k can be set to 2, 3 or 4 according to the specific environment. Finally, the SQP is used to estimate the positions of nodes by minimizing the cost function proposed in [130], which is the sum of error between the measured and estimated distance between nodes. This work was validated with a real testbed with MICAz [47] sensor nodes. However, its drawback is that it requires to create the ranging model (calibration) for every deployment environment.

2.5.2.1.6 Simulated Annealing Localization

Simulated annealing is inspired by the process of annealing in metallurgy [131], in which a solid material is heated and then slowly cooled down until it is crystallized. This process can be simulated to solve the optimal problem. Although it does not guarantee to find a best solution, it can find a global optimum with a high probability.

Kannan et al. [132] proposed a method based on simulated annealing algorithm to solve the flip ambiguity problem in the localization problem for WSNs named Simulated Annealing Localization (SAL). SAL requires *m* anchor nodes with known locations and thus the network has *n-m* unknown location nodes. In addition, before the location process starts, each non-anchor node is initialized with a random position within the boundaries of the network. The SAL method consists of two main phases: (1) estimating the localizable nodes, and (2) refinement of flipped nodes [132]. In the first phase, SAL employs the simulated annealing algorithm to minimize this cost function [132], which is the sum of errors of all unknown position nodes. The error at each node is the difference in the measured and the estimated distances between the node and its one-hop neighbors. This step results in the positions of all localizable nodes with some flipped nodes, i.e., nodes with incorrect positions. The second phase is applied by firstly identifying the nodes whose positions are likely to be flipped and then moving them to correct positions. To determine whether a node is in the wrong position, SAL compares the radio range and the Euclidian distance from itself to its non-neighbor nodes. If there is a radio range greater than the distance, then the node must be in the wrong position.

The second phase also uses the simulated annealing algorithm but with a cost function that takes into account the non-neighbors [132], and it only applies for flipped nodes.

SAL could produce more accurate results by overcoming the local minimum of the optimal problem. However, it does not guarantee obtaining the optimal answer. In addition, it requires the distance measurement which is hard to obtain in real environment. Furthermore, it requires a high node density to obtain a good result. Otherwise, flip ambiguity cannot be solved because the node is flipped but still maintains correct neighbors.

2.5.2.1.7 Support Vector Machine

Support Vector Machine (SVM) is a modern approach of learning machine for classification and regression. The idea of SVM [133] is to find the equations that divide the feature space into separable hyper-planes with maximum margins around them. The important feature of SVM is that the decision function is fully specified by a subset of training samples. This means that after training, the parameters of the model can be written as subset of training samples, which are so-called support vectors [134]. The SVM can be used for the localization in ad-hoc WSNs as shown in [135], [136], and LSVM [137]. The advantage of this method is that it is simpler and with less computational requirements than other methods. However, it requires a high ratio of anchors to obtain a good accuracy.

2.5.2.1.8 Hybrid Methods

In [138] authors proposed a localization method named Simple Hybrid Absolute Relative Positioning (SHARP) which is based on MDS [125] and APS [117]. This method consists of three phases: (1) selecting preference nodes; (2) localizing reference nodes; (3) localizing non-reference nodes. First, the reference nodes are chosen randomly or along outer perimeter of the network using the algorithm that is similar to the algorithm proposed in AFL [128] but with more reference nodes selected. Then, the MDS [125] is used to relatively localize the selected reference nodes, using the shortest distances among reference nodes. The result of this phase is the relative coordinates of the reference nodes. Finally, the locations of the remaining nodes are estimated using the reference nodes in second phase as anchors. In the final phase, each node estimates the distances from itself to the anchors using the DV-distance version of the APS method [117], and then it computes its own location using the lateration-based method.

Another hybrid algorithm is proposed in [139] which combines MDS [125] and PDM [123] in a phased approach. As most of other methods, this method requires some nodes with known positions called primary anchors. In the first phase, a subset of unknown location nodes is elected to become secondary anchors. Then, every node (including primary anchors) collects the proximity information, e.g., distance or hop count, to the primary anchors using the similar process proposed in APS [117]. After having the proximity information to all primary anchors, each secondary anchor estimates its own position using MDS [125]. In the second phase, PDM [123] is employed to create the proximity distance mapping among anchors (both primary and secondary), which is then distributed to all normal nodes. Similar to PDM, each normal node can then estimate its position using this proximity map and the table of hop count from itself to anchors. This method reduces the high number of anchors problem in PDM [123]. However, the introduction of secondary anchors reduces the accuracy comparing with PDM method.

2.5.2.2 Localization Methods for Controlled Sensor Networks

Because controlled WSNs have been becoming increasing popular, determining the locations of unknown position (mobile) nodes in this type of networks is more and more important. This section focuses on the methods that can be used to determine the positions of sensor nodes in controlled sensor networks.

2.5.2.2.1 Proximity

The proximity localization method is based on the “closest anchor” principle, i.e., the location of the mobile node is the location of closest anchor based on some measurement. The measurement can be signal strength or distance. As a result the closest anchor is the one with the strongest signal strength or shortest distance. Active Badge [25], [140] was one of the positioning systems that employs this method. The Active Badge [25], also called the tag, was attached to people, and it emitted a unique code using infrared (IR) signal every 15 seconds. This information was collected by the sensors and stored into a central database for use by the location system. The location system used the position of the sensor which received the last signal from the tag to infer the tag’s position. Another location system based on this method was Cricket [26], which based on the distance to infer the closest anchor. In order to produce an accurate distance estimate, Cricket uses a combination of RF signal and Ultra-sound. In addition, to overcome the beacon interference problems, a simple algorithm, called MinMode [26], was proposed to choose the closest beacon. For each beacon, a tag picks the mode of the distance in a time window, and chooses the beacon that has the minimum distance among all beacons. The advantage of proximity method is that it is very easy to implement. However, it only provides relative locations such as in which room the mobile node resides.

2.5.2.2.2 Centroid Method

A simple localization method that uses the measurement from multiple reference points is centroid algorithm [28]. In this method, the position of a node is determined by the arithmetic mean of the coordinates of all the beacons that are in range of it. For example, if a mobile node detects *n* beacons which are located at positions { $X_i=(x_i,y_i)$, *i=1,..,n* } then its position can be estimated using the equation $X=\frac{1}{n}\sum X_i$. This method is simple to implement and requires no distance measurement. However, its accuracy is low. In addition, it produces the same position for the node if it is in the ranges of the same set of beacons regardless of the measurements.

2.5.2.2.3 Lateration

As presented in the previous section, lateration can be used to estimate the position of a device by expressing the localization problem as a system of equations. If it is possible to measure or estimate the distance between the sensor nodes and several anchors then the localization problem can be expressed as a system of equations of circles or spheres. However, in case of the differences of time at which the signal arrives at different anchors obtained, a system of hyperbolas is formed and used to estimate the position of the transmitter. As shown in Fig. 2.5, the difference between the arrival times of a signal at two anchors restricts the possible locations of the device to be along a hyperbola in which two anchors are its foci [107]. By adding a third anchor, two more hyperbolas are formed. Intersection of two or more hyperbolas defines the possible location of the device. Similar to circle lateration, this method also faces the problem of no single point intersection and no intersection of curves. One method to this problem is to linearize the equations through the use of Taylor-series expansion and to solve it using the iterative algorithm [141]. Another method is to use the correlation techniques using the cross-correlation function of the signals [142]. The main disadvantage of hyperbolic lateration is that it requires that the time of all anchors must be accurately synchronized. In addition, its accuracy is also severely affected by noise, obstacles, and NLoS environments.

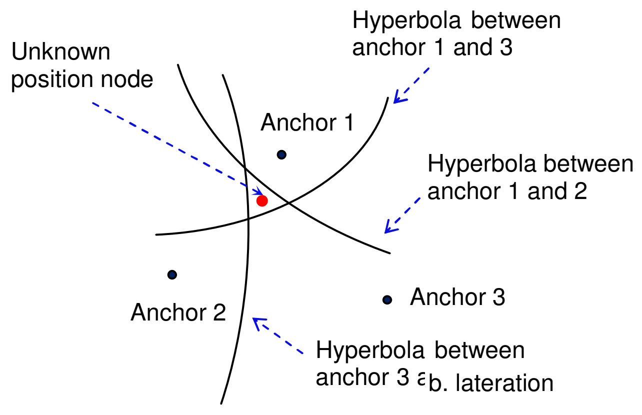

Hyperbola between anchor 1 and 3
Unknown position node
Anchor 1
Hyperbola between anchor 1 and 2
Anchor 2
Anchor 3
Hyperbola between anchor 3 ε
b. lateration

Fig. 2.5 Hyperbolic Lateration Localization Technique

Perhaps GPS [23] is the most successful system that uses this method for locating the mobile device. One of the first lateration-based location systems for sensor networks is Bat system [34]. To produce the accuracy distance estimation, Bat system employs both RF and Ultra-sound pulse. Verification-Based Localization Method (VBLM) [143] is an example of localization system that uses lateration with RSSI measurement. In order to improve the accuracy, VBLM proposed a Verification-based ranging algorithm (VBRA) algorithm to verify the reliability of the RSSI values, by using a neighboring beacon, before using them in the position estimate process.

The main advantage of lateration is that it is easy to implement. However, its accuracy is very sensitive to the distance measurement. With short range communication as in WSNs, it is very difficult to find a high accuracy distance measurement method.

2.5.2.2.4 Angulation

Similar to lateration, angulation is also based on a system of equations for the localization problem. However, instead of using distance measurement, angulation method estimates the location of an object by using the arrival angle measured at several receivers. In 2D space, the location of the object is computed by the intersection of a pair of angle direction lines. In 3D space, it is possible to use this technique for localization if the measurement of azimuth is available. Fig. 2.6 describes how angulation can be used to estimate the position of a device.

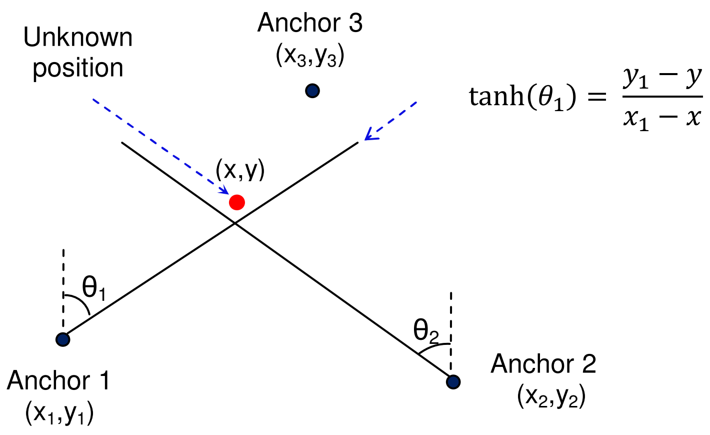


Fig. 2.6 Angulation Localization Method

The advantages of this method are that it does not require time synchronization and fewer anchors needed as comparing to lateration. However, it requires a more complex and expensive hardware by using directional antennae [144] or an array of antennae at the receivers. In addition, it needs a line of sight (LoS) between unknown position node and the anchors, which are rarely obtained in real environments. Consequently, the accuracy of this method is severely affected by the shadowing, multipath, obstacles, and non-LOS environments.

2.5.2.2.5 Kalman filter

Kalman filter [121], [122], [145], [146] is a recursive optimization estimator that is widely used in almost every fields including localization. It uses the prior knowledge of noise characteristics to account for and filter out the noises [31]. The Kalman filter processes all available measurements, regardless of their precision, to estimate the current state of the variables of interests. To apply the Kalman filter, the real world system must be described as a set of differential equations, which is the mathematical model for dynamic systems whose states we want to estimate. It is important to note that the dynamic system describes the propagation of state mean and error covariance through time.

The most common way of describing the real world system is in the form of state-space model [121], [146]:

$$\dot{x} = Ax + w$$

In which:

x is a column vector whose entries are the states of the system;

A the system dynamics matrix;

w is the process noise, which is also expressed as a vector.

There is a process noise matrix ***Q*** that is related to the process noise vector and calculated using the equation $\boldsymbol{Q} = E[ww^T]$. In addition, the Kalman filter requires that the measurements are related to the states according to the equation:

$$Z = Hx + v.$$

In which:

z is the measurement vector;
H is the measurement matrix;
v is measurement noise, which is also expressed as a vector.

Similar to process noise, the measurement noise matrix ***R*** is related to the measurement noise vector *v* according to the equation $R = E[vv^T]$. It is important to note that in case of the measurement equation is non-linear equation then it is called the extended Kalman Filter [121].

In order to implement the Kalman filter on the computer, the system dynamics must be discretized. The dynamic system for discrete-time Kalman filter is described as follows [146, pp. 124-124]:

$$x_k = F_{k-1}x_{k-1} + w_{k-1}$$

Then, the discrete form of the Kalman filtering measurement equation becomes:

$$Z_k = H_k x_k + v_k$$

Kalman filter algorithm consists of two phases: prediction and correction [146, pp. 128-129]. In the first phase the state of the system is predicted based on the dynamic model and in the second phase the predicted state is corrected by the data obtained from the measurements and the observation model. The Kalman filter algorithm tries to minimize the error covariance of the estimation; therefore, it is an optimal estimator. Fig. 2.7 describes these two phases:

Prediction Phase:

1. Estimate the next state $\hat{x}_k^-$ based on the previous estimated state $\hat{x}_{k-1}$:

$$\hat{x}_k^- = A\hat{x}_{k-1}$$

2. Compute the Covariance and Kalman gain

$P_k^- = AP_{k-1}A^T + Q$

$K_k = P_k^- H^T (HP_k^- H^T + R)^{-1}$

Correction Phase:

1. Estimate the next state base on measurement

$$\hat{x}_k = \hat{x}_k^- + K_k(Z_k - H\hat{x}_k^-)$$

2. Compute the error covariance

$$P_k = P_k^- + K_k H P_k^-$$

Fig. 2.7 Kalman Filter Algorithm

In which:

P_k: Covariance of the estimation error.

K_k: Kalman Gain

An important application of Kalman filter in localization is to improve the accuracy of GPS system as show in [147]. In addition, it is also employed for the localization problem in WSNs as proposed in [31].

2.5.2.2.6 Pattern Matching-based methods

The pattern matching-based localization methods are also called learning-based or fingerprinting based methods. The methods in this approach usually consist of two stages: (1) training stage, and (2) estimating stage. The training stage is often called offline stage because it is done offline before the location system running to response to the location request. In order to have the dataset for training the localization algorithm, the features, e.g., RSSI, of the deployed network are first collected and stored in a dataset, also called fingerprinting or training dataset. The objective of the training phase is to build a model or parameters for the localization algorithm. After having a model, the estimating stage (also called online stage) can be used to estimate position of the sensor nodes. The common feature collected for localization is RSSI because it is available in almost every wireless networks. In case of the feature is RSSI, each record of the training dataset consists of the coordinates of the collected position and a list of RSSI values from nearby anchors. There are several localization algorithms using this approach including k-Nearest Neighbors (kNN), Probabilistic-based, Support Vector Machine (SVM) and Artificial Neural Network (ANN).

k-Nearest-Neighbors (kNN)

kNN [148] is a common algorithm in machine learning and data mining for classifying a test object by finding a group of *k* objects in the training dataset that are closest (based on some similarity metric) to it. These *k* objects in the dataset are called neighbors of the test object. The resultant class of the test object is the class that predominates in *k* involved neighbors. The simplest case of kNN is assigning the test object to the class of its closest neighbor (i.e., *k*=1).

kNN can be used to estimate the location of a device by first searching the fingerprint dataset to find *k* records, i.e., positions, that have feature(s) most similar to those of the new observed measurement according to a distance function, e.g., Euclidean distance. Then, by averaging these k positions, an estimated position of the mobile device is obtained. The distances between the new observed measurement and k nearest records can be used as the weights when computing the average and it is called weighted kNN. The examples of localization systems that employ the kNN include RADAR [35], LADMARC [37], and MoteTrack [38].

Probabilistic-Based Method

Similar to kNN but instead of using the distance to measure the "similarity" between the new observed measurement and records in the fingerprinting dataset, the probabilistic-based method uses the probability theory to determine the similarity between records. As with kNN, in this method, k records with the highest probability are selected. Then, the position of the mobile node is the (weighted) average of the coordinates of these k records.

A common method is to use Bayes rule [149] to calculate the probabilities of matching between the test object and the records in training dataset. Assuming that the fingerprinting dataset has *n* candidate records $D = \{ L_i \mid i=1,...,n \}$. The class of the new observed data vector ***s*** is determined by the Bayes rule as follows:

Choose class L_i if $P(L_i \mid \boldsymbol{s}) > P(L_j \mid \boldsymbol{s})$ for i and j=1,..., n and $j \neq i$

It is normally assumed that the likelihood of each record in the fingerprinting dataset has normal or Gaussian distribution in which the mean and standard deviation (SD) of each anchor at position candidate can be calculated using the measured data. Because the probabilistic-based method takes into account the standard deviation of the measured feature(s) of each anchor, the accuracy of this method is better than that of kNN. Horus [39], [150] is an example of the usage of probabilistic-based method for estimating the mobile nodes in WLAN. In addition, Elnahrawy et al. [151] proposed Area-Based probability (ABP) to estimate the area in which a mobile node resides for WLAN. Similarly, [40] is an example of the usage of this method to estimate position of devices in indoor WSNs.

Support Vector Machines (SVMs)

As discussed in previous section, SVMs, also called kernel machines, are ”maximum margin methods that allow the model to be written as a sum of the influences of a subset of training instances” [149]. SVMs can also be used for localization in controlled wireless network as shown in [44].

Artificial Neural network (ANN)

ANN [152], inspired by the structure and operation of the brain, can also be used to solve many real world problems in different domains, including pattern recognition and classification. The neural network structure comprises numerous neurons divided into multiple layers: one input layer, one output layer and zero or more hidden layers in between these layers. The neurons are connected to each other and each connection is assigned a connection weight. The weights of the connections are determined during the training phase and are used to compute the results when receiving inputs from input neurons. Different kinds of neural networks are formed by different methods of connection among neurons. One of the common used neural network structures is feed forward, i.e., the neurons in one layer only connected to the neurons of the next layer as described in Fig. 2.8.

The ANN computes the results based on the combination of inputs, the weights of the connections between neurons and the sigmoid function [152]. For localization, the RSSI values measured at different positions can be used as inputs for ANN. During the training phase, the training algorithm uses the coordinates of the measured positions to calculate the errors. Training neural network can be seen as an optimal problem in which the errors between the outputs from ANN and the actual values are minimized. There are a number of approaches for solving this optimal problem including: gradient descent algorithms, optimization heuristics like simulated annealing or special optimization techniques like genetic algorithms [152]. After the training phase, the appropriate weights are obtained and used during the position estimate process.

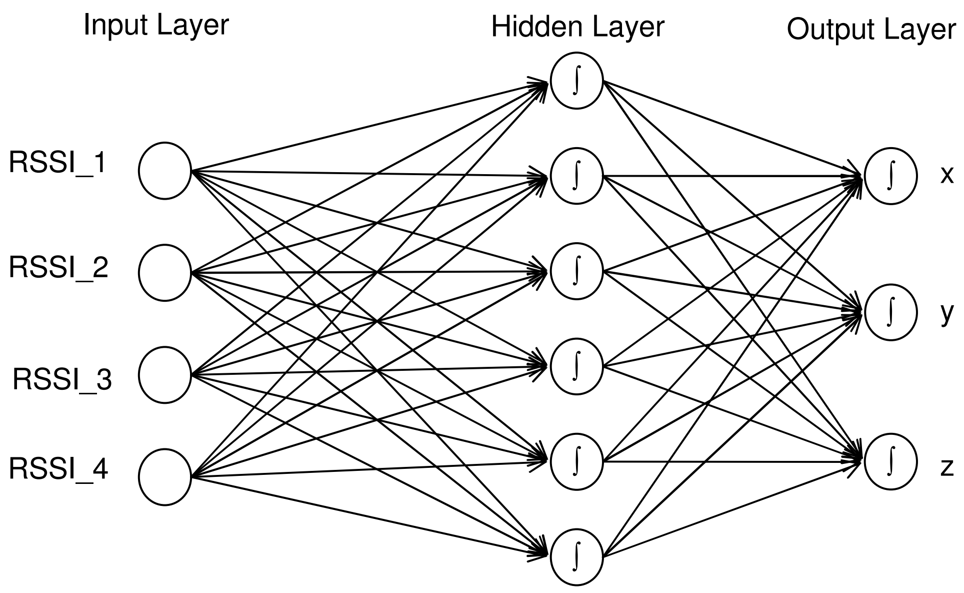


Fig. 2.8 An Example of a Neural Network with 3 Layers (4 input neurons, 6 hidden neurons, 3 output neurons)

The research on using the ANN for localization in WSNs includes [42], [153], [154]. The advantage of neural network is that it is very fast to estimate the location (online stage). However, the training stage takes a very long time and needs experiential or empirical study to choose the good structure. In addition, it cannot work well in the case the training dataset has many non-separable records.

From the study in this chapter, we can figure out that the accuracy of the localization mainly depends on the accuracy and the stability of the type of measurements. In WSNs, it is a challenge to find such an accurate and stable but cheap measurement method. As RSSI value is the cheap and available data in WSNs, it is the most common data used in Localization in WSNs. As a result, the objective of our work is to develop a scalable localization system target industrial WSNs with an acceptable accuracy.

2.6 Some Related Projects

This section reviews some projects that are related to the work done in this thesis.

One of the project that is closely related to the work in chapter three of this thesis is GINSENG project [155]. The aim of this project is to develop a performance-controlled Wireless Sensor Network that guarantees reliable and timely data delivery. The targets of this project are critical environments such as the oil refinery in which the time response, packet loss and reliability are bounded by some constraints.

WSN-DPCM project [156] is a international project that develops toolset for developing, planning, commissioning and maintaining large-scale WSNs. It includes reusable middleware for heterogeneous hardware platforms. In addition, it also has tools for assisting the planning the sensor network before deployment. This helps to reduce the time of trial-and-error iterations. Furthermore, it also consists of the integration toolset to seamlessly handle the information flow between tools.

CodeBlude [157] is a project which explored medical sensors as well as software for wireless medical devices. One of the areas of this project was 3D location tracking using radio signal information. The MoteTrack location system [38] is one of the outcomes of this project.

Smart Monitoring of Historic Structures [158] is a project which uses sensor network to monitor ambient conditions of the historic structure such as temperature, humidity, air velocity, vibration etc. This helps the owners and professional to identify the threats to produce recommendations for action.

EMMON - EMbedded MONitoring [159] is another project for monitoring the physical properties of specific geographical areas. One of its objectives is to improve reliability and fault tolerance mechanisms in WSN. In addition, it also target at the middleware for end-users to monitor and control WSN.

2.7 Summary

This chapter presented an overview of WSN, its challenges and requirements. In addition, it reviewed the research on the coexistence, integration, and localization problems.

It is important to note that the MAC protocols could provide some level of reliability for communication in WSNs. However, it usually has the problem in the noisy and interference environments in which there are other wireless networks or devices operating on the same frequency band. Cognitive radio may be a potential technique for dealing with the interference and polluted environments. However, it is too complicated for WSNs and may not work well in case of the noise and interferences change with time. Consequently, it is important to have an appropriate mechanism to provide a reliable communication for WSNs operating with environments.

Implementing TCP/IP protocol stack and web services on sensor nodes realizes the vision of IoT. However, it is not the solution for all WSNs. In fact, it is not appropriate for many types of current WSNs. As a consequence, gateway-based approach is still a common method for integrating WSNs with external environments in the foreseeable future. The primary advantage of gateway-based approach is that it hides the details of sensor networks from external environments. In addition, the developers can freely choose protocols and applications for sensor networks. More importantly, by exposing the data and functionality of a WSN as web services, WSNs can be treated as traditional networks. However, the problem with current gateway-based approach is that the gateway or proxy is application-specific, i.e., it has to be modified or reprogrammed when using for other sensor network or adding new applications to current network.

Although there is a large volume of publish studies on localization for WSNs, it is still a hard problem in terms of accuracy. The main reason behind this is that is difficult to have an accurate, reliable, and low-cost measurement technique for WSNs. In addition, the scalability of localization system is also a concern because the sensor network usually comprises a large number of nodes and is deployed in a large region. Consequently, it is necessary to have a scalable, low cost and near real-time localization system for controlled WSNs that can produce an acceptable accuracy.

In summary, the work in this thesis tackles three main problems for WSNs: (1) reliable communication, (2) integration, and (3) localization.

3 Quality of Channels of IEEE 802.15.4 Compliant Sensor Networks and Dynamic MAC

Summary

One of the crucial requirements of WSNs is to maintain its operation uninterruptedly for a long duration. Besides the energy, routing and security, there are other factors that might affect the reliability of a sensor network such as noise and interference at the deployment environment. The effects of these factors are different from place to place and from time to time. In addition, their effects might also be different on different channels of a standard compliant device. This chapter presents a study of quality of channels of IEEE 802.15.4 compliant sensor networks at different environments. In addition, it also presents a proposed solution for providing the reliable communication for sensor networks in noisy and interference environments. More importantly, the proposed solution includes mechanisms to deal with the noise and interference that are changeable with time.

3.1 Introduction

WSN is different from other types of networks in that the end users seldom interact directly with the nodes, but mainly with the applications at the control centre. The reason behind this is that the sensor nodes do not have a user interface. In addition, they may be deployed into areas to which the users may not have access. Moreover, there could be so many nodes that users cannot deal with them individually. Therefore, energy efficiency and high reliability are the main concerns when designing and deploying sensor networks. This study focuses on the latter requirement, i.e., reliability for sensor networks, without neglecting the former requirement.

There are several factors that affect the reliable communication of WSNs including the noise and interference caused by the other wireless networks, e.g., Wi-fi, Bluetooth, cordless phone, machinery and other devices. Because of the limitations of sensor nodes, their radios are more susceptible to noise and interference than those of other wireless technologies. Consequently, the effects of these factors on the quality and stability of the sensor networks are even more severe.

Each wireless communication standard usually supports a set of discrete channels, allowing a wireless network to utilize a single channel or a subset of these channels. Therefore, multiple wireless networks of the same standard or different standards of the same frequency band can coexist in the same area by using different channels. However, several questions arise for this situation. First, how to determine which channels are not occupied? This means that how to determine unused channels in an area in which other wireless networks exist? In addition, how to determine the effects of the above-mentioned factors on different channels of a standard compliant device? Moreover, how to deal with the noise and interferences in case of the new wireless networks or other devices are added. In fact, all of these questions are related to the problem of dynamically selecting the most appropriate channels during the operation for a sensor network. This chapter presents a study and a solution for this problem. In particular, it presents the results of a study about the quality of different channels of IEEE 802.15.4 compliant sensor networks in several environments. More importantly, it details the proposed MAC protocol to deal with the noise and interference that are changeable with time, allowing WSNs to coexist with other wireless networks and to work smoothly in noisy environments.

3.2 An Empirical Study of Quality of Channels of IEEE 802.15.4 Compliant Sensor Networks

A defining characteristic of wireless communication is that its signal strength varies over time, location, and frequency [160]. In addition, the radio frequency (RF) signal is influenced by multiple factors such as interference, noise, multi-path, shadowing, etc. These factors affect the error rate, delay, and the stability of the signal strength in the WSNs and thus their reliability and the quality of service. Furthermore, most wireless networks, including WSNs, are deployed using the default or a random channel, thus making the interference problem worse.

In this section, we present the experimental studies of the quality of channels of IEEE 802.15.4 compliant sensor networks in ISM band. We are particularly interested in the study of quality of wireless sensor networks in differences environments both academic and industrial as most current studies and experiments were done in purely academic or laboratory. We conducted experiments at several different locations including an oil refinery where we implemented WSNs as the case study in the context of the FP7 GINSENG project [155]. Our study shows that it is very difficult to predict the quality and reliability of the different channels of a sensor network at because the environment conditions greatly influence the network performance. Consequently, empirical approach is a suitable method for choosing the appropriate channels to deploy WSNs in noisy and interference environments.

3.2.1 IEEE 802.15.4 Standard

IEEE 802.15.4 [48] was intended to be the key enabler for low complexity, ultra low power consumption, and low data rate wireless connectivity among inexpensive fixed, portable and moving devices. In fact, it was proposed as a standard for WSNs. IEEE 802.15.4 based networks can utilize three Radio Frequency (RF) bands: 868–868.6; 902–928 and 2400–2483.5 MHz; these are referred to as 868, 915, and 2450 MHz bands, respectively. The 2450 MHz band is commonly known as the Industrial, Scientific and Medical (ISM) band. The frequency bands, modulation techniques, and data rates of IEEE 802.15.4 are described in Table 3.1. The frequency bands 868 and 915 MHz can utilize Binary Phase Shift Keying (BPSK), Amplitude Shift Keying (ASK), or Orthogonal Quadrature Phase Shift Keying (O-QPSK) modulation while the ISM bands (2450 MHz) only use O-QPSK modulation. This standard divides the available spectrum in the three bands into a total of 27 channels as follows [48]:

- channel k = 0, at the frequency of 868.3 MHz
- channels k = 1…10, at frequencies 906 + 2(k – 1) MHz
- channels k = 11…26 in the ISM band, at frequencies 2405 + 5(k – 11) MHz. Channel allocation in the ISM band is illustrated in Fig. 3.1.

Table 3.1 Frenquency Bands and Data Rates of IEEE 802.15.4

PHY (MHz)	Frenquency band (MHz)	Modulation	Bit rate (kb/s)	Symbol rate (ksymbols/s)
868/915	868–868.6 902–928	BPSK BPSK	20 40	20 40
868/915	868–868.6 902–928	ASK ASK	250 250	12.5 50
868/915	868–868.6 902–928	O-QPSK O-QPSK	100 250	50 62.5
2450	2400–2483.5	O-QPSK	250	62.5

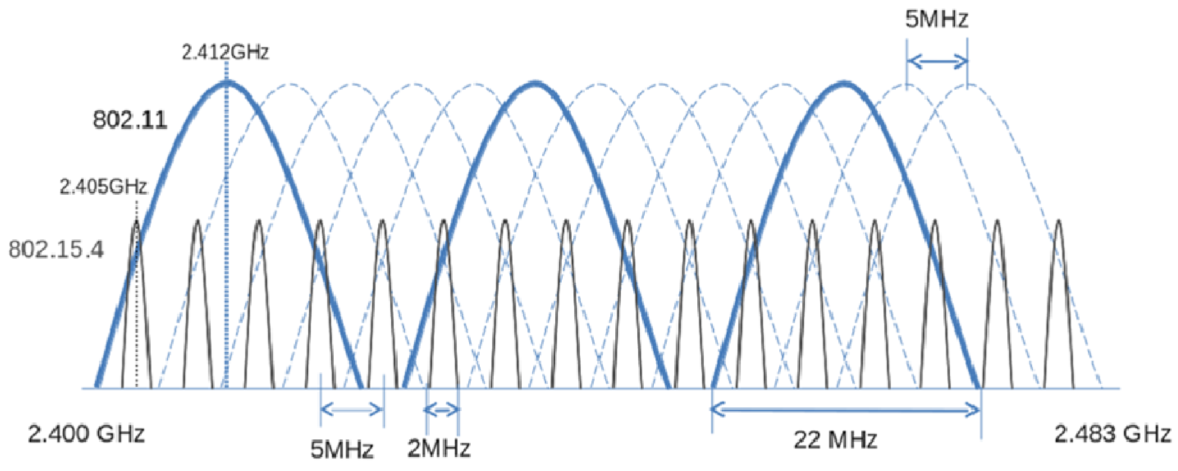


Fig. 3.1 Interference Between IEEE 802.15.4 and IEEE 802.11g

The PHY protocol of IEEE 802.15.4 can handle packets with the payload up to 127 bytes each. IEEE 802.15.4 networks support two main types of topologies: peer-to-peer and star. These networks can operate in beacon-enabled mode, which utilizes the slotted CSMA/CA access mechanism, or beaconless mode, which employs the unslotted CSMA/CA. In the beacon-enabled mode, contention-free access can be provided by the coordinator, i.e., the nodes can request a guaranteed time slot (GTS) of appropriate duration and the coordinator decides whether to accept or reject the request [48], [161].

As the ISM band is the common used band and supported by most sensor vendors, we did our experiments on sensor networks operating on the channels of this band.

Because ISM band is also used by other wireless network protocols (e.g., Bluetooth, IEEE 802.11b,g,n), IEEE 802.15.4 based sensor networks frequently coexist with other wireless networks, affecting each others' quality and reliability. However, the effects of this interference may not be the same on all channels. We are experiencing this problem in the context of the FP7 European Project GINSENG [155] in which a real WSN was implemented at Galp Energias refinery, Portugal. While at first the sensor network was configured to operate on the default channel (e.g., channel 26), we soon discovered that the hazardous refinery environment (containing machineries, pumps, tubes, various metallic structures, etc) greatly influenced the networks performance, which was very good in our early laboratory prototypes. This issue brought several questions to our attention: do the different channels of IEEE 802.15.4 compliant WSNs have the same quality? How are they affected by factors such as interference and noise? How is the quality of channels of WSNs in different environments? In order to find the answers to these questions, we decided to conduct an empirical study about the characteristics of the channels of IEEE 802.15.4 compliant WSNs in different environments.

The main contribution of this work is to propose an experimental procedure study the characteristics of different channels of IEEE 802.15.4 compliant sensor networks. In addition, different metrics (RSSI, loss rate, delay) of the different channels of IEEE 802.15.4 compliant sensor network in different environments were measured and analyzed. The results of this study showed that the performance and reliability of the IEEE 802.15.4 channels are channel-specific and location-dependent. As a matter of fact, it is necessary to do the empirical study of the deployed environment before selecting a channel or channels to use for a sensor network. As far as we know this is the first time that WSNs are being used in critical environments like refineries. From the scientific point of view this is very important because refineries represent one of the most critical industrial environments.

3.2.2 Related Work

The major studies in wireless communication are about radio propagation modeling [162], [163], which models the behavior of radio wave propagation signals in different environments. These models help to predict the quality and reliability of wireless networks in different environments. However, it is required to have the knowledge to choose the right model for a specific environment. Therefore, the accuracy of these methods is limited since different models give different results. In addition, in some environments, it is very difficult to find a suitable propagation model.

In wireless communication, the Received Signal Strength Indication (RSSI) is the measurement of the power level of the received signal. In addition, in [164] RSSI and Link Quality Indicator (LQI) were used to study the spatial and temporal characteristics of IEEE 802.15.4-compliant sensor network in a specific environment. In this study, the RSSI and LQI were measured at different locations in a specific room. The measured information could be used to predict the performance at any location in the room. A similar work was done by Doherty et al. [165] which studied quality and stability of different channels and of different channel paths. However, they studied the characteristics of channels on only one environment (i.e., the printing factory in Berkeley, California) and did not present a comparison with other environments with different conditions. In addition, in this study the characteristics of channels could be affected by internal interference (i.e., other sensor nodes in the same network).

3.2.3 Experimental Environments

In our experiments we used TelosB sensor nodes [47], Contiki Operating System [95], and X-MAC protocol [62], a duty-cycle (i.e., it uses awake, sleep intervals) low power MAC protocol for wireless sensor networks. It reduces latency and energy consumption by letting the senders use a short preamble with target address. When a receiver wakes up and receives a preamble having a target address equal to its address, the receiver will send an early ACK to inform the sender that it is ready to accept a packet. The short preamble saves energy at the transmitter and receiver with low latency. X-MAC protocol does not support retransmissions in case of packet errors (e.g., by collisions or interferences). In our experiments, the X-MAC was set to turn on the radio to check the channel at the rate of 8 Hertz (i.e., 125 ms). The transmitted power in the experiments was set to 0 dBm (i.e., 1 milliwatt).

In order to study the characteristics of the channels, different environments have been selected to perform the experiments. The first one was a room without interferences from other ISM wireless networks. The second environment was an open space also without the presence of any other ISM wireless networks. These two environments were considered “clean environments” because there were no interferences from other wireless networks, no obstacles, and no obvious noise sources. The third environment was our laboratory at the Department of Informatics Engineering of the University of Coimbra. This is a noisy and interference environment because there exist several IEEE 802.11g wireless networks that operate on the channels 1, 6 and 11. The interference between these wireless networks and the IEEE 802.15.4 standard is shown in Fig. 3.1.

The final location is an industrial environment at the Sines refinery, Galp Energia, Portugal. Although there are no other wireless networks that interfere with the IEEE 802.15.4 within the refinery, there is a considerable amount of noise caused by several types of machines, pumps, etc working 24 hours a day.

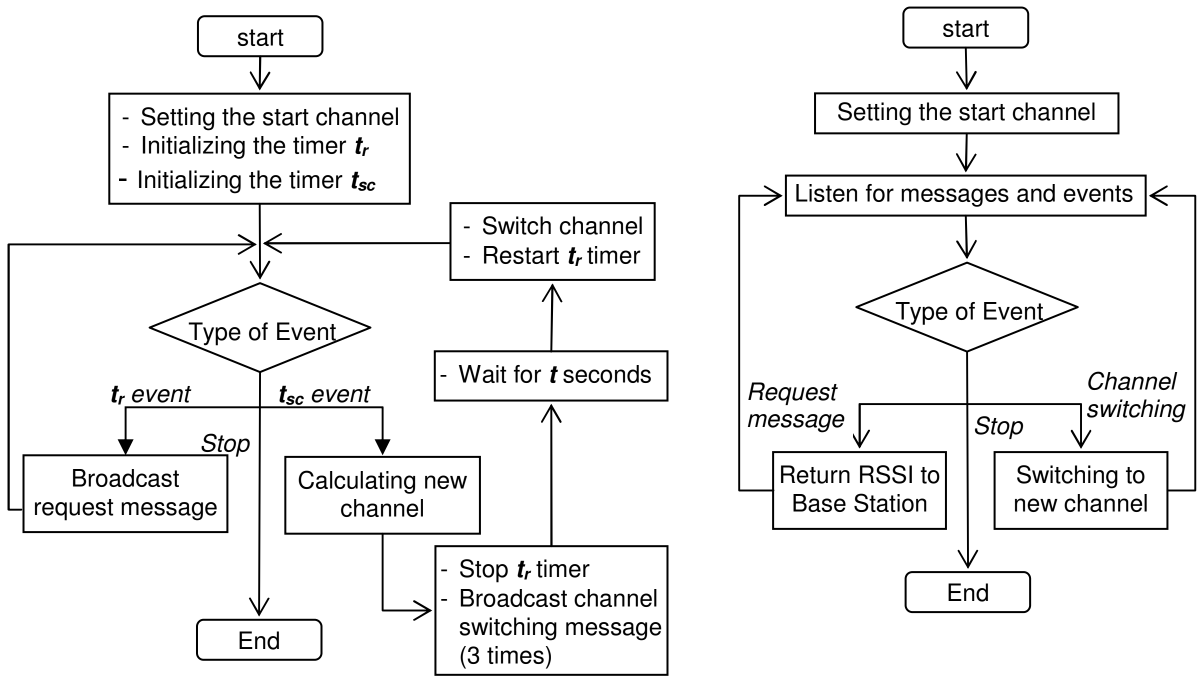
3.2.4 Study Method

The following data was collected to study the characteristics of different channels of the IEEE 802.15.4 based WSNs:

- Channel number
- Message sequence number
- Received Signal Strength Indication (RSSI) of each packet
- Delay time (the time it takes to transmit a packet from sender to receiver)

In order to avoid internal interference among sensor nodes, a simple sensor network with two motes was setup to gather the necessary data. One mote acted as base station and was connected to a computer to collect and record the data for post-processing. This mote also controlled which channel the sensor network should operate on and when it would switch to a different channel. The workflow of the base station and that of the normal node are described in Fig. 3.2a and b, respectively.

The base station starts to operate on a predefined channel, which is set manually in the code or at installation time. As described in Fig. 3.2a, after setting the start channel, it initializes two timers. The first one, which is fired periodically every t_r time units, is used to send request messages. These messages are used to collect the metrics, e.g., RSSI, delay and loss rate, for evaluating the characteristics of the channels. The second timer, which is fired periodically every t_{sc} time units, is used to control the operating channel, i.e., when the network should switch to a different channel. When the t_{sc} event occurs the base station calculates the new channel on which the sensor network should operate. It then broadcasts the channel switching messages three times to insure that all nodes receive the request. It is important to note that before sending the channel switching messages the base station stops the timer t_r. In order to make the system work smoothly, after broadcast the switching channel messages the base station waits for a while (e.g., 15 seconds) before switching to the new channel. After switching to new channel, the base station restarts its t_r timer to continue the measuring process. In our tests, t_{sc} and t_r were set to 5 minutes and one second, respectively.


start
- Setting the start channel
- Initializing the timer t_r
- Initializing the timer t_{sc}
- Switch channel
- Restart t_r timer
Type of Event
- Wait for t seconds
t_r event
t_{sc} event
Stop
Broadcast request message
Calculating new channel
- Stop t_r timer
- Broadcast channel switching message (3 times)
End
start
Setting the start channel
Listen for messages and events
Type of Event
Request message
Channel switching
Stop
Return RSSI to Base Station
Switching to new channel
End

a. The workflow of the Base Station b. The workflow of the normal node

Fig. 3.2 The Workflow of the Nodes in the Experimental Network

Like the base station, all the other nodes in a sensor network are set to start with a predefined channel. The predefined channel on the nodes and base station must always be the same. After booting, the nodes start listening for the messages and other events on this pre-defined wireless channel. When receiving a request message from the base station, the node will get the RSSI of that message and send this information to the base station. If it receives a channel switching message, it will switch to the indicated channel, and start to listen on this new channel. This process is repeated indefinitely.

Although the communication between two motes cannot represent the traffic model of a typical real multi-node WSN, it is enough to study the characteristics of channels of IEEE 802.15.4 based sensor networks. However, we also did some experiments with a multi-node sensor network (1 base station and 3 normal nodes) to evaluate how the internal interference affects the performance of the sensor network.

Because the main objective of the experiments is to study the characteristics of channels of the IEEE 802.15.4 based sensor networks, the uniform traffic model was used. Although it is unrealistic traffic model, uniform traffic model is sufficient for studying the metrics and for understanding the characteristics of IEEE 802.15.4 based sensor networks. In this simple sensor network, the base station broadcasts a request message to the other node every one second (this schedule can be changed), which includes the message sequence number for tracing and computing the loss rate. In order to calculate the round-trip time between the base station and the other node, the base station records both the time when it sends a request message as well as the time when it receives the returned message.

3.2.5 Experimental Results

3.2.5.1 The Characteristics of Channels in Clean Environments

In the first two experiments we intended to study the characteristics of the IEEE 802.15.4 based sensor networks in a clean environment, i.e., no interference from other ISM wireless network sources, no obvious noise source and no obstacles. For the indoor environment, we did the experiments for 20 hours. As shown in Fig. 3.3a, the average received signal strength of channels varies similar to a sine line. It begins with a low RSSI then alternatively increases and decreases. As we can see, the RSSI of channels 11 and 18 were lower than the rest. In addition, some middle channels (e.g., 17, 18 and 19) have outliers with rather low signal strength (< –75 dBm) that might affect the loss rate. As shown in Fig. 3.3b, some channels have a higher packet loss rate than the others, especially channel 17.

The Fig. 3.3c presents the delay of transmission on each channel. Although the average delay was not much different among channels, some channels had outliers, which may be caused by collisions, and therefore packets lost. Although the network is simple and only comprises two nodes, packet collisions still occur because the communication between two nodes is two-way. When a packet was delayed at the received node, the response packet sent from the received node could probably collide with a new packet sent by the base station. The delay was caused by the processing or by the duty cycled of X-MAC [62] protocol. In addition, the large packet delay could also be caused by the quality of the antenna. As simplistic design philosophy and the constraints of sensor nodes, its radio often has minimum complexity (quality). Moreover, the antennae of sensor nodes are anisotropic and RSS of radio is very susceptible to the environment: a small change in position or direction of the sensor node could result in a large variance in RSSI values. These factors lead to the instability of sensor radio. As we see in Fig. 3.3, the channels with the highest loss rate usually have the lowest signal strength with a larger variation (i.e., standard deviations) and/or outliers in signal strength or delay. For example, in case of channel 17, its signal strength had many outliers with very low value as well as various outliers in delay. Consequently, its loss rate was very high.

Similarly, despite having good signal strength, channel 24 had several outliers in delay, and thus its loss rate is higher than that of other channels.

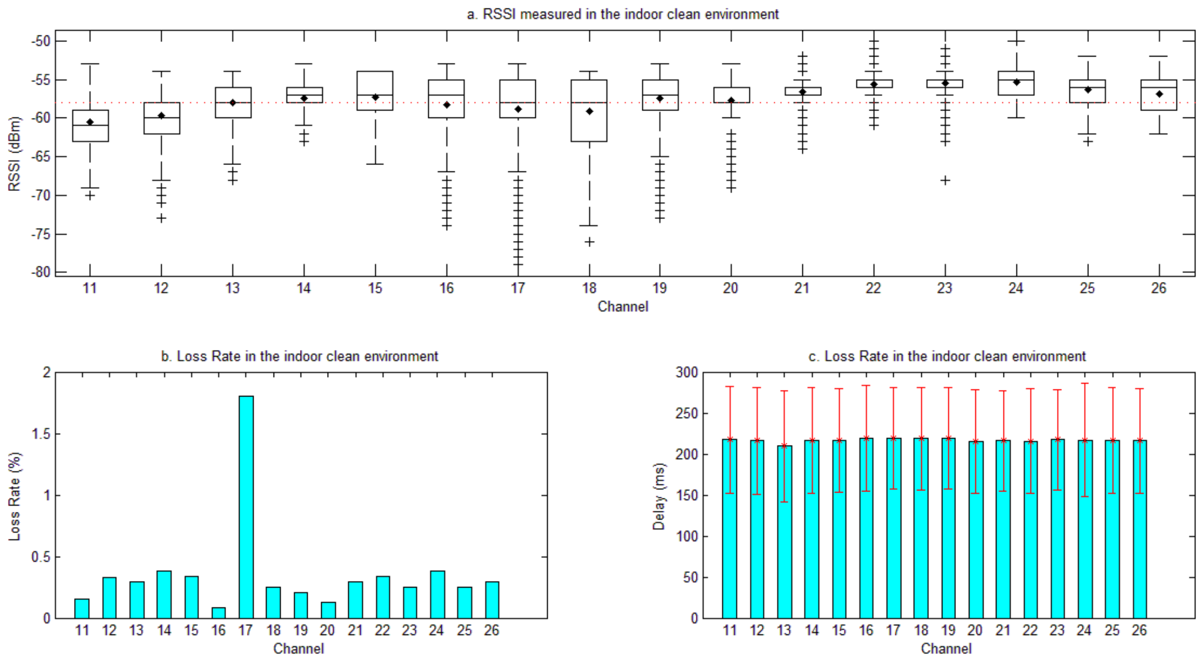


Fig. 3.3 Experimental results in the clean indoor environment

To study the variation of signal strength over time in different channels of IEEE 802.15.4 based sensor networks, a continuous experiment over 12 hours was performed. In this experiment, the sensor network switched to new channel every 5 minutes, which means that each channel was measured nine times (t1…t9). Fig. 3.4**Erreur ! Source du renvoi introuvable.** shows the temporal variation of signal strength for each channel at different periods. The RSSI at each period is the average of the measurements over 5 min. As we can see, some channels (e.g., 17, 18, and 19) had a greater variation than others. The varying behavior of the received signal strength over time shows that the reliability of some channels is not stable. For instance, as shown in Fig. 3.4, the signal strength of channels 17 and 18 were very good at some periods but very poor at others.

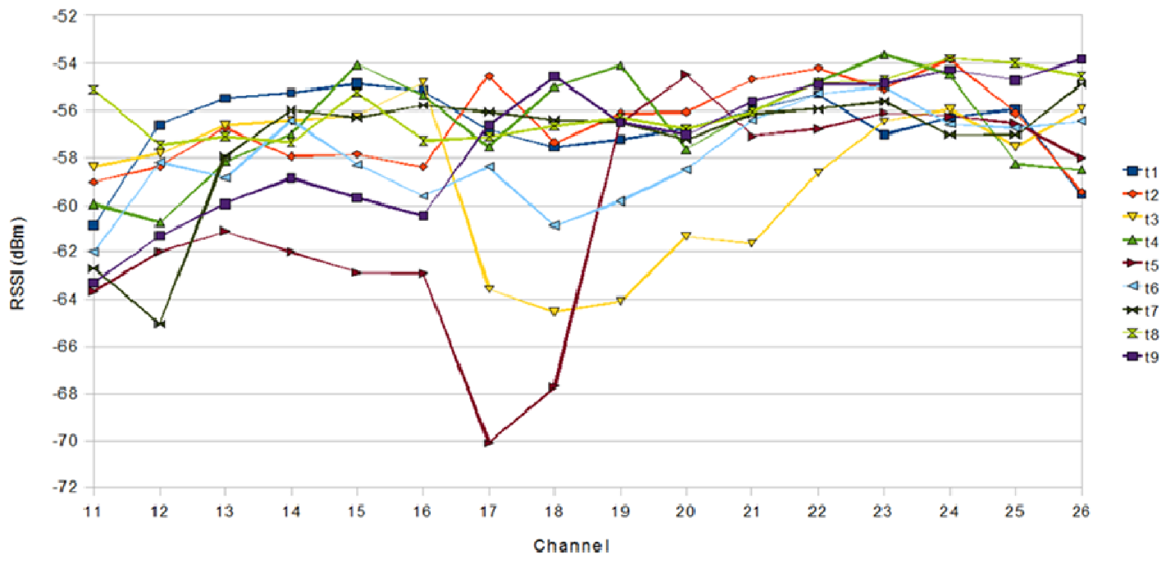


Fig. 3.4 The Variability of the RSSI with Time in Clean Indoor Environment

In addition to the indoor clean environment, we also did some experiments with the outdoor clean environment. Similar to the indoor clean environment, some channels (e.g., 11, 12, 13, and 14) had lower RSSI values than others as depicted Fig. 3.5a. In addition, the channels with low RSSI usually have more packet loss, taking as an example the channels 11, 13, and 15 as shown Fig. 3.5**Erreur ! Source du renvoi introuvable.**b. The average delays are not so different between channels, but similar to the indoor clean environment case, i.e., the channels with high packet loss have outliers in delays.

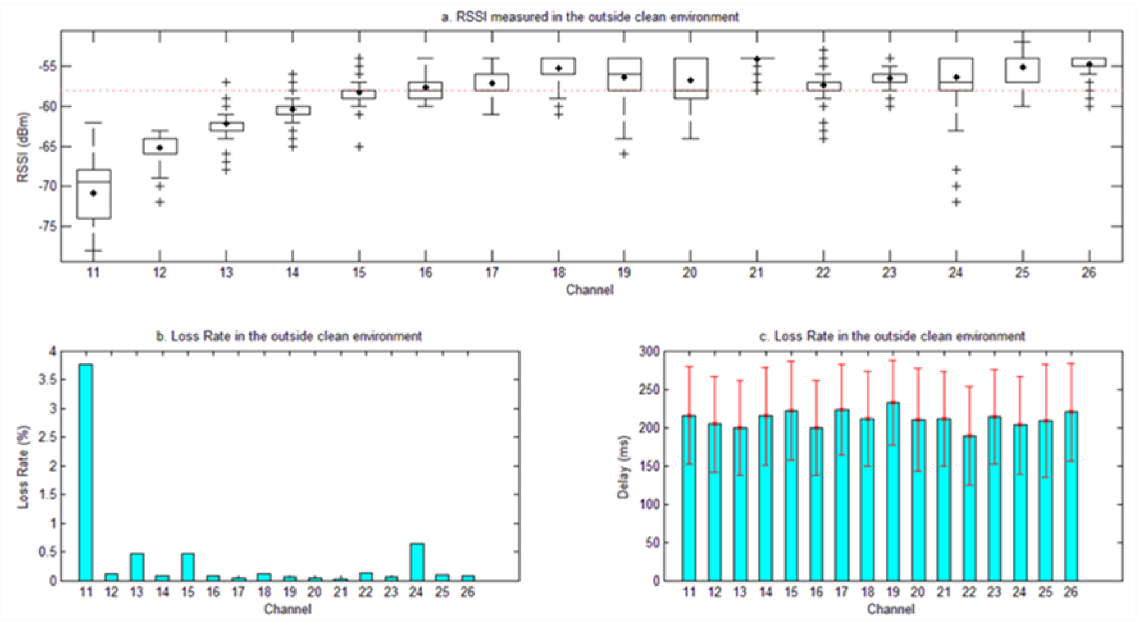


Fig. 3.5 Measurement results in the clean outdoor environment

3.2.5.2 Effects of Interference on IEEE 802.15.4 based Sensor Networks.

To study how the interferences from other ISM wireless networks affect the IEEE 802.15.4 based sensor networks, we did numerous experiments at our laboratory at the University of Coimbra. Several IEEE 802.11g wireless networks operating on channel 1, 6, and 11 present in the laboratory building. The interference between these wireless networks and an IEEE 802.15.4 based network is described in Fig. 3.1. From this figure, we can guess that the channels 15, 20, 25, and 26 potentially have better quality (signal strength, loss rate, delay, etc) and reliability than the others. The results of our experiments over 10 continuous hours were depicted in Fig. 3.6.

As shown in Fig. 3.6a, besides the non-interfered channels, some other channels also have acceptable quality and reliability such as 16, 17, 19 and 21. We can also see that the best channels (high signal strength, less loss rate, and short delay time) are not the non-interfered ones. In terms of loss rate channel 16 and 19 were the ones with the greatest performance. It is important to note that the results depicted in Fig. 3.6 are similar to the clean environments in which some initial channels (e.g., 11, 12 and 13) are worse concerning signal quality and loss rate.

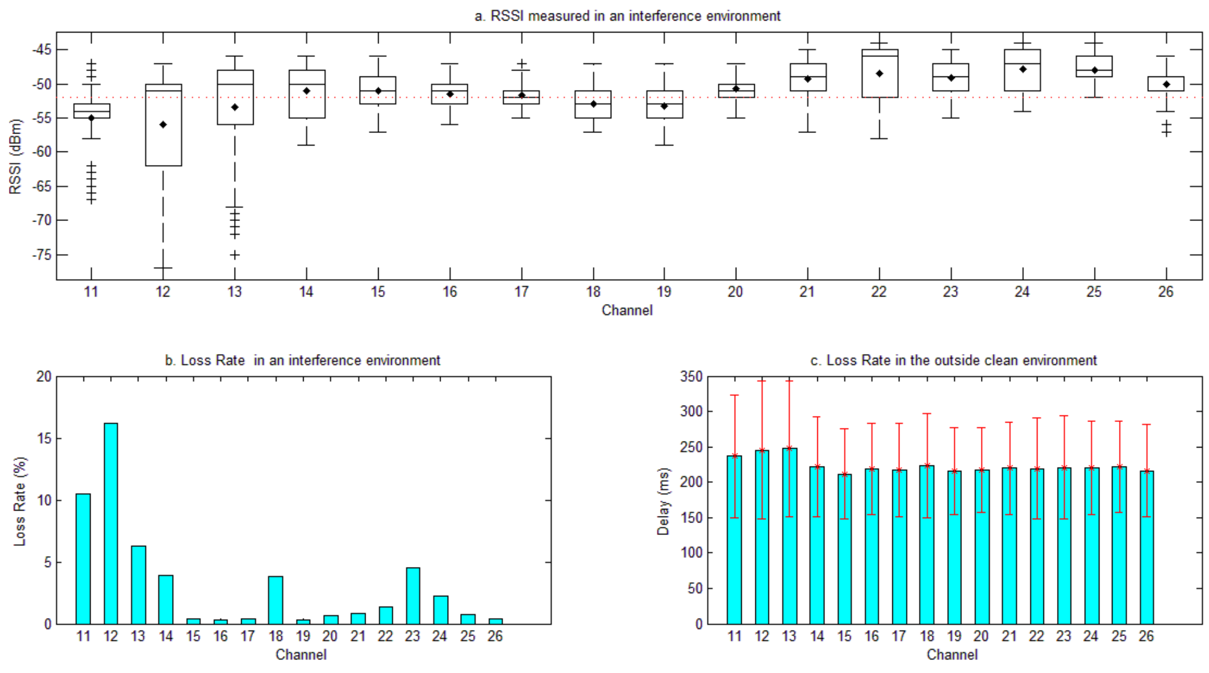


Fig. 3.6 Experimental Results in an Interference Environment

3.2.5.3 IEEE 802.15.4 Channel Quality in Noisy Environment

The final environment where we did the experiments was the Sines Refinery, Galp Energia, Portugal. This is the environment in which the real sensor networks have been deployed, as part of GINSENG project [155], for monitoring and controlling the physical environment. As shown in Fig. 3.7, the results are not easy to predict as in case of pure interference environment presented in previous section. Although the RSSI of the first channel (channel 11) is better than in the other channels, in accordance to environments previously studied, its loss rate is high due to some sporadic conditions. In addition, the large RSSI variation of this channel is also leading to instable channel. From the results of Fig. 3.7a, we also see that channels 16, 18, 19, and 20 are more stable than the others since their signal strength is less spread (less variance). Channel 23 is the worst in terms of both signal strength and loss rate. A more important point in the result of this experiment is that although there is no interference from other wireless networks, the loss rate of all channels are very high. The reason behind this is the noise caused by the infrastructure of the refinery, e.g., machinery, bumps, etc.

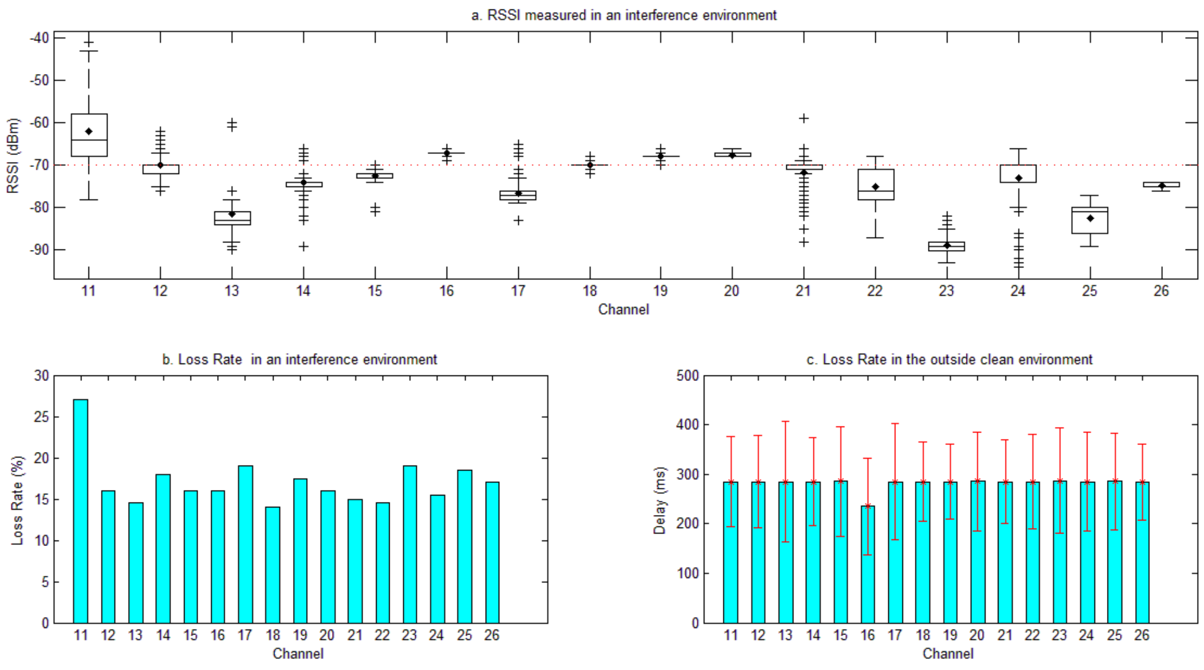
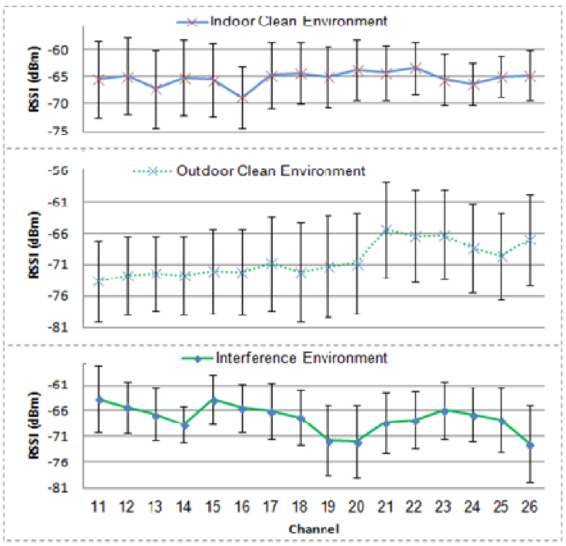


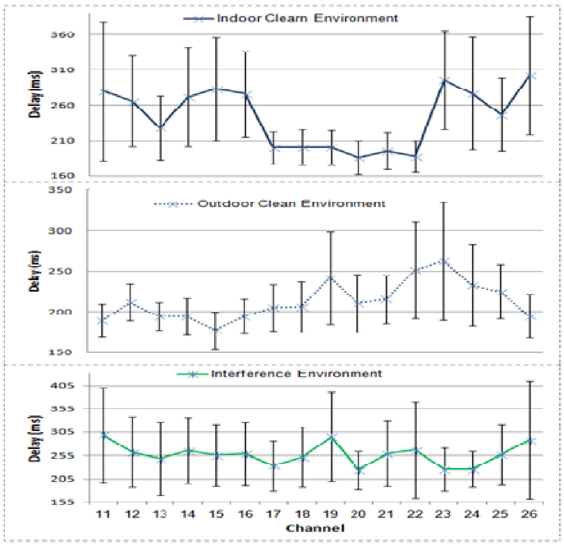
Fig. 3.7 Experimental Results in an Oil Refinery

3.2.5.4 Characteristics of Channels of IEEE 802.15.4 in Multi-motes Sensor Network

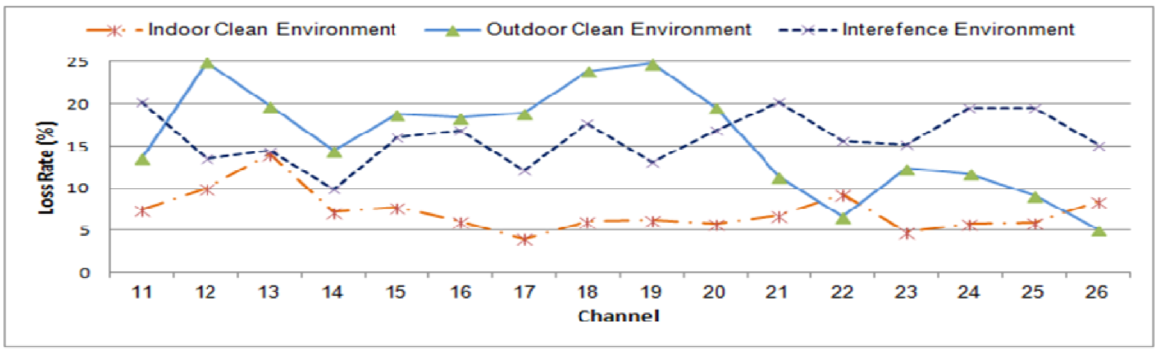
To see how the internal interference influences the characteristics of IEEE 802.15.4 based sensor network, we did several experiments with a four-mote sensor network in three different environments. The Fig. 3.8 shows the results of these experiments. As we can see from this figure the internal interference significantly affects the quality of channels because the increasing in the number of sensors causes the collisions increasing, therefore, influencing the RSS, loss rate, etc. However, the effect was not the same in all channels. In addition, as in case of simple 2 mote network, the quality of channels also depends on the environments.



a. RSSI measurement on a multi-mote sensor network



b. Delay on a multi-mote sensor network



c. Loss Rate on a multi-mote sensor network

Fig. 3.8 Experimental Results of a four Mote Sensor Network

As shown in Fig. 3.8, a channel is good in one environment may become worse in another. As an example, the loss rate of channel 19 indoor clean environment is good but it become worse in the outdoor clean environment. In terms of RSSI, channels 15, 22, and 23 are stable than the others. As for delays, channels 13, 14, 17, 18, 20, and 21 are better. Concerning loss rate, channel 14, 22 and 23 are better.

3.2.6 Discussion

From the experimental results over the different environments we could make several remarks about the characteristics of channels in the IEEE 802.15.4 based sensor networks.

- The quality and reliability of sensor networks are affected by multiple factors including noise, interference and obstacle. In addition, these effects are not the same on different channels.
- The characteristics of channels also depend on the deployment environment. In clean environments or the ones with the presence of known interference sources, by using the knowledge of present wireless networks we could choose a-priory the appropriate channels for deploying a wireless sensor network. However, in environments with noisy sources, predicting the best channels is very difficult without an empirical study.
- The quality of signal strengths of a channel also varies with time. In some cases, a channel is good at a time but very bad at some others.
- The signal strength has significant impact on the performance and on the reliability of the wireless communication.
- In WSNs, because of the limited battery of sensor nodes, it is required that the radios transmit at very low power. Therefore, the effects of noise, interference, obstacles, etc on the WSNs are more severe than on other wireless networks.
- There may be other hidden factors that affect the quality and reliability of different channels of a sensor device.

From these studies, we recognized that the noise, interference and other factors significantly affect the performance of IEEE 802.15.4 compliant sensor networks. More important, the effects of these factors are not the same on different channels. Consequently, it is very difficult to predict the quality of different channels of a sensor network at the deployment environment. From the results of our experiments, we can conclude that when deploying a wireless network, especially sensor networks in noisy and interference environments, it is necessary to have an experimental evaluation phase, where the behavior of different wireless channels in the deployment environment is analyzed in order to select the most suitable one(s). Another important point to note is that the conditions of deployment environment, e.g., noise, interference, can be changed during the operation of WSNs. Therefore, it is important to have mechanisms to deal with such changeable environments. The next section presents our proposed solution to this problem.

3.3 Dynamic Medium Access Control protocol (DynMAC)

Wireless communication is very useful and flexible but, on the other hand, it is also susceptible to noise, interference, multi-path, obstacles, among other problems. As the wireless communication presents almost everywhere, the problems of interference, spectrum pollution, and network coexistence have been increasing. Thus, this leads to several challenges to assure the quality and reliability of the wireless network in such conditions, especially for industrial and critical environments.

3.3.1 Context

The demand for ubiquitous and wireless devices has grown exponentially in recent years, as more and more applications were created. However, the extensive use of these devices in the same location causes problems because many of them use the same unlicensed radio spectrum known as ISM bands. In addition, ISM bands are also used by other devices such as microwave ovens, remote controls, cordless phones, Bluetooth communications, Hi-Fi and video systems. Although most of these devices have small ranges and use signals with low amplitude, their interference and noise in the ISM spectrum is not negligible.

In industrial scenarios, however, the effects induced by common ubiquitous mobile devices are lower due to the strict control typical of these environments. Nevertheless, the interference problem still arises because of the multiple wireless devices working in the ISM spectrum, such as monitoring and actuator devices. In addition, as industrial applications demand very strict requirements in regards to packet delay and packet loss, the interference may lower the expected quality of service (QoS). Because WSNs are increasingly used to replace old cabled monitoring and actuator systems, the coexistence of different wireless networks and devices may result in several problems including communication failures or inadmissible response time. These problems are especially serious in critical and industrial systems.

Because IEEE 802.15.4 based WSNs operate on the same frequency band as that of WLAN (IEEE 802.11 b/g/n), the most common wireless communication existing almost everywhere, and the interference will occur if they are deployed in the same area. As shown in Fig. 3.1, these two standards divide frequency band into channels of 5MHz and 22MHz respectively and they overlap in almost all extension of the spectrum. This demonstrates that the frequency spectrum in the ISM bands may become overloaded even for the WSNs. Several studies were done to understand how the interference from these two types of networks affects each other.

The studies in [166] showed that at some places the 2400 MHz frequency spectrum, a frequency used by several wireless networks, had an occupation of 90%. In addition, Zhou et al. [86] predicted that the growth of wireless communication networks using the ISM spectrum would suffer overlapping problems. The coexistence of different networks and devices that operate in the same frequency, or in adjacent frequencies, may lead to harmful interference, limiting the capabilities of the applications and, in some cases, resulting in the complete shutdown of those networks [167]. The study in [1] showed that with the interference of IEEE 802.11 network the Packet Error Rate (PER) of IEEE 802.15.4 can be up to 95% when the interferer is in the distance of 1.5 meters. Inversely, the throughput of IEEE 802.11network can be reduced up to 30% when the IEEE 802.15.4 in a short distance [2]. In addition, Toscano and Bello [81], [82] figured out that even in networks environments only consisting of WSNs, the interference still exists. By testing IEEE 802.15.4 networks their results showed that interference depends on the transmission power, on the distance between nodes and on the duty-cycle. Our study presented in previous section showed that the quality of different channels of IEEE 802.15.4 compliant WSNs varies from place to place. In addition, in the same place the quality of channels also varies from time to time. Moreover, the effects of noise and interference are very difficult to predict especially in noisy environment such as refinery. Consequently, it is necessary to have mechanisms for WSNs to operate in the interference and noisy environments.

3.3.2 Related Work

WSNs deployed in industrial and critical environments require strict performance control especially in regards to packet delay and loss. Most of the problems arise during packet transmission and relate to the transmission medium (e.g. signal path-loss, noise and interference) and poor hardware. Controlling the transmission power, improving the antennas, and carefully placing transmitters and receivers can partly reduce the effects of noise and path-loss. Interference occurs due to the existence of more than one network or by the spectral spread in some wireless standards. Solutions to mitigate or avoid interference include selective licensing of spectrum by area, use of hardware standards and use of signal coding. However, in a non-licensed frequency spectrum such as the ISM, there is no guarantee of noninterference. Consequently, in this frequency bands, any interference from ISM devices must be tolerated as unlicensed operations are typically permitted to use these bands.

Two different types of interference in WSNs are co-channel and adjacent channel. Co-channel interference is defined as the use of the same frequency by more than one network or device in the same area [83]. This interference cannot be solved with the increase of the signal power, as that would increase the interference and the communication problems in any neighbor networks. Adjacent channel interference occurs when consecutive channels are used by different devices in the same area, which leads to the degradation of both signals. To avoid this type of interference, channels in a wireless standard are separated in frequency. However, that may not be sufficient because the filters and receivers used by radios are imperfect and do not cancel all the interference [83]. That effect may even be more visible when transmitters and receivers from different networks using adjacent channels are closer to each other. To prevent this, better filters can be used in receivers and non-adjacent channels should be selected used if possible.

The problem of WSN coexistence has been broadly researched and one of the early recommendation for coexistence between WLANs and WPANs is IEEE 802.15.2 -TG2 [4] . In addition, a new IEEE 802.19 Wireless Coexistence Working Group [168] was formed to develop standards for coexistence between wireless standards of unlicensed devices. The objectives of this group are to guarantee the coexistence (CA – Coexistence Assurance), i.e., to allow multiple wireless networks to operate in the same location without causing significant interference to one another. However, current devices do not support most of these recommendations yet.

Researches focusing the coexistence problem propose some solutions that can be classified in two different classes regarding their mechanisms: collaborative and non-collaborative. Collaborative mechanisms are based on the exchange of information between networks to minimize the mutual interference. On the other hand, non-collaborative mechanisms do not require the involved networks to cooperate. The mechanisms for coexistence between wireless networks are also referred to Cognitive Radio (CR) which based on the Software Defined Radio (SDR) [89] to make use of frequency bands efficiently. Examples of such mechanisms are Dynamic Spectrum Access (DSA) and Opportunistic Spectrum Allocation (OSA) which allow the secondary users to use the free hole or channel in the frequency band [5] without affecting the primary users.

The principles of CR can be applied to WSN to efficiently use the frequency spectrum and to support the coexistence of networks. To accomplish that, CR allows nodes to explore the frequency spectrum using an opportunistic mode, and to adjust the transmission parameters (frequency, transmission power and codification) based on the information gathered from the environment. This means that the enable CR nodes have ability to adapt to the surrounding environment by reconfiguring, in an intelligent way, all the transmission parameters [5], [88].

A coexistence collaborative mechanism was presented in [167] which explored the synchronization capabilities of WSNs. In this work, each sensor network had a coordinator to manage the traffic in the network. In addition, there is a central entity that coordinates the channels used by the involved networks. It was required that all WSN coordinators have wireless and wired interfaces and that the communication to the central entity is made using an Ethernet network. Results in this study showed that the nodes' lifetime were increased and proved that coexistence was possible.

Dynamic Spectrum Access Protocol (DSAP) [90] is a central collaborative mechanism for managing and coordinating spectrum access. This protocol aimed at mitigating the congestion and interference between networks by adjusting the channels used by the nodes. To accomplish this, the DSAP server, also called arbitrator, keeps track of its clients and channel conditions in the region. When a client wants to communicate with another one, it has to negotiate the channel with the arbitrator. Results show that the DSAP reduces interference and improves the throughput. However, this protocol is not appropriate for controlling access for multiple types of networks because it requires a central coordinator which has a radio map of the deployment environment, i.e., knowledge of the channels currently in used in the region. In addition, it cannot deal with the effects of dynamic noise and interference in the communication.

The principles of DSA are to make the spectrum sensing, choose the best channel/frequency available and to dynamically reconfigure the devices radio. This mechanism has been used in cognitive or intelligent radios. Akan et al. [169] showed that these same techniques may be applied to WSN to solve coexistence problems.

A framework for Cognitive Radio Sensor Networks (CRSN) was proposed in [91]. In this work, the authors proposed two spectrum decision protocols for selecting the best wireless channel based on the application's QoS requirements. However, this work was only implemented in the simulations. In addition, the proposed protocols are based on CSMA/CA whose response time is not deterministic and therefore is not suitable for industrial environments.

Frequency Hopping Spread Spectrum (FHSS) has been used as an alternative solution to the coexistence of WSNs. According to [87], channel hopping can reduce interference and increase resilience between neighbor networks. However, this mechanism uses a pseudo-random sequence to make the frequency hops and does not consider the quality of different channels. If interference exists in more than one channel, FHSS technique may result in loss of packets and intermittent disruptions.

To provide a reliable WSN for industrial environment with performance assurances, several studies were made and projects implemented. The GINSENG [155] developed a reliable medium access protocol called GinMAC [69], [70]. It is a TDMA based protocol and contains specific mechanism to improve reliability and to assure maximum delays. Also, it uses a specific topology control mechanism and implements message routing.

The problem with the existing MAC protocol is that it cannot deal with the dynamic noise and interference, i.e., the noise and interference occur during the operation time of the sensor network. The DynMAC introduced in the following sections provides mechanisms to this problem. Because the current implementation of DynMAC is based on GinMAC [69], [70], the next subsection presents an overview of this protocol.

3.3.3 Ginseng MAC protocol (GinMAC)

The aim of the GINSENG project is to develop a performance-controlled Wireless Sensor Network that guarantees reliable and timely data delivery [155]. The targets of this project are critical environments such as the oil refinery in which the time response, packet loss and reliability are bounded by some constraints. In order to fulfill these requirements, GinMAC [69], [70] was developed to provide a reliable and energy efficient control for WSNs. It assures a time-critical network by using a TDMA mechanism and also by implementing a topology control mechanism that ensures the reliability of time-critical data delivery. As a case study, the GINSENG project implemented two WSNs in the oil refinery at Sines, Portugal.

3.3.3.1 Topology Control Mechanism

The network topology supported by GinMAC [69], [70] is a tree in which the sink node is the root of the tree and the other nodes, consisting of sensors and actuators, are the child nodes. The topology of GinMAC based sensor network is defined by two main parameters: maximum hop H; and fan-out degree $O_h(0<h\leq H)$ [69], [170] at each tree level h. The O_h specifies the maximum number of children associated with each node at level h-1. It is important to note that the fan-out degree at the root node is always defined as $O_0 = 1$ because there is only one root node in a tree. From these parameters, the maximum number of nodes (N^{max}) that this topology can accommodate is calculated by the equation 3.1.

$$N^{max} = 1 + \sum_{n=1}^{H} \prod_{h=1}^{n} O_h \quad (3.1)$$

However, in the GINSENG project the maximum number of nodes per tree was limited to 25 to assure time restriction in industrial application.

3.3.3.2 GinMAC Slot Allocation

In GinMAC, time slots are used exclusively, i.e., if a slot is allocated to one node it cannot be reused by other nodes. Each sensor or actuator has a different time slot to transmit and receive data to/from the sink node. The GinMAC [69], [170] super frame, F, contains a number of basic slots that allow each sensor to send one message to the sink and the sink can transmit a command to every actuator. In addition, it also contains additional time slots to improve the transmission reliability. Moreover, GinMAC frame may also contain unused slots to improve energy consumption [170].

The GinMAC basic slots accommodate two different types of traffic: the upstream and downstream. The upstream is the traffic flow from sensor nodes to the sink. Each leaf node requires one time slot within F to communicate data to its direct parent node. A parent node requires a slot for each child node plus one slot for its own data. Therefore, the number of upstream slots for each node at level h is calculated as follows

$$S_h^{up} = O_{h+1}.S_{h+1}^{up} + 1 \text{ (3.2) with } S_H^{up} = 1.$$

Because there are $\prod_{i=1}^{k} O_i$ nodes at level k, the total number of basic upstream slot for this level is $S_k^{up} \prod_{i=1}^{k} O_i$. Consequently, the number of basic slots of upstream is calculated by the equation 3.3 [170]:

$$S^{up} = \sum_{h=1}^{H} S_h^{up} \prod_{i=1}^{h} O_i \qquad (3.3)$$

On the other hand, the downstream is the traffic from the sink to the actuators. The sink should be able to send one data packet to each actuator within a frame. Therefore, the sink requires at least as many basic slots as the number of actuators. In addition, the number of slots allocated for nodes at level h is the minimum between the maximum actuators in the network and the number of nodes below this level. Assuming that the maximum number of actuator nodes in the network is N_a^{max}, the number of basic downstream slots for each node at level h is calculated as follows:

$$S_h^{down} = \min\left(N_a^{max}, \sum_{i=h+1}^{H} \prod_{j=h+1}^{i} O_j \right); \; with \; S_H^{down} = 0 \; (3.4)$$

Consequently, the number of basic slots for downstream is computed using the equation 3.5:

$$S^{down} = \sum_{h=0}^{H-1} S_h^{down} \prod_{i=0}^{h} O_i \qquad (3.5)$$

Thus, the total of basic time slots is $S_{total} = S^{up} + S^{down}$ (3.6).

To illustrate, let's examine the sensor network in Fig. 3.15. With this network we have H=3, O_1=3, O_2=1, and O_3=2. Applying the equation (3.3), we have S^{up}=27. Assuming $N_A^{max} = 2$, from equations (3.4) and (3.5) we have S^{down} = 14. The basic slot allocation of the GinMAC frame for this example network is shown in Fig. 3.9.

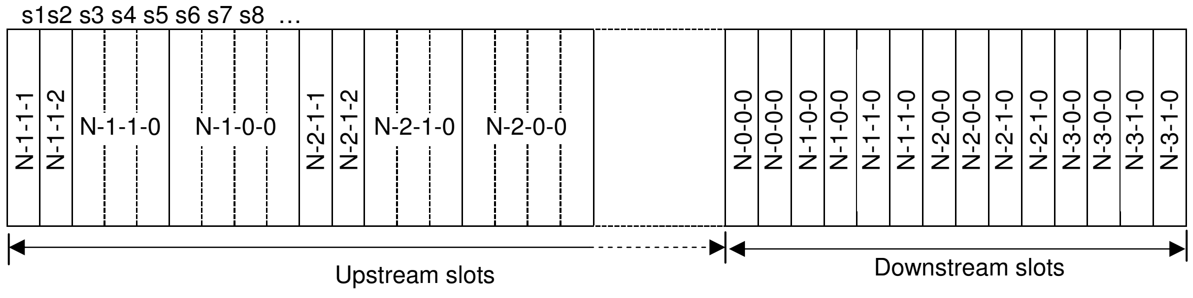


Fig. 3.9 Slot Allocation for the Tree in Fig. 3.15

The main advantage of GinMAC [170] is its assurance of good performance and reliability, i.e., loss rate and delivery delays are within acceptable boundaries at all times. In GinMAC, each node is aware of its relative position in the tree and knows the slots assigned to itself, its children (to handle sensor data messages) and parent (to handle sink data messages). This allows a node to transfer its data in a collision-free mode and thus the behavior of network is deterministic. In addition, it allows nodes to sleep during the time slots of others. Moreover, the tree structure of WSNs is automatically built based on the node identification and GinMAC automatically provides the routing.

In spite of having good overall performance, GinMAC with the fixed and preconfigured channel mechanism of traditional MAC protocol cannot guarantee the reliability in noisy and interference environments which are changeable with time. In order to overcome this while avoiding the complexity of cooperate coexistence of DASP and full CR, we proposed Dynamic MAC protocol (DynMAC), which employs the dynamic channel reconfiguration mechanism. It includes most of the properties found in cognitive radios (sensing, decision, and sharing of spectrum). Furthermore, to maintain the network resilience, a mechanism was proposed to allow nodes to automatically recover from the connection loss.

3.3.4 Dynamic Channel Allocation MAC Protocol for WSN (DynMAC)

Although the original GinMAC had mechanisms to reduce the problem of packet loss and to improve the delay, it does not have an efficient mechanism to automatically avoid interference to allow the coexistence of wireless networks. In addition, it cannot deal with the noise or interference introduced by new networks or other devices. Consequently, it is necessary to have a new solution for such problems.

The goal of the DynMAC protocol is to minimize the effects of noise and interference on WSNs. In particular, it provides mechanisms to avoid the effects of noise and interference by automatically detecting the best channel and configuring the network operate on that channel. It is important to note that the proposed protocol can deal with the new noise and interference introduced during the operation of the WSNs. The design of DynMAC is based on the techniques of non-cooperative coexistence. Thus, there is no centralized coordination between wireless networks in the same region. DynMAC takes into account industrial and critical environments and has the same constraints as those assumed by GinMAC [69], [70], i.e., low packet loss and bounded delay. In order to ensure the network requirements, such as delay and delivery rate, a time-slotted technique (TDMA) is used, so the sink node knows all nodes in the network, as well as their hierarchical position. The best channel decision is computed in at the sink node. However, all nodes collaborate with the choice of the global best channel. Furthermore, to ensure the resilience of network, the common control channel (CCC) is not used in the implementation.

DynMAC adds an additional reliable level to the GinMAC [69], [70] protocol by including the periodically evaluation of the spectrum, the recovery from lost links, and the reconfiguration of transmission parameters by using techniques similar to those used in cognitive radio. The cognitive characteristics of DynMAC protocol are based on the sensing of the environment conditions, making decision on best channel, sharing of information with network nodes. This cognitive capacity of the protocol allows the dynamic and periodic reconfiguration of channels for WSNs, taking into account the variations of the noise and interference. Furthermore, to ensure the resilience of the network, two mechanisms were employed in DynMAC: (1) Packet Error Rate (PER) threshold (2) lost link monitoring. The former requires every node to monitor its PER over a specified period of time, e.g., the last 5 minutes. If the PER of the last time period exceeds a threshold, e.g., 5%, the node will send an alert to the sink. Based on the alerts received from the nodes, the sinks will decide when a re-evaluation of the best channel is needed. For instance, the sink will start the re-evaluation of the best channel when it received more than 3 alert messages from the normal nodes. The lost link monitoring mechanism allows the node to detect and to recover from a link loss when it happens. If a node cannot receive the super-frame for a predefined time, e.g., 30 seconds, it assumes that the link to its parent is lost. Consequently, the node is forced to rescan the operating channel of the network.

The DynMAC protocol consists of four main phases to add reliability for WSNs: (1) network synchronization, (2) global best channel selection, (3) periodically re-evaluating the best channel and (4) Recovery from connection loss. The following subsections details these phases.

3.3.4.1 Network Synchronization

This phase is only run once to form the WSN. The purpose of this phase is to allow the sink to select a channel for network and to allow the normal nodes to detect the channel of the sink and join the network. In this phase, the process running on the sink and on normal nodes are different. In order to avoid problems with the choice of default common channel, which may lead to unstable network operation, the sink node chooses a best channel based on RSSI and then broadcasts the information to the network. On the other hand, the process running on the children nodes scans different channels until it receives a message from a specific sink node.

3.3.4.1.1 Local Best Channel Selection

This process is run by the sink to evaluate the quality of different channels and to select the best one. The best channel in this case is called local best channel because it is only based on the local information collected by the sink node. Two metrics used to evaluate the channel quality are the RSSI value and the frequency of the RSSI values that are greater than the CCA threshold. It is important to note that the RSSI value associated with a received packet indicates the signal power. Therefore, the higher RSSI value is the better quality of signal. However, the RSSI values collected when no nodes transmitting indicate the level of noise and interference. Thus, the meaning of RSSI values is reversed, i.e., the higher the RSSI value, the worse the channel's quality. Accordingly, the best channel is the one that has the least accumulated RSSI and low frequency of RSSI values greater than the CCA threshold. Algorithm 1 describes the steps of the best channel selection process.

```
1   Procedure SinkSensing
2   for (1 to N) do
          /*  N:  the number of time to scan the spectrum*/
3       for (c to 11..26) do
4           set channel(c)  // set  c  as  working  channel */
5           current rssi = get current rssi()
6           rssi values[c-11]+= current rssi
           /*  keep  the  maximum  RSSI  of  the  channel  c     */
7           if (current rssi > CCA THRESHOLD) then
8                rssi count[c-11]++
    /* Ascending  order  sorting  of  accumulated  rssi     */
9   acc channel index = index  sort(rssi values)
10  channel index = cost computing(acc channel index)
11  return (channel  index[0]+11)
```

Fig. 3.10 ***Algorithm 1***: Sink node - locally best channel selection

Initially, during the spectrum sensing, the sink node samples 16 channels, channel 11 to 26, N times to collect the information for evaluating the quality of channels (lines 2–8). The RSSI accumulated values of the channels are stored in the array *rssi_values* (line 6). In addition, the frequency of the RSSI values that are greater than the CCA threshold is also counted and stored in the array *rssi_count* (lines 7–8). After finishing the spectrum sensing, the channels are sorted in ascending order of the accumulated RSSI values (line 9). The index sorting is used to make the process of selection of the best channel easier (the element at the first index (0) is the best channel). Then, the cost of each channel is calculated and sorted (line 10). The process of computing cost for each channel is shown in Algorithm 2. Because the channels are sorted in ascending order by its cost, the best channel is the one at the first position (line 11).

```
1. Procedure CostComputing
2. cost=1
3. for (i to 0..15) do
         /* get the channel at the index i */
4.     channel = acc_channel_index[i]
5.     Channel_cost[channel]+=cost
       /* add the frequency as additional cost */
6.     Channel_cost[channel]+=rssi_count[channel]
       /* computing the cost based on accumulated rssi for next channel */
7.     if rssi_values[acc_channel_index[i+1]] > rssi_values[channel] ) then
8.         cost++
9. return index_sort(channel cost)
```

Fig. 3.11 ***Algorithm 2***: Computing Cost for Channels

As shown in Algorithm 2, the RSSI cost, the cost for the accumulated RSSI metric, is initially set to one (line 2). For each channel, its cost is first assigned to RSSI cost of that the channel (line 5). Then, the threshold cost, i.e., the frequency of the RSSI values greater than CCA threshold, for that channel is added to the channel's cost (line 6). It is important to note that the channels have the same accumulated RSSI value will have the same RSSI cost. When the accumulated RSSI changes, its cost is increased by one unit (lines 7-8). Finally, channels are sorted according to their cost (from lowest to highest cost) (line 9).

After choosing the best channel, the sink node sets it as its operating channel. Finally, the sink node inform all other nodes about the channel on which it is running by building the control frames with the network's GID (Group Identification) and broadcasts them to the network.

3.3.4.1.2 Network Joining

The child nodes have to find the channel used by the sink and join the network. Algorithm 3 describes the process for the child nodes to detect the channel on which the sink node is currently operating.

```
1   Procedure ScanningChannel
2   $C_i$ = 11
3   while (true) do
4       set_channel($C_i$ )
5       if (exist frame( )) then
                /* if exists frame in channel */
6           get frame( )
7           if (valid frame( )) then
                /* frame $\in$ sink's GID */
8               break
9       If ($C_i$ <26) then
10          $C_i$++
11      else
12          $C_i$=11
13  return ($C_i$ )
```

Fig. 3.12 ***Algorithm 3***: Scanning the Communication Channel of the Sink

During its booting, a child node repeatedly scans the 16 channels in order to find the communication channel of the sink. This process starts by setting the node to scanning on channel 11 (line 2 - 4). At each channel, the node checks whether there is a frame waiting to be received or not (lines 5). If there is, it will get the frame and analyse it to see whether it is from a valid sink, i.e., the same GID (lines 6–7). In the case of a valid frame, the scanning process is stopped and the node finishes its booting process (lines 7–8). On the other hand, if there is no frame or the frame is not from a valid sink, the node will sense the next channel (lines 9-12). This process is repeated until a valid channel is found. The detected channel is returned and used in the joining network process of the child node (line 13).

After detecting the sink's channel, the node will join the network by setting its radio channel to that of the sink and start exchange the frames with the sink. After receiving the joining frame from the node, the sink saves information about this new joining node and sends an ACK message back to the node. The ACK message informs the node that the joining phase is completed.

3.3.4.2 Global Best Channel Selection

Because the best channel chosen by the sink node only uses the local information at the sin, it may not be a good channel for the entire network. The reason is that the noise and interference at the child nodes might be different from those at the sink. Therefore, it is necessary that all nodes in the network contribute to the process of choosing the best channel. This process should be started when all the nodes have already joined the network. However, in the real environment the full network may never be reached for some reason, e.g. some nodes are not available. Therefore, we define a *stable* state for the network. We consider a network is in *stable* state if there at least one child node joined the network for long enough duration (e.g., 5 minutes). When the network is in *stable* state, the process of choosing the best global channel is started. This process is shown in Fig. 3.13 and consists of the following steps:

1. The sink node broadcasts messages to solicit information about the channel conditions at other nodes. The broadcast message is sent 3 times to make sure that all nodes receive at least one request.
2. When receiving the broadcast message from the sink, the normal node forwards this message to its children. The node then samples the RSSI values on all channels a number of times. The process of sampling of RSSI values is the same as the one done at the sink in the local best channel selection process (Algorithm 1).
3. The node then employs the Algorithm 2 to compute the cost of each channel and to sort them in ascending order of the cost.
4. The ordered channel list (not RSSI values) computed by the normal node in step 3 is then sent to the sink.
5. When the sink has enough information from network nodes, it will decide which channel is the best one. The process of choosing the global best channel is described in Algorithm 4.
6. After choosing the best channel and it is different from the current working channel, the sink will broadcast three switching channel messages to ask other node to switch to the new channel.
7. When receiving the switching channel message from the sink, child node will forward it to its children. To ensure that at least one of these broadcast messages reaches the leaf node, the intermediate child nodes will wait at least three switching channel messages or until a predetermined duration elapsed,

e.g., 15 seconds. After the waiting condition passes, it will switch to new channel.

8. The sink will switch to new channel after finishing sending the last switching channel message.

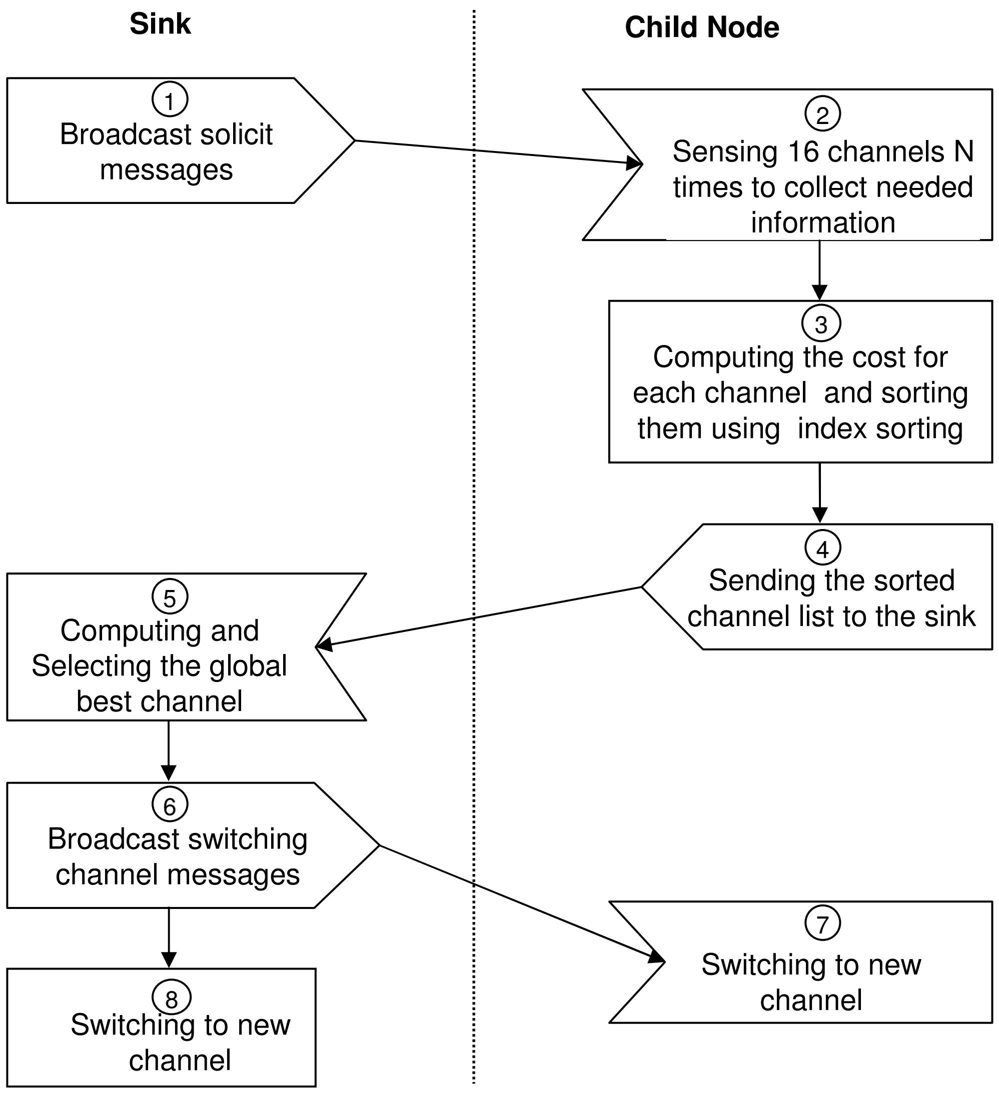

Sink
Child Node
1
Broadcast solicit messages
2
Sensing 16 channels N times to collect needed information
3
Computing the cost for each channel and sorting them using index sorting
4
Sending the sorted channel list to the sink
5
Computing and Selecting the global best channel
6
Broadcast switching channel messages
7
Switching to new channel
8
Switching to new channel

Fig. 3.13 The Process of Selecting Global Best Channel.

Because the sink only gets an ordered list of channels (from the best one to the worst) from the normal nodes in the network in order to decide which channel is the best one, the procedure shown in Algorithm 4 is employed.

```
1   Procedure GlobalBestChannel
    /* Compute the cost for each channel */
2   for (node_id ∈ nodeList) do
3       for (pos in 0..15) do
            /* get the channel at pos */
4           channel = Channel_index_list[node id][pos]
5           channel cost[channel]+=pos+1
            /* Store the worst channel list */
6           if (channel index list[node_id][pos] == 15) then
7               bad_channel[channel]+=1
    /* Sorts channels by cost and store in channel index global */
8   Sort_channel(channel_cost, channel_index _global)
    /* Choosing the best channel */
9   best _channel = channel _index _global[0]
    /* Reselect the best channel if it exists in bad_channel_list */
10  c=0;
11  while ( (c < 16)&&(bad _channel[c] > 0) ) do
12      c++
13      If (c<16)
14          best_channel = channel_index_global[c]
15  return best_channel
```

Fig. 3.14 ***Algorithm 4***: Choosing the Global Best Channel.

The global best channel is selected based on the total costs of channels. In order to compute the total cost for channels, it is necessary to assign a cost for each position of the ordered lists obtaining from the normal nodes. For simplicity, the cost of the channel is also its position in the sorted list, i.e., the cost of the first position is 1, the second position is 2, etc. Consequently, the total cost of each channel is calculated as described in (lines 2–5). To avoid choosing the worst channel of some nodes in the network, i.e., the channel located in the last position of the ordered channels, the sink node also stores a list of the worst channels (lines 6–7). The list of costs of the channels is then sorted, in ascending order by cost, and stored in the *channel_index_ global* array (line 8). The global best channel is the channel in the lower position in the channel cost list that does not appear in the worst channel list (lines 9–14). In case there is no such channel, the channel in the first position of the channel cost list is chosen as best channel.

3.3.4.3 Periodically Re-evaluating the Best Channel

Because the quality of the channel may vary with time, the best channel at one period may become the worse (e.g., high lost rate) during the operation of the network. As a result it is necessary to periodically re-evaluate the quality of the channels. Two possible approaches are: (1) the sink periodically sends the request to the normal nodes to solicit the channel information to re-evaluate the best channel (2) the nodes periodically evaluate the quality of the current channel based on different metrics, such as error rate or on the number of lost links, and send this information to the sink.

In DynMAC, the second approach is employed using the PER as the evaluation metric. Every normal node periodically checks its PER and if it is higher than a threshold (e.g., 1%), the node will send a message to the sink stating this information. When the sink receives the information, it will decide whether there is a need to re-select the global best channel. In our implementation, the sink makes the decision based on the number of nodes that send the re-evaluation request. Because the sensor networks usually operate for a long time if the pure accumulated PER is used for evaluating the current condition of the channel then it will take very long for detecting dynamic noise and interference. Consequently, DynMAC employs the PER over a predefined time interval, to evaluate the channel condition. Particularly, in our implementation, we use the PER of the last 5 minutes as the evaluation metric. The best channel re-evaluation process is the same as the process of the global best channel selection described in previous section.

3.3.4.4 Recovery from Connection Loss

During network operation any node may lose the connection to its parent for different reasons. One example of such scenario is that the node did not receive a switching channel message from the sink. In this case, the sink switches to the new channel, leaving the node working in the old channel. Therefore, it is necessary to have a mechanism for the node to recover from such a situation. To resolve this issue, the node is forced to re-scan the communication channel of the sink if it cannot communicate with its parent for a specific duration. To do this, a child node runs the Algorithm 3 to scan the sink’s channel.

3.3.5 Experiments and Results

In order to evaluate the mechanisms implemented in the DynMAC protocol, the Contiki operating system [95], together with TelosB [47] sensor nodes, was used. As a first step, DynMAC was evaluated using the COOJA simulator [171], [172] provided together with ContikiOS. COOJA simulator was used to make a first evaluation of the settings that would be used later in the real testbed. The structure of the network used for experiments is shown in Fig. 3.15. Within this network, the number of slots of the super-frame was set to 100. Therefore, each super-frame has 1000 ms (10 ms per slot).

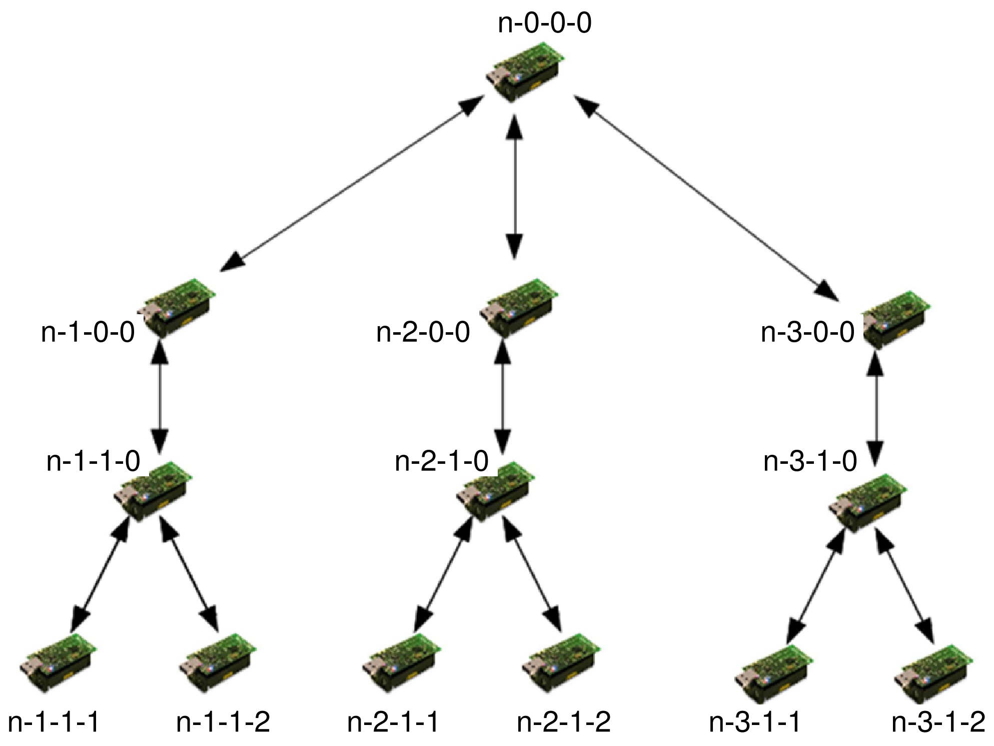


Fig. 3.15 Testbed sensor network

3.3.5.1 Experiments with Simulation

COOJA simulator [171], [172] was used to test the functionality of the proposed algorithms. Specifically, the scanning, the coverage, and the handoff time were measured.

3.3.5.1.1 Scanning and Network Coverage Time

The first simulation was done to evaluate the scanning and the network coverage time. For the scanning time, it measured how long it takes for the nodes at different levels to detect the channel on which the sink is currently working. For the network coverage time, it is measured the time for all nodes to successfully join the network. In these tests, we measured the time from the moment when the sink finished its booting. The results of the experiments concerning the scanning time are shown in Table 3.2 and in Fig. 3.16.

As shown in Table 3.2, some nodes at level 1 can immediately detect the channel on which the sink is running during, i.e., on the first super-frame (112ms). The scanning at this level has a maximum of 9 super-frames (8648 ms), and an average of about 4 super-frames (3842.68 ms). For the nodes at Levels 2 and 3, they also take the similar amount of time to detect the channel of the sink (or its parent). It means that the node can detect its parent on the first super-frame. Furthermore, most of the nodes (75 percent) can detect their parents during the first 5 super-frames (4860ms). However, for the node at Level 3, sometimes it takes a little bit longer up to 15 super-frames (14264 ms).

Table 3.2 Scanning and Booting Time of Nodes at Different Levels (Simulation)

Statistic	Level 1 Scanning time (ms)	Level 1 Finish booting time (ms)	Level 2 Scanning time (ms)	Level 2 Finish booting time (ms)	Level 3 Scanning time (ms)	Level 3 Finish booting time (ms)
Minimum	112	160	24	72	24	136
Q1	2228	2652	784	1170	822	1074
Median	3798	4054.5	2104	2352	2236	2468
Q3	4860	5462	2483.75	2753.25	4264	4554
Maximum	8648	8920	8872	8984	14264	14856
Average	3842.68	4175.21	2309.26	2569.97	3056.15	3332

In addition to the scanning time, the nodes also need time to initialize the parameters for their environment to finish the booting process. In most cases, it takes a node less than 600ms to finish its booting. In our experiments with the simulation, after the detection of the parent channel, the node needs a maximum of 729 ms. From Table 3.2 we can estimate the coverage time of the network, that is, the maximum duration for all nodes in the network to detect and join the network. In this case, the coverage time was less than

33 seconds (8920ms + 8984ms + 14856ms = 32760ms). We also repeated this experiment numerous times to measure this coverage time and in all the experiments it took less than 17 seconds (maximum 16920ms).

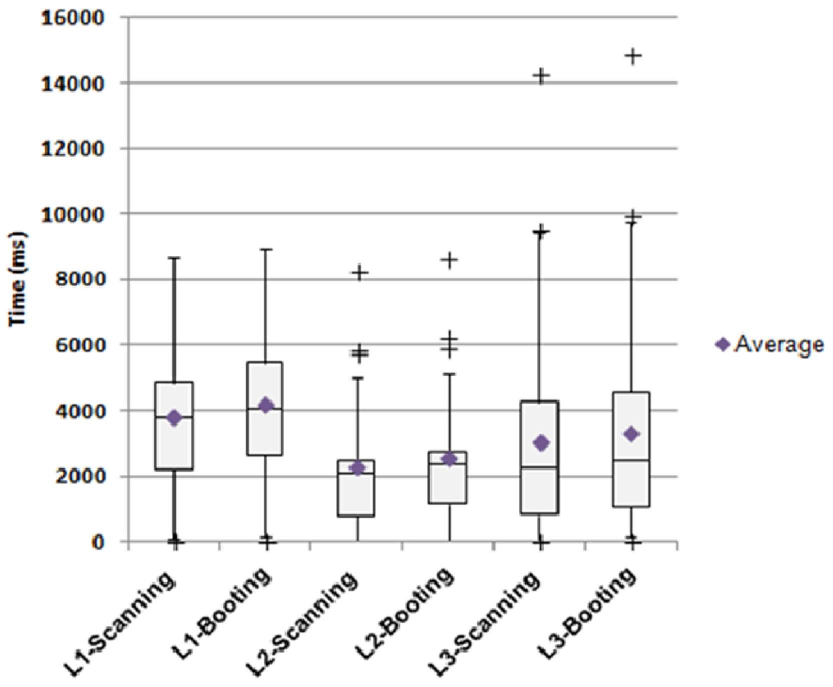


Fig. 3.16 Scanning and Booting Time at Different Levels (Simulation).

3.3.5.1.2 Handoff Time

In this context, handoff time is the time that a node (e.g., mobile nodes) takes to rejoin the network, that is, resynchronize itself with its parent after leaving the network. From the simulation, it takes from 3 ms to 384ms for a node to resynchronize with its parent node. If this node is not a leaf, its children also have to resynchronize with it and with the sink. From the experiments, it is very fast for other nodes to resynchronize with its parent (maximum 678ms).

3.3.5.2 Experiments With Testbed

In addition to simulation, we also set up a testbed using TelosB motes [47], and using the same topology as depicted in Fig. 3.15. The objective of the experiments using testbed was to validate the mechanisms proposed in DynMAC. More important, the experiment with the testbed proved that the proposed solution is feasible.

3.3.5.2.1 Evaluation of the Quality of Different Channels

The first experiment was done to evaluate the quality of different channels of IEEE 802.15.4 based sensor network by employing the Algorithm 1 to identify the best one. The test was repeated 1500 times and the number of times that each channel was chosen as the best one as well as the worst was counted. The result of this experiment is described in Table 3.3 and in Fig. 3.17. Out of 1500 tests, channel 26 has appeared as the best channel for 833 times (55.53%). Other channels that also appeared as good channels with a high frequency were 25 (9.07%), 16 (6.4%), 17 (6.07%), and 13 (5.06%). On the other hand, channel 23 appeared as the worst one with the rate of 42.8%). The second and the third worst channels were 24 (21.13%) and 11 (13.73%), respectively.

As shown in Fig. 3.17, there were several cases a channel sometimes identified as best channel but the other time identified as the worst one. One possible reason for this is that the noise and interference are dynamic and the wireless communication among devices might also have gap interval, i.e., no transmission. Consequently, if a channel is scanned during the gap interval, it is more likely that it will be identified as the good channel.

Table 3.3 Experimental Result of Evaluating the Local Best Channel.

Channel	Frequency appeared as the best channel	Frequency appeared as the worst channel
11	50	206
12	18	86
13	76	23
14	26	37
15	69	13
16	96	8
17	91	12
18	13	24
19	19	19
29	5	30
21	53	43
22	7	31
23	5	642
24	3	317
25	136	2
26	833	7

One important point to note is that the result of this experiment correctly reflected the current environmental conditions. It can be seen from the Fig. 3.17 that in most of the time the channel the channel 23 and 24 were identified the worst ones. The reason is that there is an IEEE 802.11g wireless Access Point (AP) operating on the channel 11 positioned very near the sink (1 meter). Consequently, this AP significantly affects the quality of the channels of IEEE 802.15.4 based WSNs. Similarly, the experimental result also showed that 26 and 25 were selected as the best channel with a very high frequency. It is explicable because, in the experimental location, these channels did not interfere with other wireless networks. For other channels, because there are many WIFI networks operating on the channels 1, 6, and 11, their quality depends on the traffic rate of these networks. In fact, as shown in Fig. 3.17, there are still some good channels that can be used for WSNs such as channel 16 and 17.

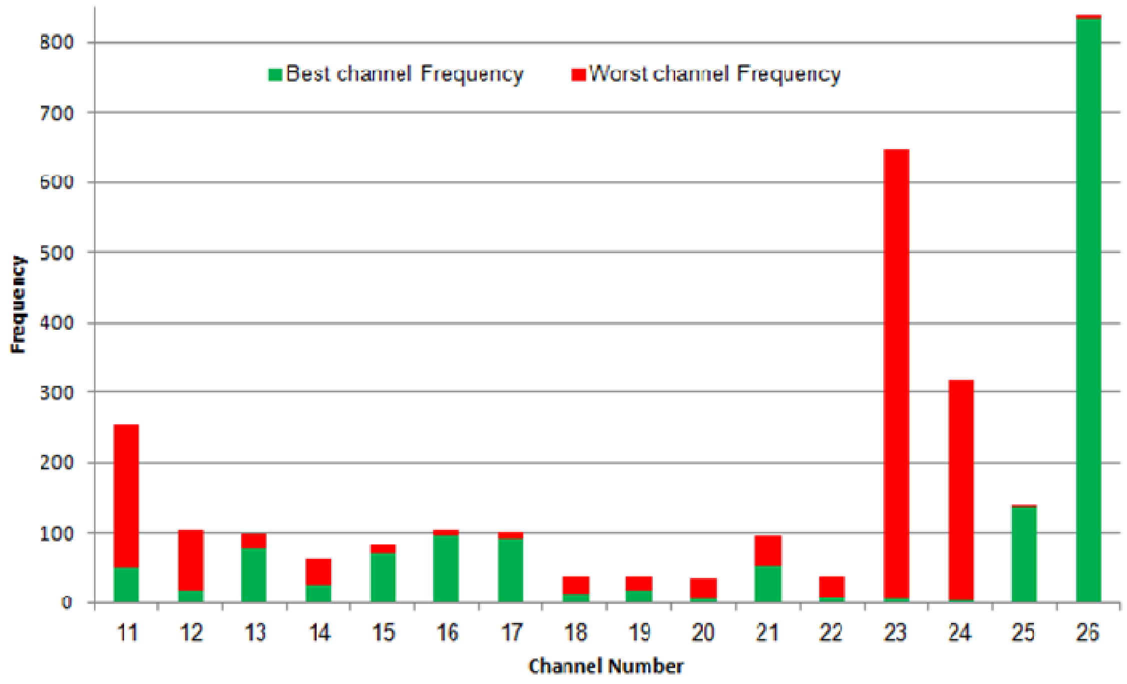


Fig. 3.17 The Quality of Channel at the Sink

To evaluate the differences in performance between the identified good channels and worse ones, we did numerous experiments with three best channels (26, 25, and 16) and three worst ones (23, 24, and 11). In these experiments, the packet loss rate of each selected channel was measured with two MAC protocols: X-MAC [62] and DynMAC. The objective of this test was not to compare the performance between these two protocols but to see how they perform on the different channels. Because X-MAC [62] is a CSMA based MAC protocol, we set up a testbed with only two nodes: one for sending packets and the other for collecting packets and calculating the packet loss rate. The reason for this simple testbed was to avoid the internal interference among the nodes in the WSN. The testbed for the DynMAC has the same topology described in Fig. 3.15. The result of these experiments is shown in Fig. 3.18.

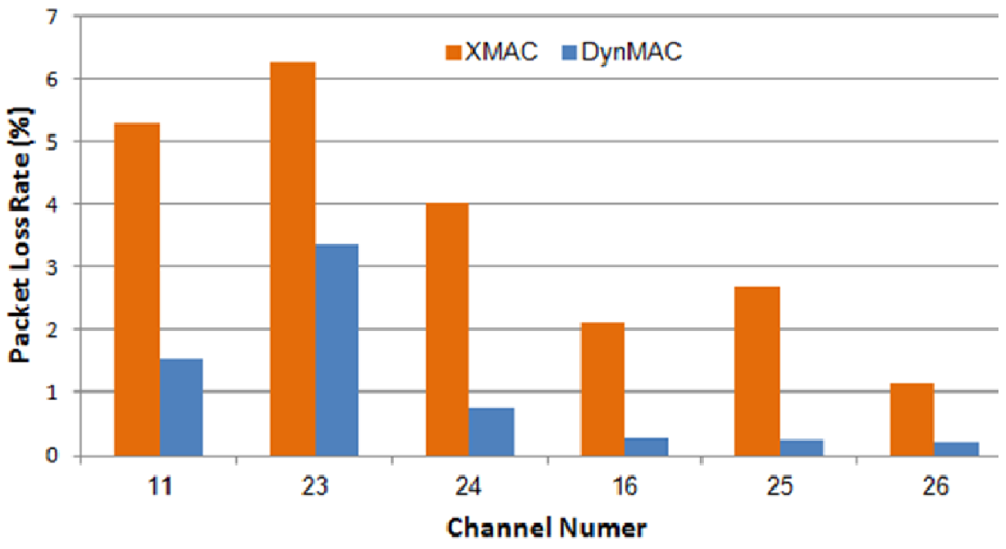


Fig. 3.18 Loss Rate of Good vs Worse Channels.

It can be seen from Fig. 3.18 that there is a significant difference in loss rate between the best and worst channels. With X-MAC, a simple two-node testbed, the packet loss rate of the worst channel was more than 6% while that rate of the best channel was less than 3%. For the DynMAC, because it is a TDMA protocol with the acknowledgment and retransmission mechanism, the loss rate was significantly reduced. However, there is still a noticeable difference between the best and the worst ones. For the worst channel, the loss rate could be up to more than 3% while that rate for the best one is about 0.25%. Considering the experimental results, it could be concluded that the selecting the right communication channel could significantly improve the performance of a WSN.

3.3.5.2.2 Scanning and Network Coverage Time

The next experiment we did was to measure the scanning time of the nodes and the network coverage time. The former refers to the time it took for a node at different levels to detect the channel on which the sink is currently running was measured. On the other hand, the latter measures the total time it takes for all nodes to successfully join the network. In these tests, the time was measured from the moment when the sink node finished booting. The experimental results concerning the scanning time using simulation are shown in Table 3.4 and Fig. 3.19.

Table 3.4 Scanning and Booting Time of Nodes at Different Levels (Testbed)

Statistic	Level 1 Scanning time (ms)	Level 1 Finish booting time (ms)	Level 2 Scanning time (ms)	Level 2 Finish booting time (ms)	Level 3 Scanning time (ms)	Level 3 Finish booting time (ms)
Minimum	16	168	8	88	8	88
Q1	120	432	160	392	160	376
Median	424	832	384	720	336	668
Q3	688	1048	664	1048	658	954
Maximum	984	1352	1328	1720	2120	3496
Average	432.35	745.41	459.63	794.35	477.24	761.41

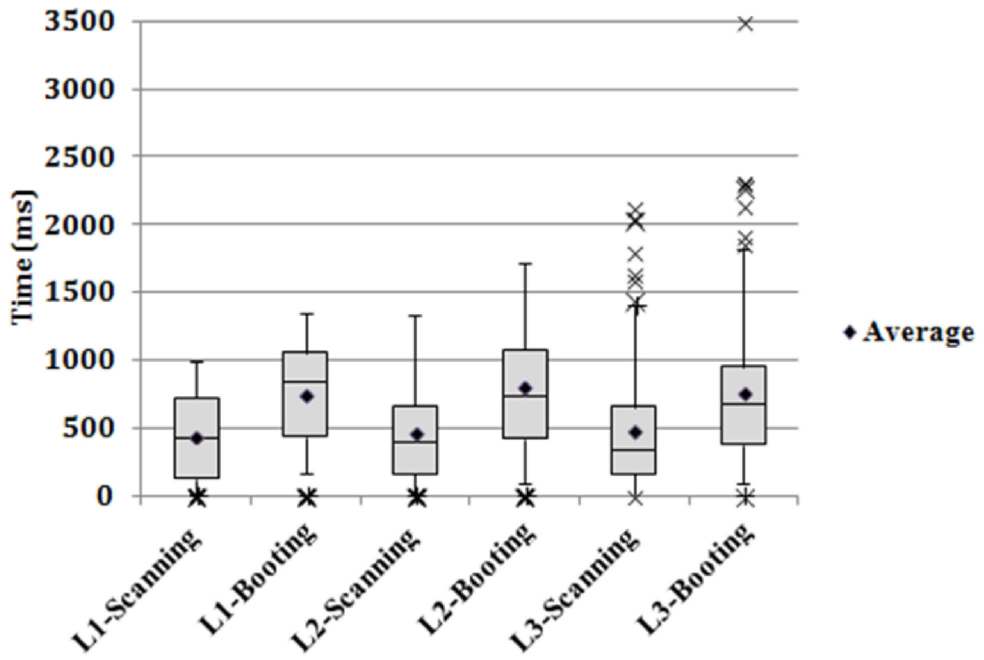


Fig. 3.19 The Scanning and Booting at Different Levels (Testbed)

As shown in Table 3.4, it is very fast for a node to scan and detect the channel of its parent. In most cases the nodes only take 1 super-frame (less than 1 second) to detect the communication channel of the sink. However, in some cases, it takes up to 3 super-frames (2120 ms) to scan the operation channel of the sink node, a situation that occurs mainly from nodes at a level far away from the sink. This is reasonable because nodes at higher levels have to wait for their parents to join the network before they can detect them.

Similarly to the simulation result, after knowing the channel of the sink node, the nodes need time to finish its booting. Observing the experimental results obtained from the testbed, we saw that this duration was similar to those obtained from simulation. However, in some cases, it takes a little bit longer for the node to finish booting. In our experiments, there was a case where it took 1696 ms for a node to finish booting after it detected the channel. As shown in Table 3.4, the coverage time of the network can be estimated and it takes less than 7 seconds: (1352ms maximum booting time at level 1 + 1720ms maximum booting time at level 2 + 3496ms maximum booting time at level 3 = 6568ms). We did numerous experiments to measure the network coverage time. And most of the time it took about 3 seconds for all nodes to form the entire network. In addition, the maximum network coverage time was about 6040ms.

3.3.5.2.3 Dynamic Noise and Interference Detection

Besides the ability to select the best channel automatically, DynMAC is also able to deal with dynamic noise and interference, which occur during the sensor network's operation. The mechanism how DynMAC can realize this function is described in Section 3.3.4.3. To prove that the proposed mechanism is applicable and workable solution, we did numerous experiments. In the experiments, the time interval for computing the PER was set to 5 minutes and the threshold was 1%. It means that if the PER of the last 5 minutes is equal or greater than 1% then the normal node will send an alert message to the sink. In addition, if the sink receives 3 or more alert messages from the nodes it will start the best channel re-evaluation process.

In order to evaluate this functionality of DynMAC, during the normal operation of the WSN, we tried to introduce the interference in its currently communication channel (e.g., channel 26). We did this by putting 4 sensor nodes continuously broadcast on the working channel of the sensor network. The interference caused by these 4 sensors affected the PER of some nodes in the network. Consequently, these affected nodes detected the interference and sent warning messages to the sink. Observing the operation of sensor network, we recognized that after introducing interference about 10-15 minutes the sink started the best channel re-evaluation process. In addition, the effect of this process was that the sensor network was switched to a new channel, e.g., from channels 26 to 25.

3.3.5.2.4 Recovery from Connection Loss

Another type of experiment we did was to evaluate the ability of a node to recover from the connection loss. It is important to note that the connection loss in this context is mainly referred to the case in which the normal nodes did not receive any switching channel request message from the sink. The result of such a scenario is that the sensor network switches to operate on another communication channel but some specific nodes. Consequently, these nodes have to somehow resynchronize themselves with the sink to continue to communicate.

In order to test whether this functionality can be achieved, during the switching channel process we moved a node to a place in which it could not communicate with its parent. Then, after the sensor network successfully switched to the new channel, that node was moved back to its original position. We did a number of experiments with two types of normal nodes: leaf and intermediate nodes. The experimental result showed that it is very fast for these nodes to detect its parent and re-establish its communication. In most cases, it took a node about 3 seconds, with maximum less than 10 seconds, to resynchronize with its parent.

3.4 Summary

The work presented in this chapter focuses on the reliable communication of the WSNs. It first discusses the experimental studies of the characteristics of channels of 802.15.4 compliant sensor networks. The results of this study show that the quality of channels of WSNs depends on the deployment environments and varies with time. In addition, it is difficult to predict the quality of different channels based on theoretical models. Consequently, empirical study is the appropriate method for choosing the appropriate channel when deploying sensor networks. More importantly, this chapter presents our proposed MAC protocol, DynMAC, to allow WSNs to coexist with other wireless networks as well as to operate in noisy environments. The proposed protocol adds additional reliable level to GinMAC by allowing the WSN to dynamically adapt to the noise and interference conditions of the deployment environment. In particularly, it employs the mechanisms for best channel evaluation, noise and interference detection, and lost communication recovery. DynMAC were successfully evaluated using both simulation and real testbed. The experimental results showed that our mechanisms resolve the configuration problems of the WSN in noisy and interference environments while maintaining the application requirements under critical scenarios.

4 The Integration Framework and Sensor Traffic Description Language (STDL)

Summary

WSNs are considered the bridge between physical and digital worlds, and they are envisioned to become an integral part of our daily life as well as an important element of the Future Internet. Therefore, integrating WSNs into external networks and applications is an undeniable requirement. The problem of current integration solutions for WSNs is their adaptability, i.e., the ability to reuse gateways and proxies in a multitude of sensor networks with different types of protocols and data frames. One reason behind this problem is that it is difficult or even impossible to standardize the structure of data inside the frame because there are a huge number of possible formats. Consequently, it is necessary to have a mechanism to deal with this problem. Our approach for this problem is to propose a framework that uses a language for describing the traffic in sensor networks named Sensor Traffic Description Language (STDL). In order to reuse the framework on a new sensor network, it is only necessary to describe the network's frame structures using STDL. This chapter details proposed framework, STDL and its prototype implementation.

4.1 Introduction

The major applications of WSNs are monitoring and controlling their target environments. They are as a bridge between physical to digital worlds. Therefore, in most cases, WSNs cannot operate in a complete isolation, but they need to be monitored and/or managed by control centers, which hosts Supervisory Control and Data Acquisition (SCADA) systems or other applications. The interoperability between WSNs and the external applications is a challenge because of their differences in communication protocols as well as diversity of possible sensor data formats. The solution for this problem is either to implement the same protocol on both environments or to add a gateway and/or a proxy between them.

Interconnecting WSNs with IP networks is desirable because it offers the opportunity to integrate WSNs with the future Internet, i.e., Internet of Thing (IoT). The recent researches have been proven that it is possible to implement both IP protocol stack [173], 6LowPAN [15] and web services [17], [18], [19], [20] on the sensor nodes. However, the limitations of sensor nodes in terms of memory, computation, communication and power source make it difficult and inefficient to deploy the full TCP/IP protocol stack and web services into all sensor nodes. Consequently, some optimal mechanisms such as header compression [15], Message Compression [20], packed JSON [18], EBHTTP [103], UDP binding [18], [20], etc need to be applied to the original standards to make it feasible for sensor nodes. As a result, the current solutions for interconnection such as 6LowPAN [15] and integration such as Tiny web services [17], WoT [19], and sMAP [18], and CoAP [20] still needs a bridge, proxy or gateway for the external applications to interact with sensor networks. In addition, allowing directly access to sensors from the Internet brings many challenges such as security, energy efficiency, and routing. Consequently, integrating IP stack and web services to sensor nodes is not a solution for all types of WSNs. As a matter of fact, the gateway or proxy approach for interoperating between WSNs and external applications will continue exist in the foreseeable future.

Other works on integrating WSNs with the external environments includes GSN [13], SensorWeb [104], VIP Bridge [12]. The common feature of most of these works, excluding VIP Bridge, is that the data, and/or functionalities of sensor nodes and networks are exposed as web services, which make the interoperability with applications over Internet easier. However, the problem with the current gateway-based integration solution is their adaptability. i.e., the gateway or proxy is not adaptable to different types of data formats. This means that the new drivers or parsers need to be developed when applying the gateway or proxy for a new sensor network or when adding new sensors or applications to existing one.

The Open Geospatial Consortium's (OGC) [173] has been working on series of specification named Sensor Web Enablement (SWE) for making sensors and sensor systems discoverable, interoperable over the Internet. SWE consists of a series of open standard specifications for discovery of sensors and sensor systems, for exchanging and processing sensor observation, and for tasking of sensor and sensor system. The SWE standards can be divided into 2 groups: (1) Models and schemes for encoding sensors and sensor observations; and (2) open web service interfaces. The former consists of Sensor Model Language (SensorML) [175], Observations and Measurements (O&M) [176]. The latter comprises Sensor Observation Service (SOS) [177], Sensor Planning Service (SPS) [178], and PUCK [179]. The SOS offers the web service interface for the client applications to retrieve the measurement and the description of sensors and sensor systems. The response formats of the SOS are XML-based data encoding using SensorML or O&M. SensorML is used to encode the descriptions while O&M is used for the measurements and observations from the sensors and systems. In addition, the user can task the sensors to perform appropriate actions through SPS web service interface. The SPS provides a list of observations that the users can assign to sensors or sensor networks. These four standards allow the clients applications to discover, and to access the sensors' measurement as well as to task the sensors via gateway. The PUCK protocol [179] was integrated into SWE in 2011 to enable plug and play sensor networks.

The above solutions provide a method for client applications to access the sensor data through the gateway. An equally important aspect is how the gateway interacts with the sensors and sensor networks. This means how the gateway can discover and analyze the data from sensors and sensor networks to make it available for use by the application and how it can send the commands to the WSN. The traditional approach for this problem is to request the sensor nodes to format the data according to the format required by the provided drivers [13]. Another method is to add a software driver or analyzer for each sensor or data frame format [13], [104]. In order to make the sensors as plug and play components of the gateway, the IEEE 1451 family standards [180] has been proposed. One of the core components of this family standard is the definitions of Transducer Electronic Data Sheets (TEDS), which are embedded into the transducers (sensors or actuators), to allow the interoperability between different manufacturers, and to make their data analyzable. Although it provides a standard way to exchange data, the software drivers and TEDS documents also needed to be manually developed and installed on every sensors. Recently, SWE integrated PUCK protocol [179] to store and automatically retrieve metadata and other information to/from the sensor nodes. The information stored in the nodes' memory is called PUCK memory and may include the IEEE 1451 TEDS, SensorML, or even the driver code. The gateway, which supports PUCK protocol, can automatically retrieve and utilize the information from sensor when it is installed [179]. In addition, if the driver code is available on the sensor node, it is downloaded into and executed on the host to translate the sensor raw data, using TEDS or SensorML, into the required format, e.g. OGC O&M object. The PUCK protocol brings another level of plug and play capability for sensor devices. However, it requires implementing PUCK documents on every sensor devices. In addition, to make a device as plug and play component the driver code has to be physically stored in the PUCK memory before deployment. Consequently, it is not appropriate for WSNs that comprises many sensor nodes.

Making the interoperability framework adaptable to different types of WSNs is challenges for several reasons. First, each type of sensor networks may have its own data frame structures and the organization of data inside a frame also contributes to this complexity. The problem is that the data from sensor networks is mainly consumed by the front-end applications, not directly by the end users. Therefore, only a minor change in the data section of a frame produces a totally different frame, and it leads to innumerous possible data formats. For instance, assuming that a sensor node has a frame containing two data fields (e.g., temperature and humidity), and if for some reason, the positions of these two fields is swapped. For the machine, this is a totally different frame, and it requires modifying the program code to analyze the content of the frame. Consequently, the gateway or proxy has to be modified (reprogram or add new methods) every time there is a change in the data frame formats.

Bearing in mind the previous points, the work in this chapter focuses on a solution for analyzing and extracting useful data from every sensor data frame between the framework and WSNs. Our approach to this problem is to propose the Sensor Traffic Description Language (STDL), which describes the possible data frame formats presented in the sensor networks. It plays a similar role to PUCK documents. However, it does not require adding the description documents to every sensor but only to the proxy. For the interaction with client applications, the proposed framework employs open web services standards similar to those of SWE [174]. However, in order to make it easy and more compact to integrating with application platforms such as Facebook [181], Second Life [182], the RESTful web services [101] and encoding method similar to those used in sMAP [18] are employed. The following sections present the proposed model, STDL, its prototype and illustration applications.

4.2 The Interoperability Model

The main aspects that were concerned when designing this model were the interoperability, reusability, scalability and extensibility. The first aspect refers to the ability of the gateway to provide methods for other application environments to easily and transparently interact with sensor networks. In addition, the interface for accessing the internal sensor data and functionalities should be unified and standardized. The reusability, in this context also called adaptability, is the ability to use the proposed model for different WSNs without reprogramming or modifying. The third concern is about the ability of the model to handle the increase in the number of sensor nodes and sensor networks. The final aspect, extensibility, is about the ability to easily add new components to the model. Consequently, we come up with a general model as it is presented in Fig. 4.1. The details on how to obtain the above-mentioned objectives will be discussed in the following paragraphs and sections.

In order to create a system that is able to respond to a large number of concurrently requests, we employed a multi-layered software architecture. As shown in Fig. 4.1 the model uses the proxy and gateway as a mediate layer for interoperability between sensor networks and the external applications, which monitor and control them. The proxy interacts directly with the WSNs, getting and analyzing data frames from the sensor networks, and then sending them to the gateway for storage. It also passes commands from the user applications to the sensor networks. The gateway allows front-end applications to interact with sensor networks, acting as a bridge between the sensor networks and the Internet. Both proxy and gateway may also comprise some other facility services such as authentication and authorization.

Both proxy and gateway are designed using the event-based principle. To add a new component to the framework, developers can register the listeners that capture events of interest that happen in the sensor network. For instance, to support the localization, the positioning client registers to the "*data frame arrival*" event of the proxy to get the necessary information to send to the localization engine on the gateway. This event-based model allows the system to be extensible easily.

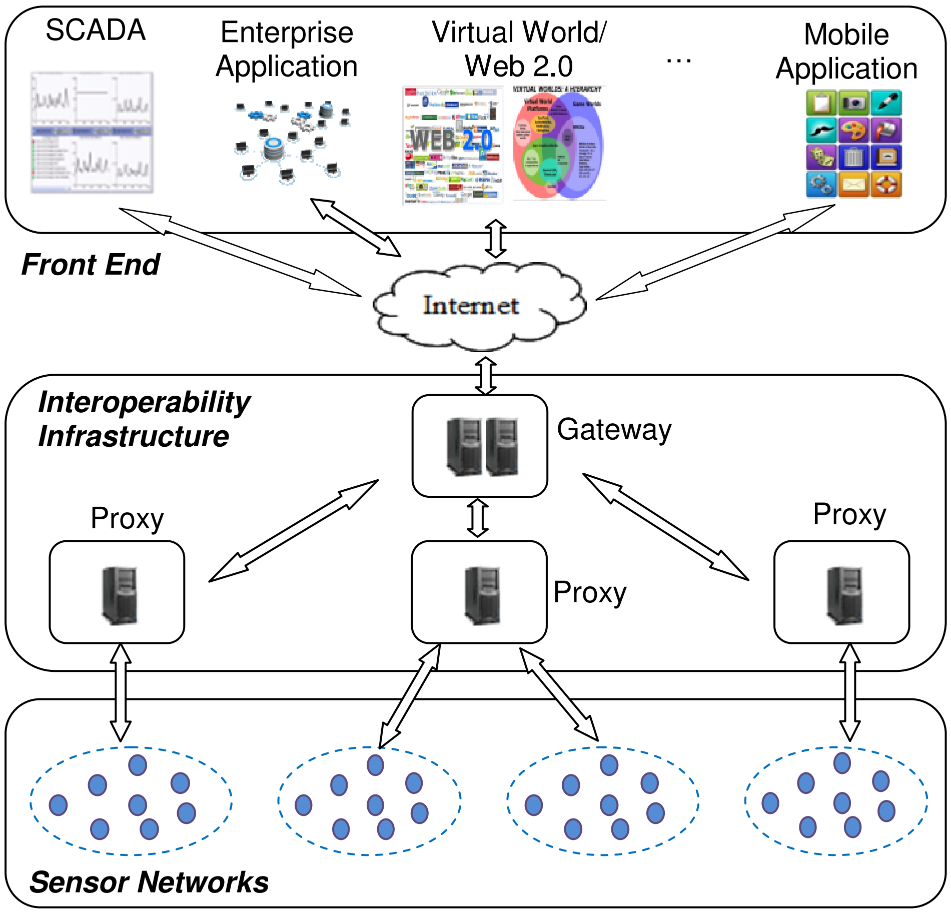


Fig. 4.1 The General Model for Interoperability

It is worth noting that every sensor network is associated with at least one proxy, and a proxy could serve more than one sensor networks. Every proxy is associated with at least one gateway to communicate the traffic of the sensor network to the data storage. There can exist multiple proxies and gateways in a single network. This type of architecture makes the proposed model scalable to apply for large sensor networks.

4.2.1 The Gateway

The gateway, also called web service gateway, is the entry point that allows front-end applications to interact with the sensor networks. The gateway hosts the middleware that implements the main functionalities of the system. The core components of the middleware are depicted in Fig. 4.2. The gateway uses a database for storing the sensed data and other necessary data.

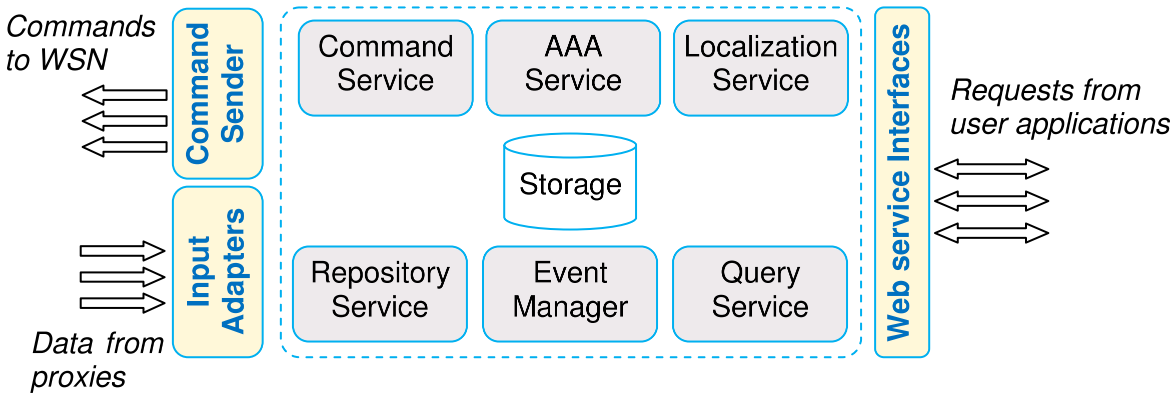


Fig. 4.2 The Core Components of Middleware of the Gateway

The middleware provides a set of input adapters and a command sender to intercommunicate with sensor networks or other smart devices through the proxies. The *Input Adapter* accepts the sensor data from the proxy and stores it into the data storage by using the repository service. It also accepts the localization requests from the proxy. On the other hand, the *Command Sender* is used to send commands from the control application to the sensor networks. Both *Input Adapters* and *Command Sender* can be implemented using several protocols including sockets, JMS, XML-RPC and web services. The current implementation is web service, i.e., the communication between proxies and the gateway uses web services.

In order to make the seamless interoperability between the sensor networks and the font-end applications, the data and functionality of sensor networks are exposed using web service (Web Service Interfaces component). The data from the sensor networks can be retrieved through the web service interface, stored and visualized from everywhere. The main advantage of the web service is that it isolates the services from the consumers. In addition, any changes of the middleware will not affect the applications consuming the services provided that its interfaces keep intact.

The web service interface component is supported by three essential components: (1) Query service; (2) Command service; and (3) Event manager. The first component is responsible for processing the query requests from the external applications. If the request is for data, it will search the appropriate data from the storage and send it to the corresponding application. On the other hand, if it is a command, then the *Command Service* will take its role to process and send the request to the sensor network via proxy using the *Command Sender*. In the case of periodical requests (tasking), the *Event Manager* will process this type of demands. It employs the publisher-subscriber pattern to allow client applications to register for the events of interest.

Equally important, the middleware of the gateway also integrates some other useful services such as Authentication, Authorization and Auditing (AAA), and localization service. The AAA service provides the basic security for the system. The localization service is responsible for estimating the location of the device. This service is very useful for numerous applications, namely health-care and monitoring workers in hazardous environments. The details of localization service will be presented in chapter 5.

4.2.2 The proxy

It is worth noting that the gateway is not a standalone entity, but it needs the presence of its collaborators, i.e., the proxies, to feed it with data as well as to allow it to send the commands to sensor networks. The proxy is responsible for obtaining the data frame from the sensor network, analyzing and publishing them to the gateway. In addition, it also accepts commands from the user applications, and sends them to the sensor networks. The core components of the proxy are shown in Fig. 4.3.

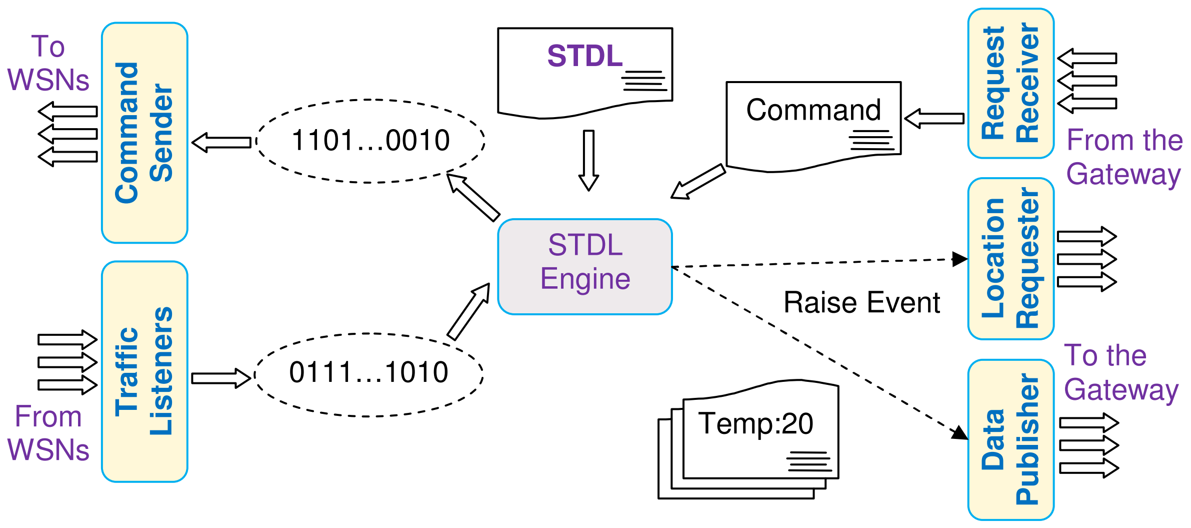


Fig. 4.3 The Components of the Proxy

The interaction between proxy and gateway is via their corresponding components. In particular, the *Data publisher* component of the proxy is responsible for forwarding sensor data to the *Input Adapters* component of the gateway for storage. The proxy also supports localization by using the *Location Requester* to send the requests to the location engine on the gateway. Similarly, the *Request Receiver* component of the proxy accepts the commands from the user application via the *Command sender* component of the gateway.

Another important component of the proxy is the *Traffic Listener* that listens for the data from sensor networks. Because there are several methods for sensor networks to communicate with the proxy (e.g., the serial port or TCP/IP), it is necessary to have different types of listeners, one for each communication method. The traffic listener simply listens for incoming frames, and then forwards them to the STDL engine for further processing. Currently, we implemented two types of traffic listeners on the proxy: one for serial port and the other for IP communication.

It is important to note that the most important component of the proxy is the STDL engine which makes the proxy be adaptable with different sensor networks. It is responsible for translating the raw data frame into the meaningful data for other components. When receiving a raw frame from the listener, the STDL engine translates it into the one or more messages and raises the corresponding data events, which are handled by other components such as the *Data Publisher* or *Localization Requester*. The *Data Publisher*, when triggered by a data event, gets associated message and sends it to the gateway for storage. The *Location Requester* collects the necessary data from multiple events and sends them to gateway's localization engine, which estimates the position of a device. The structure of the event message will be detailed in the following section.

In addition to translating raw frame to data message, the engine also translates the commands from the user applications into the format that the sensor nodes can process. When receiving user application commands from the gateway through *Request Receiver*, the STDL engine translates them into a format that the sensor nodes can process. The engine then passes the commands to the *Command Sender* component which sends it to the sensors.

The most important point to note is that the STDL engine is independent of the type of sensor networks. This means that it can be used for any sensor networks without reprogramming. In addition, the crucial element that makes the engine and thus the framework adaptable to different types of sensor networks is STDL. The details of the STDL and how it can help to do this are presented in the following sections.

4.3 Sensor Traffic Description Language (STDL)

In order to make the proposed model adaptable to diversity of sensor networks' protocols and applications, we proposed a language for describing the traffic of sensor networks named Sensor Traffic Description Language (STDL). The objective of SDTL is to formally and precisely describe the structures of data frames in WSNs so that the proxy, i.e., STDL engine, can extract needed data fields from the frames. It plays the similar role as those of IEEE 1451 TEDS [180] or PUCK documents [179] in that they describe the sensors and the measurements. However, it differs from these two standards in several ways. First, it only focuses on the data frame formats and the needed information. This means that it does not include detailed information such as manufacturer, serial number, etc. In addition, STDL documents only need to be put in the proxies and not in every sensor nodes. Moreover, it does not require a description for each sensor but one description for a group of sensors that produce the same data frame format.

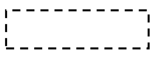
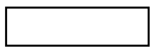
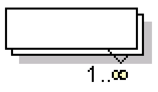
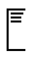
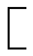
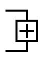
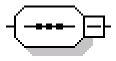
The motivation of this work is to reduce the complexity as well as the time for developing the monitoring and controlling applications development for sensor networks. Normally, the developers have to develop a special module or method (i.e., frame analyzer) to extract the data for each type of raw frames in a specific sensor network. This work is tedious, time consuming, and error-prone. In addition, even a small change in the network such as adding a new type of sensor or modifying the structure of a frame also requires reprogramming the analyzer. This means that the analyzer is very sensitive to data formats of the frame. With our proposed approach, when there are any changes to the current network or when applying it to a new sensor network, we only need to describe the structure of the new frames using STDL and add this description into the engine.

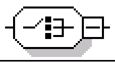
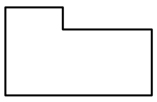
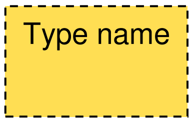
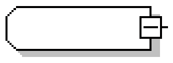
4.3.1 Overview of the Language

The aim of STDL is to add the adaptability to the infrastructure for interoperability between sensor networks and application environments, and to simplify the application development process. To provide this functionality, STDL has to be general enough to describe the structures of as many types of sensor networks' data frames as possible. In addition, it must be formal and concise, and be able to be completed in computer programs. Equally important, it should be simple and easy to use. Consequently, we decide to employ XML as the based language, i.e., it uses the tags to describe data frame structures.

Like other languages, STDL provides a set of key words (vocabulary) and rules (grammar) to constrain how the key words are combined together to describe the structure of data frames as well as permissible content of the data. As STDL is an XML-based language, it is natural to use XML schema (XSD) [183] to create its constraint rules. Because XSD is a text-based language, reading its content directly is very tedious and difficult to follow. In addition, it will be difficult to convey the concepts to other interested people. Therefore, it is useful to present the syntax of the language graphically. Consequently, we employ the notations used in [184] and [185] to create the content model diagram of STDL. The meaning of these notations is described in Table 4.1.

Table 4.1 The Notations Used in the Content Model Diagram

Notation	Description
	An optional element or attribute, i.e., min occurrence: 0 and max occurrence: 1
	A required single element or attribute, i.e., min occurrence: 1 and max occurrence: 1
	A repeated required element, i.e., min occurrence: 1 and max occurrence: unbounded ***Note:*** - If the min occurrence is 0 then this element becomes a repeated optional element and the line around it becomes a dash line instead of solid line - The max occurrence could be any number greater than 0, e.g., 5
	An element with simple content, i.e., it only contains text
	An element with complex content, i.e., it can contain other elements or attributes
	An element with complex content that has child elements
	A sequence of elements

	A choice of elements
	Represent a list of attributes or constraints of an element
	Represent a complex type inside the content model diagram
	Represent a complex type as a global element

With regard to designing a language to describe the traffic in sensor networks, there are several essential aspects that need to be considered. The first and crucial one is how to uniquely determine the type of each frame because a program can only extract the useful data fields when frame is correctly identified. It is generally considered that the frame type field can be used to identify the structure as well as the data inside the frame. However, in some cases the frame type field does not uniquely identify the frame but a group of frames instead. For instance, with the Internet Control Message Protocol (ICMP), to uniquely identify a message an application has to combine two fields: the type and the code (subtype). Accordingly, we have to take into account these points when designing STDL.

The second key aspect is the structure of the data in a frame. Because the data from sensor networks are consumed by the applications not directly by the end user, it is important for the application to know exactly how to extract needed data from a specific frame, i.e., the fields and their positions, correspondingly. From working experiments with sensor networks, we divide the frames in WSNs into three main categories: simple frames, data table frames and complex frames. The first category is the frames that merely consist of a list of the data fields such as temperature and humidity. The second type contains a list of data row in its payload, and each row contains a list of data fields. The final type includes the frames that contain a list of other frames inside its payload, i.e., a list of simple frames or a list of data table frames or a mixed list of both types.

All these issues will be carefully examined in the STDL and discussed in the following subsections.

4.3.2 The General Content Model of STDL

As it is an XML-based language, it is natural to use XML Schema (XSD) [183] for creating its constraint rules. To make the description of the language easily to understand and apply, we present the language using the graphical notations described in Table 4.1. The key components constitute a frame is described in Fig. 4.4.

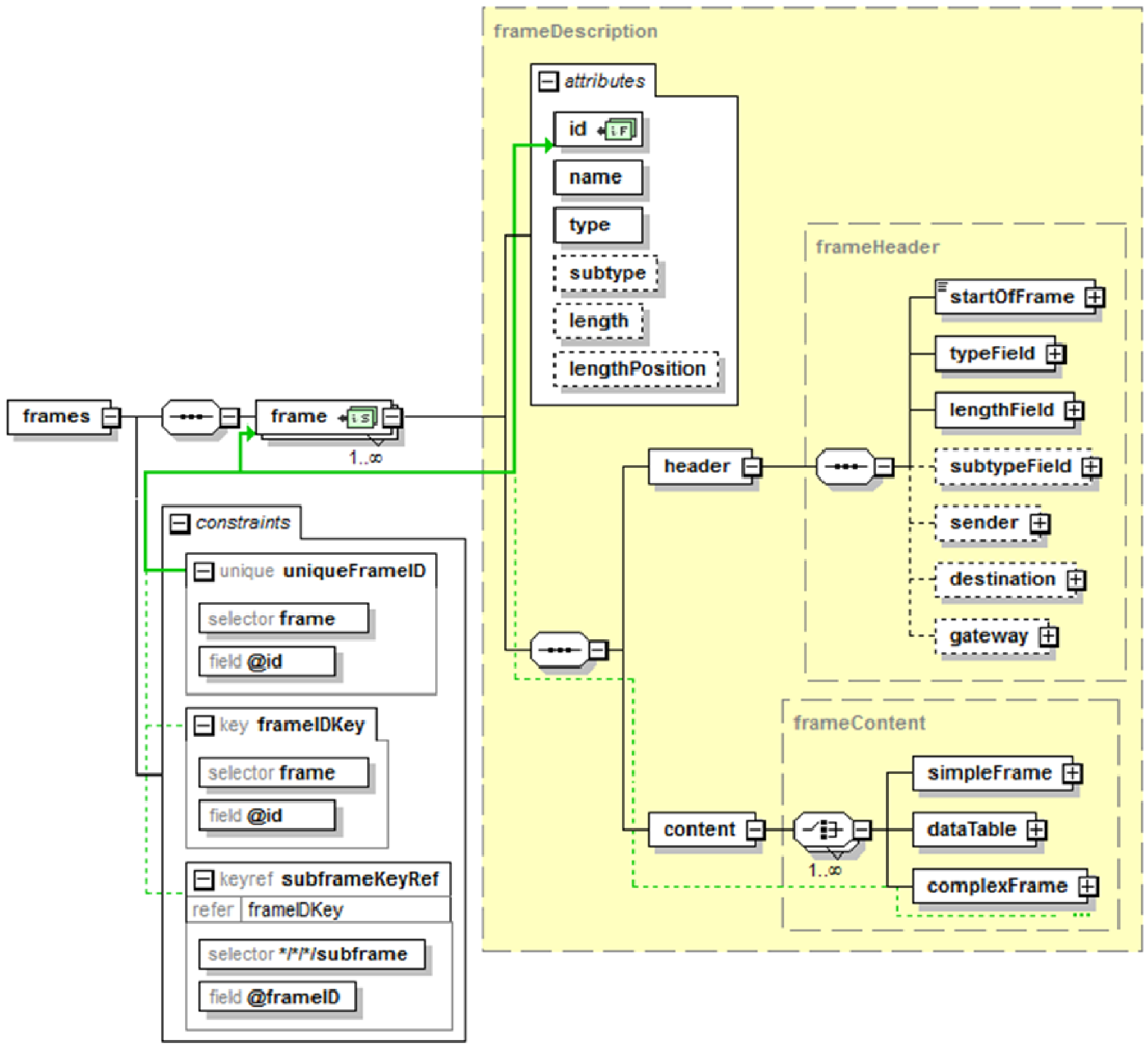


Fig. 4.4 The General Content Model of STDL

As shown in Fig. 4.4, the traffic in WSNs can be described as a set of frames (frames element). Each frame is described by three main elements, which are described by the complex type named ***frameDescription*** (the dashed rectangle with yellow background): (1) attributes; (2) header; (3) content. The attributes uniquely identify a specific frame and determine the table of the data storage into which the frame's data should be saved. The header element describes how to get the identification data from the instance frame, i.e., the raw frame received from a sensor network. The content element describes what data need to be extracted from the instance frame. Besides the elements for describing the structures of the raw frames, STDL also includes the constraints to regulate the values of the some attributes of the frame structures.

To make the discussion consistent and easy to follow, in the following sections, the words “raw frame“ or “instance frame” refer to the frames receiving from or sending to the sensor networks. On the other hand, the words “frame structure” or “frame description” refer to the specification of the raw frame in the form of STDL.

4.3.3 The Frame Identification

The first issue that needs to be considered is the description of information that distinguishes different frames in a sensor network. The attributes of an STDL *frame* element are used to specify this information. Their contents can be divided into two groups: (1) identifying the raw frame; and (2) naming the frame (semantic). The former comprises the *type*, *subtype*, *length*, and *lengthPosition* attributes. The latter includes the *name* and *id* attributes.

The *type* attribute usually contains the value corresponding to the type field in the raw frame. It is the key for the STDL engine to associate a raw frame to its description in the list of frame structure for that sensor network. As mentioned in previous section, however, the *type* attribute alone in some cases cannot uniquely determine the frame. Hence, the *subtype* attribute comes to play its role. Because *subtype* is not always needed, it is an optional attribute. Both attributes accept non-negative integer as their contents. It is clear that by combining of the *type* and *subtype* attributes it is possibly to describe every possible frame. During the analyzing process, when the value(s) of a type and/or subtype (if applied) field(s) of a received raw frame match those of a frame structure, the STDL engine will use this frame structure as a reference to extract the rest of the data.

Additionally, in some cases the sensor frame does not have the length field but it has a fixed length. In these cases the *length* attribute can be used to determine whether the received frame is valid. This attribute is optional because the information it provides is not essential. If this field exists and its value is greater than 0 then the matching raw frame has a fixed length. The *lengthPosition* attribute is used to specify the start position from which the length of frame is counted. The default value is 0 and means the length is for the entire frame.

The data extracted from the raw frame eventually needs to be stored for further processing. This means that the proxy must know where to send the decoded data. Because a table is usually considered the outermost element of a database with which an outside entity may interact, we employ the table's name as a mechanism to link a frame to the data storage. The *name* attribute of the frame element serves this purpose and its value indicates the corresponding table name in the database into which the content of this type of frame should be stored. The *id* attribute is used as the unique identifier of a frame, i.e., its primary key. The usage of this attribute will be discussed in the section that describes the frame content.

To illustrate how to apply the information described so far, let examine a raw frame from a TinyOS [94] sensor node as shown in Fig. 4.5. The STDL description of the identification part for this simple frame is shown in Fig. 4.6. The important point to note here is that the value of the *type* attribute in the frame description must be 11, i.e., the same value of the type field in the raw frame. In addition, the *lengthPosition* attribute has value 5 to indicate that the length of the frame starts at the position 5, i.e., it does not consist of the header part. On the other hand, the values of *id* and *name* attributes are assigned by user. With this frame, the *subtype* attribute does not exist because the *type* attribute alone is sufficient to identify the frame.

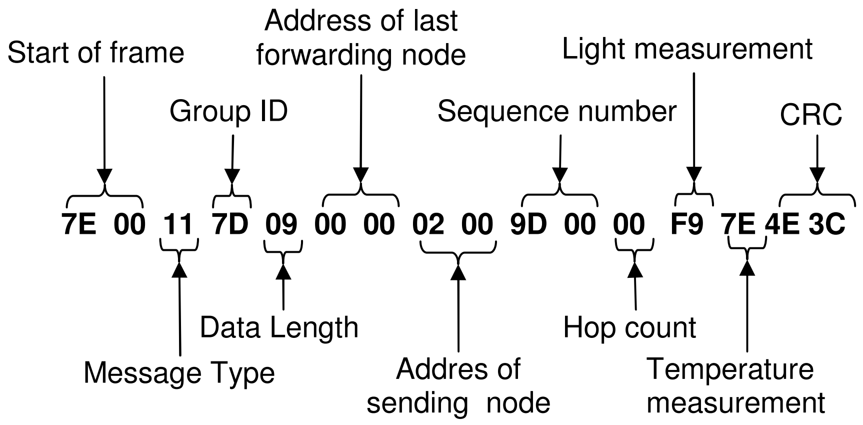


Fig. 4.5 A Simple Frame From a WSN with TinyOS

Having examined how to produce patterns to distinguish between different types of frames, the following sections present how to get essential information from the raw frame to identify it and how to extract the interested data from it. A frame's description is divided into two sections: the header and the content. These two sections are described by the complex types *frameHeader* and *frameContent,* respectively.

```
<?xml version="1.0" ?>
<frames>
   <frame id="1" name="light_temperature"
          type="11" length="0" lengthPosition="5">
     …
   </frame>
   …
</frames>
```

Fig. 4.6 STDL for a Part of a Simple Frame

4.3.4 The Frame Header Specification

The objective of frame header is to help the STDL engine to extract the specific information from an instance frame to search for its description, i.e., associate a raw frame with its description. As mentioned in previous sections, a raw frame can be specified uniquely by a *type* and an optional *subtype*. The STDL header section of a frame specification dictates how the above fields are retrieved from a raw frame. It is worth noting that the header specification is not used to describe the real header of the frame but its main purpose is to get enough information to uniquely identify the description of a particular raw frame.

As shown in Fig. 4.7, one of the required elements of a frame header is the *startOfFrame,* which is a unique sequence of bits at the beginning of the frame. This element is useful to deal with the problem of heterogeneity and diversity of frames in WSNs because different sensor networks use different start of frame sequences. The content of this element can be a sequence of bits or a list of hexadecimal numbers in the form of *0xnn ... 0xnn*. It also has a *numberOfBit* attribute which specifies the number of bits of this field. In order to constrain the *startOfFrame* to contain only the sequence of bits or a list of hexa decimal value, the simple types are defined as shown in Fig. 4.8. The first simple type name *binaryOrHexa* uses *union* element to indicate that its value is either of the type *hexaDecimalList* or *binaryNumber*. These two simple types employ the pattern technique to restrict their possible values to a list of hexadecimal number a binary string, respectively.

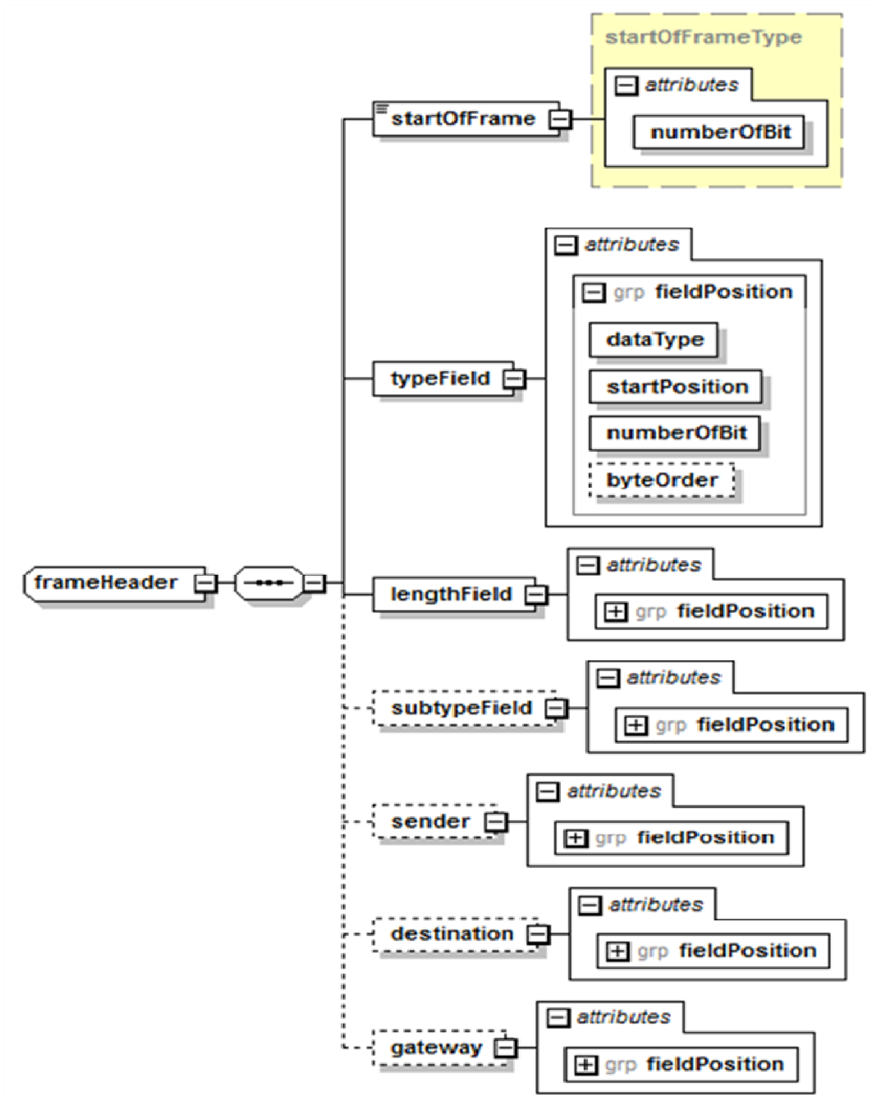


Fig. 4.7 The Content Model of the Frame Header Description

The next three elements *typeField, subtypeField*, and *lengthField* are used to specify how to get the values of the type, the subtype, and the length fields from the raw frame, respectively. The crucial point to note is that the engine must know how to extract the data from the raw frame. As a result, these elements have the same structure, and each one consists of four attributes: *dataType*, *startPosition*, *numberOfBit* and *byteOrder*. The *startPosition* attribute specifies the position of the field in the raw frame. The *numberOfBit* attribute indicates its length in bits. Both these attributes are restricted to non-negative integers. The *dataType* attribute is used to indicate the type of the data. Currently, STDL supports the following data types: *string, uint8, int8, uint16, uint16, uint32, int32, ulong,* and *long*. The *byteOrder* attribute specifies the encoding method and its values either '*little_endian*' and '*big_endian*' for little endian and big endian byte order, respectively. By default, *'little endian*' is assumed.

```
<xsd:simpleType name="binaryOrHexa">
   <xsd:union memberTypes="hexaDecimalList
binaryNumber"/>
</xsd:simpleType>

<xsd:simpleType name="hexaDecimalList">
   <xsd:list>
      <xsd:simpleType>
         <xsd:restriction base="xsd:string">
            <xsd:pattern value="0x[0-9A-F]{2}"/>
         </xsd:restriction>
      </xsd:simpleType>
   </xsd:list>
</xsd:simpleType>

<xsd:simpleType name="binaryNumber">
   <xsd:restriction base="xsd:string">
      <xsd:pattern value="[01]+"/>
   </xsd:restriction>
</xsd:simpleType>
```

Fig. 4.8 The Simple Type for a Sequence of bits or Hexadecimal

Besides these above essential elements, the description of a frame's header may also comprise three optional elements: *sender*, *destination* and *gateway*. These elements are included in the header part because they present in most of the frames. The purpose of these elements, as implied by their names, is to describe the address of the original transmitter, receiver and gateway devices, respectively. These elements have the same structure as that of the previous three elements.

As an illustration, Fig. 4.9 shows the header's specification for the raw frame in Fig. 4.5. The elements of header section are specified inside the <header> tag. It is also important to note that the *subtypeField* element does not exist in the header section because in this case it is not necessary. With the information in the header, the STDL engine knows how to get the needed information from the raw frame. For example: suppose that the engine wants to get the value of the type field in raw frame. From the *typeField* element in the header description, it knows that this field is situated at position 2 from beginning of the frame, and it has 1 byte. Combining these two pieces of information, the engine obtains the value 17 (11 hexadecimal) from the raw frame. In this case, the *byteOrder* attribute is not necessary because the value of this field has only one byte.

```
<?xml version="1.0" ?>
<frames>
   <frame id="1" name="light_temperature"
          type="11" length="9" lengthPosition="5">
     <header>
       <startOfFrame numberOfBit="16">0x7E 0x00</startOfFrame>
       <typeField startPosition="2" numberOfBit="8"
                                          dataType="uint8"/>
      <lengthField startPosition="4" numberOfBit="8"
                                          dataType="uint8"/>
      <sender startPosition="7" numberOfBit="16"
                                          dataType="uint16"/>
      <destination startPosition="5" numberOfBit="16"
                                          dataType="uint16"/>
     </header>
     …
   </frame>
   …
</frames>
```

Fig. 4.9 The STDL Header Description for Simple Frame in Fig. 4.5

4.3.5 The Frame Content Specification

The objective of frame content specification is to specify what information is needed and how to get the needed data from instance frames. It is noticeable that it is not necessary to have a one to one mapping between the content of a raw frame and its specification. This means that the content specification could include information from the header section of a raw frame. Because the *field* type is a core data type that is extensively used in the frame content description, the next subsection is dedicated to this data type.

4.3.5.1 The Field Type

The most important and useful aspect of STDL is how to help the engine to extract the needed information from the raw frames and to give them some meaning. In order to fulfill this requirement, the *field* data type is designed for describing the fields in a raw frame. Each field is described by six attributes as shown in Fig. 4.10. The attributes *dataType*, *startPosition*, *numberOfBit* and *byteOrder* have exactly the same meaning as discussed in previous section. The other two attributes are used to add the semantics for the described filed. Particularly, the *name* attribute is used name the described field, which is used as a field name in a table in data storage. The *unit* attribute is a string that indicates the measurement unit of the field's content.

As previously mentioned, the frames in WSNs could be divided into three main categories. Consequently, there are also three types of the STDL content specification, *simpleFrame*, *dataTable*, and *complexFrame*, as shown in Fig. 4.10.

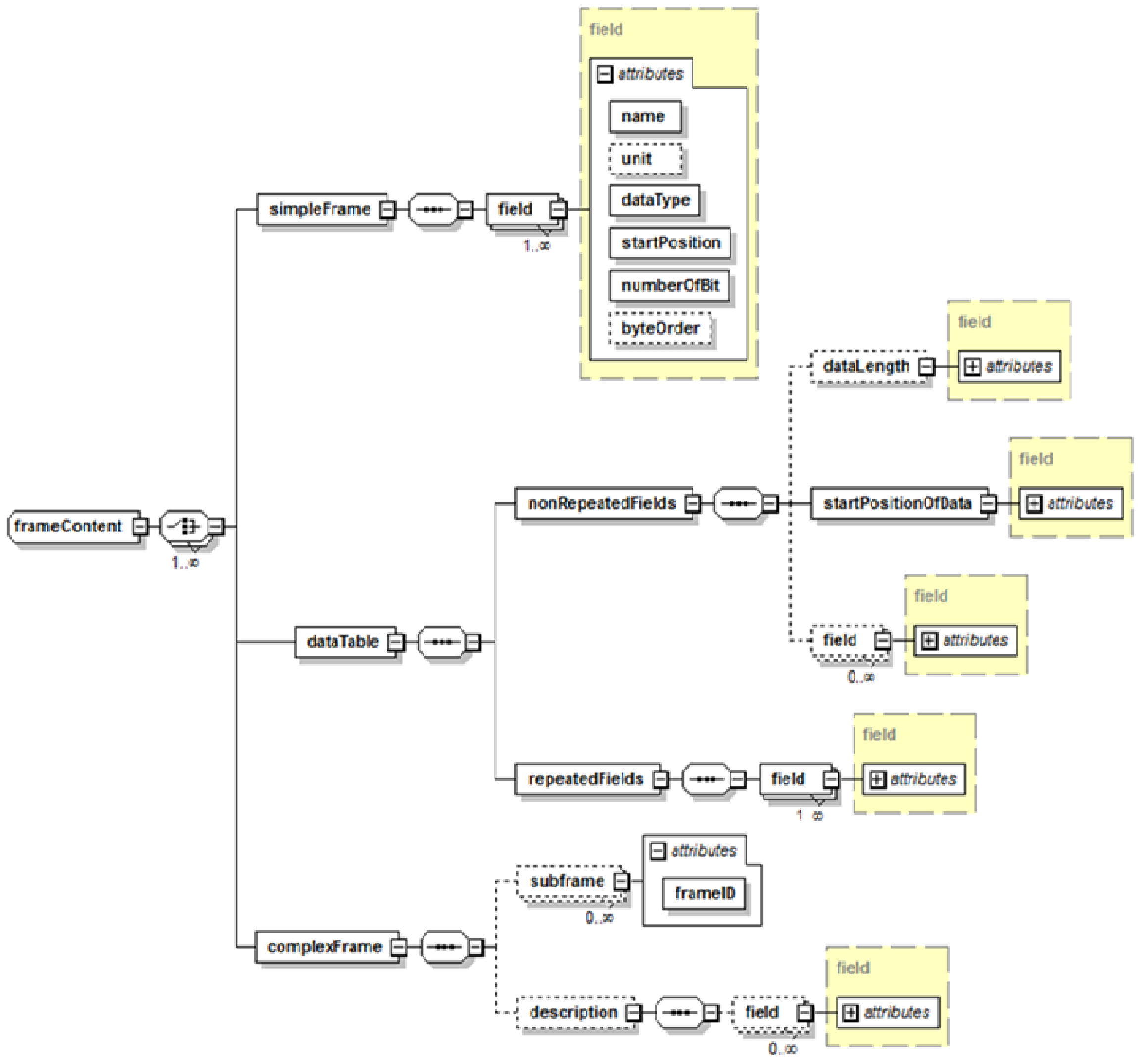


Fig. 4.10 The Model of Frame Content Specification

4.3.5.2 Simple Frame Description

The *simpleFrame* type is used to describe the type of frames that merely consist of a list of data fields. Each field of simple frame corresponds to a field of the raw frame and is described by the *field* type discussed in previous section. As an illustration, Fig. 4.11 shows a description for the raw frame in Fig. 4.5. In this example, it is assumed that the only needed information is the sending node identification, light and temperature.

Consequently, the content element of the frame description only comprises three fields: *senderId*, *light*, and *temperature*, respectively.

```
<?xml version="1.0" ?>
<frames>
   <frame id="1" name="light_temperature"
          type="11" length="9" lengthType="0">
      <header>
        <startOfFrame numberOfBit="16">0x7E 0x00</startOfFrame>
        <typeField startPosition="2" numberOfBit="8"
                                       dataType="uint8"/>
        <lengthField startPosition="4" numberOfBit="8"
                                       dataType="uint8"/>
      </header>
      <content>
        <simpleFrame>
          <field name="senderId" dataType="uint16"
              startPosition="7" numberOfBit="16" unit="none"/>
          <field name="light" dataType="uint8"
               startPosition="12" numberOfBit="8" unit="lux"/>
          <field name="temperature" dataType="int8"
                 startPosition="13" numberOfBit="8" unit="F"/>
        </simpleFrame>
      </content>
   </frame>
   …
</frames>
```

Fig. 4.11 Frame Description of the Raw Frame in Fig. 4.5

Based on the frame description in Fig. 4.11, when receiving a raw frame having the format as in Fig. 4.5, the STDL engine will extract only the sender identification, the temperature, and the flight information from it. In addition, the extracted information will be stored in the table name "*light_temperature*", constrained by the attribute *name* of the frame element, on the storage. Equally important, the "*light_temperature*" has three fields for storing the extracted data: *senderId*, *light*, and *temperature,* constrained by the *name* attribute of *field* elements.

4.3.5.3 Data Table Frame Description

The second type of frame is called data Table because its body contains a list of repeated measurement of different types of data. This type of frame can be used to describe the aggregated data in WSNs. One possible scenario for its usage is when a sensor node buffers multiple samples before offloading data to the base station. Another possible case is when the intermediate nodes combine their collected data with that received from other nodes into a single frame and then send it to the base station. The *dataTable* element is used to specify such a data frame.

As shown in Fig. 4.10, the content of a *dataTable* frame are divided into two parts described by *nonRepeatedFields* and *repeatedFields* elements. The former comprises a list of fields that describe the information related to the repeated data in the raw frame such as its start position (*startPositionOfData*) and its number of the repeated items (*dataLength*). In addition, it also comprises a list of fields to be stored in the data storage such as sender, time, etc. The later consists of a list of repeated fields in the data portion. Each field of the raw frame is described by the *field* type. Fig. 4.12 and Fig. 4.13 are examples of data table frame and its description structure. However, because this data table is contained in a complex frame, we will explain them all together in the next section.

4.3.5.4 Complex Frame Description

Besides two fundamental types of frames, when working with real world sensor networks, it happens to have a scenario where a frame may contain one or more simple frames or data table frames. We deemed such frames as complex and described them using the *complexFrame* element. Because the complex frame contains other frames, it is necessary to describe other frames as regular frames and then refer to them in the complex frame. Consequently, specifying a complex is rather simple. As shown in Fig. 4.10, it consists of a list of *subframe* elements which only has one attribute named *frameID*. The *frameID* attribute refers to the *id* attribute of another frame described in the same document. The list of *subframe* elements is optional, i.e., it may not appear in the description of a complex frame. In this case, the complex can contain any frames described in the STDL document. Additionally, there is also some additional information to describe the general data for the frame. This information is specified using the *description* element.

The relationship between *frameID* and *id* attributes of frame description is described by the constraints of XSD [183]. Particularly, In order to make the *id* attribute unique, the *unique* constraint, which specifies the value of a specific attribute of an element must be unique among a set of elements, is utilized. In addition, the *key* constraint also applies to the *id* attribute to make it a key. The *keyref* constraint is applied to the *frameID* attribute to establish a link between its value and that of the *key* attribute of the frame elements.

The complete description of STDL in Extended Backus-Naur Form (EBNF) is described in Appendix A.

To illustrate how to describe the last two types of frame, consider a raw frame as showed in Fig. 4.12. This is a complex frame that contains data table frame used in a sensor network developed by Eneida [186]. The example frame consists of three repeated fields: *temperature*, *humidity* and *voltage*. The STDL description for this type of frame is shown in Fig. 4.13.

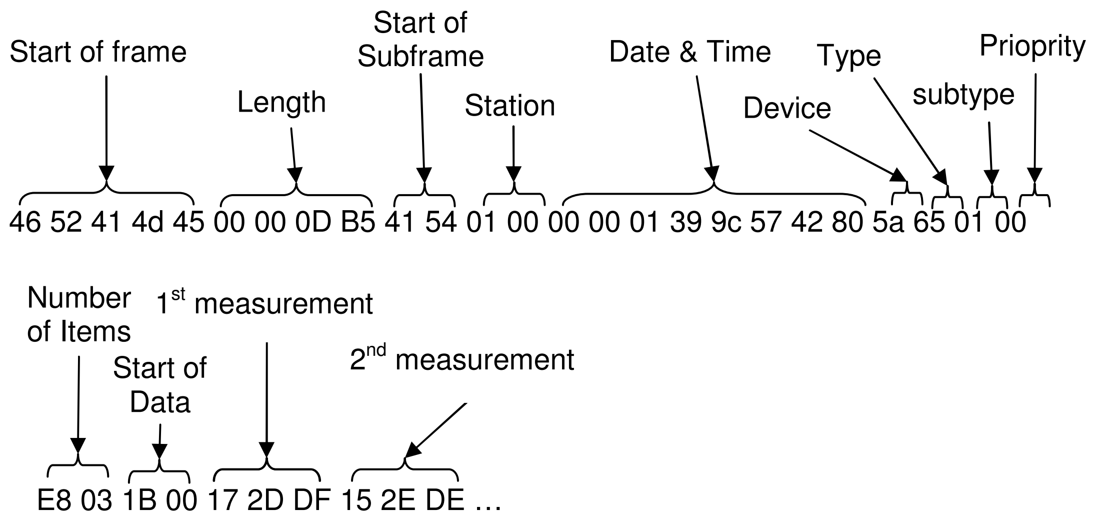


Fig. 4.12 An Example of a Complex Frame Containing a Data Table

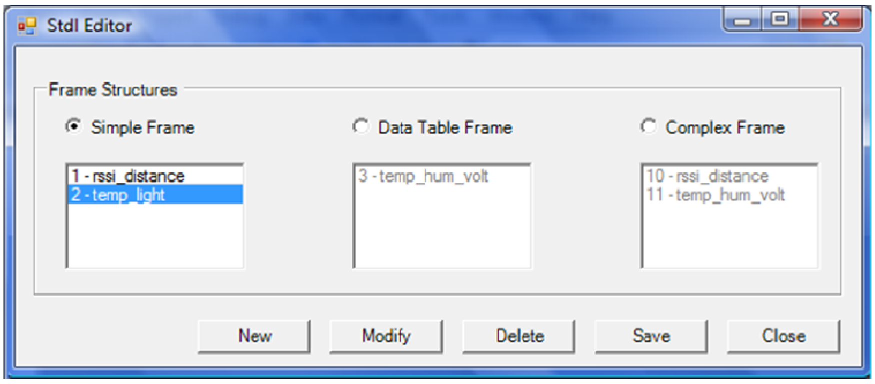
This raw frame in Fig. 4.12 is a complex one because it contains another frame inside its payload. As shown in Fig. 4.13, the inside frame is described by a structure frame named "*temp_hum_volt*" and its *id* is 5. Its content is specified by the *dataTable* element whose *repeatedFields* element has three sub-elements (temperature, humidity, and voltage) for describing the repeated data fields in raw frame. The description of the complex frame contains a sub-frame with the value of its *frameId* attribute is 5. This means that this complex frame contains another frame having an *id* value of 5, i.e., the data table frame mentioned above. Because the complex raw frame does not have a field type to identify it, the *type* filed of the first inner frame is used instead.

```
<frames>
  <frame id=”5” name=”temp_hum_volt”
       type=“101“ subType=”01” length=”0“ lengthposition=“0“>
   <header>
     <startOfFrame numberOfBit=”16”>0x41 0x54</startOfFrame>
     <typeField startPosition=”13”
                     dataType=”uint8” numberOfBit=”8” />
     <subTypeField startPosition=”14”
                     dataType=”uint8” numberOfBit=”8” />
     <lengthField startPosition=”16”
                     dataType=”uing16” numberOfBit=”16”/>
   </header>
   <content>
    <dataTable>
      <nonRepeatedFields>
       <startPositionOfData name=”startPosition”
         dataType=”uint16” startPosition=”18” numberOfBit=”16”/>
       <dataLength name=”numberOfItem” dataType=”uint16”
                          startPosition=”16” numberOfBit=”16”/>
       <field name=”station” dataType=”uint18”
                            startPosition=”2” numberOfBit=”16”>
     </nonRepeatedFields>
     <repeatedFields>
        <field name=”temperature” dataType=”int8”
                 startPosition=”0” numberOfBit=”8” unit=”C”/>
         <field name=”humidity” dataType=”uint8”
                 startPosition=”1” numberOfBit=”8” unit=”%”/>
         <field name=”voltage” dataType=”int8”
                 startPosition=”2” numberOfBit=”8” unit=”V”/>
      </repeatedFields>
    </dataTable>
   </content>
  </frame>
<!—Describe a complex frame --!>
  <frame id=”10” name=”temp_hum_volt”
                     type=”65” length=”0” lengthPosition=”9”>
    <header>
      <startOfFrame numberOfBit=40”> 0x46 0x52 0x41 0x4d 0x45
      </startOfFrame>
      <typeField startPosition=”22” numberOfBit=”8”/>
      <lengthField startPosition=”5”
                dataType=”uint32” numberOfBit=”32”/>
   </header>
   <content>
     <complexFrame>
          <subFrame frameId=”5”/>
     </complexFrame>
   </content>
 </frame>
   …
</frames>
```

Fig. 4.13 STDL Description for the Content of the Raw Frame in Fig. 4.12

4.3.6 STDL Editor

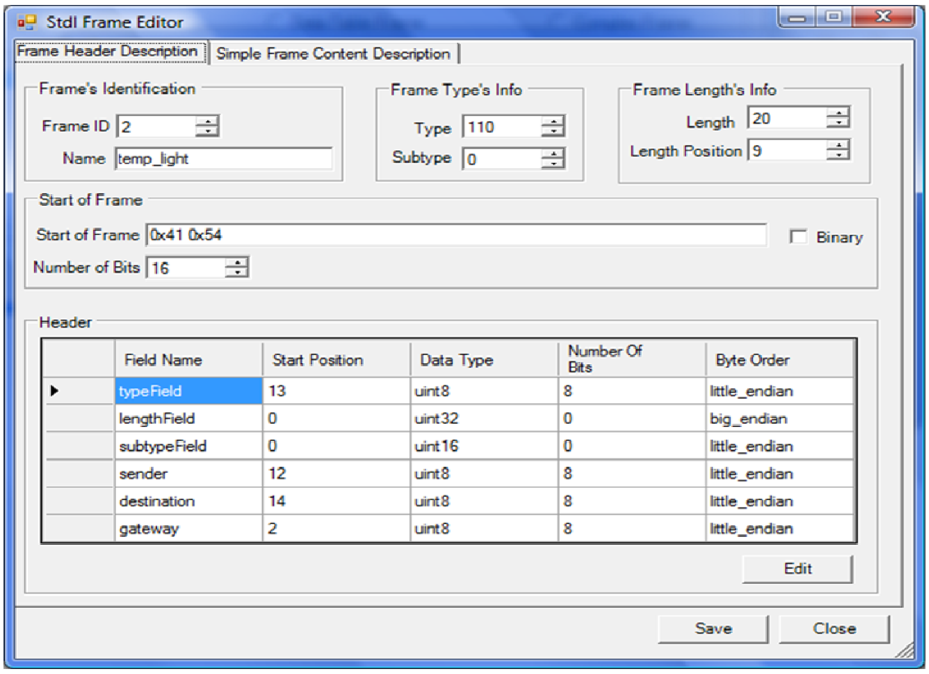
To facilitate the creation of the specification of frame structure, a graphical STDL editor was developed. This editor helps the users to manipulate the frame structure easily and quickly. In addition, it eliminates the need to work directly with XML, which is tedious and error-prone. More importantly, it is not necessary for the users to know the syntax of STDL to create the frame specifications. Fig. 4.14, Fig. 4.15 and Fig. 4.16 show the green shots of the main menu of the STDL editor, the frame header and the simple frame content composers respectively.



[✓ Simple Frame] Data Table Frame Complex Frame

Simple Frame	Data Table Frame	Complex Frame
1 - rssi_distance	3 - temp_hum_volt	10 - rssi_distance
2 - temp_light		11 - temp_hum_volt

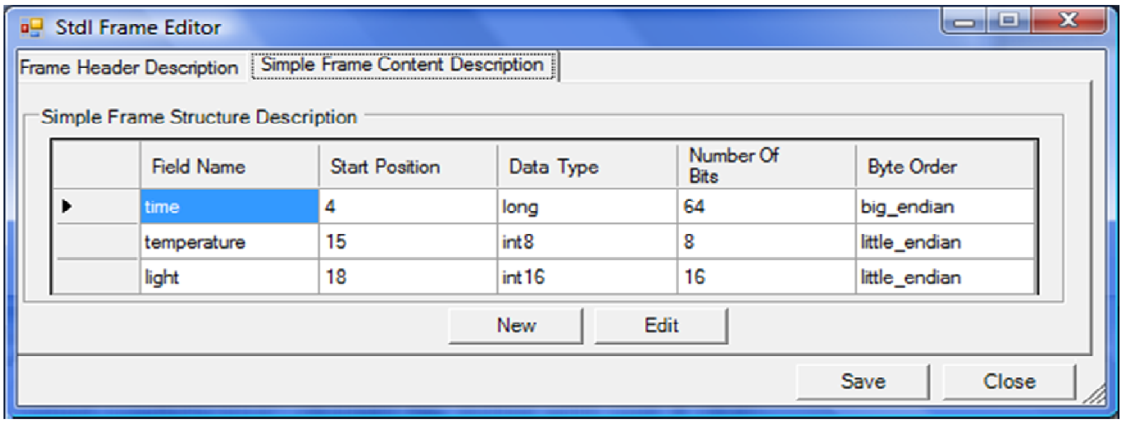
Fig. 4.14 The Main Menu of STDL Editor



Frame ID: 2
Name: temp_light
Type: 110
Subtype: 0
Length: 20
Length Position: 9
Start of Frame: 0x41 0x54
Binary: ☐
Number of Bits: 16

	Field Name	Start Position	Data Type	Number Of Bits	Byte Order
▶	typeField	13	uint8	8	little_endian
	lengthField	0	uint32	0	big_endian
	subtypeField	0	uint16	0	little_endian
	sender	12	uint8	8	little_endian
	destination	14	uint8	8	little_endian
	gateway	2	uint8	8	little_endian

Fig. 4.15 The Header Composer


Stdl Frame Editor
Frame Header Description
Simple Frame Content Description
Simple Frame Structure Description
New
Edit
Save
Close

	Field Name	Start Position	Data Type	Number Of Bits	Byte Order
▶	time	4	long	64	big_endian
	temperature	15	int8	8	little_endian
	light	18	int16	16	little_endian

Fig. 4.16 The Simple Frame Content Composer

4.4 The STDL engine

Turning now to the question of how STDL can be used to make the proxy adaptable. As described in previous sections, STDL is only a mean to describe the traffic of sensor networks. Clearly, it is useless unless there is a tool to realize it. This is the place where the STDL engine comes to take its role. It is the core part of the proxy. As shown in Fig. 4.3, the STDL document acts as the "brain" of the engine, guiding it through the processing of a received raw frame.

Prior to explaining the details of the algorithms for analysis process of the raw frames, it is important to understand the general model of the STDL engine. In order to make the proxy more flexible and extensible, the event-based model is employed in the STDL engine where an event is raised after the engine processes a raw data frame. Another important point is that the engine employing JSON method [99] for encoding the extracted data in the event's message.

The engine comprises two main components: a parser and an analyzer. The parser takes STDL document as its input, checks its syntax, and produces a list of frame structures for using by the analyzer. The analyzer takes the raw frames as its inputs and uses the corresponding frame description in the frame structure list to extract the necessary data. The analyzer also accepts commands in form of JSON messages from the ***Request Receiver*** component of the proxy and transforms them into the raw packets to send to the sensor network. Fig. 4.17 shows the fundamental components and workflows of the STDL engine.

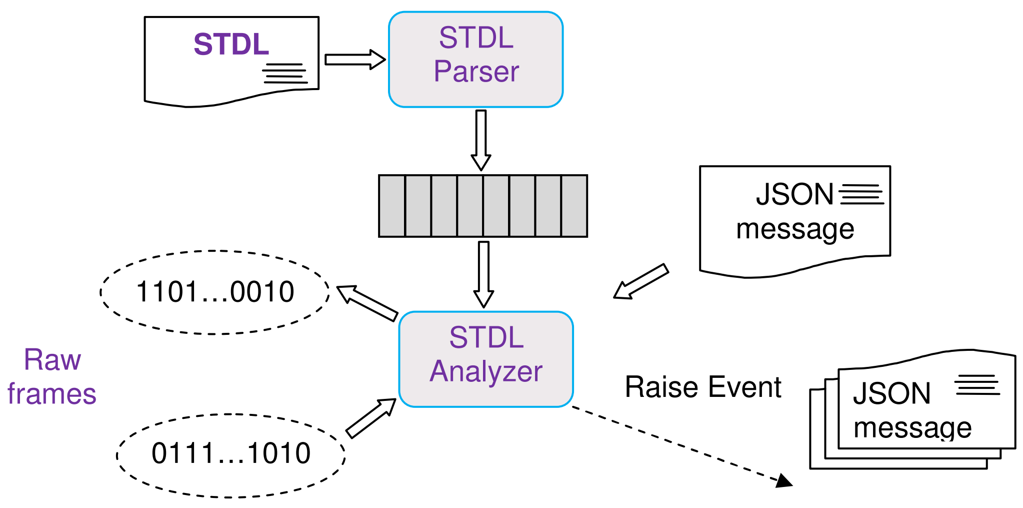


Fig. 4.17 STDL Engine

The analysis process of a raw frame comprises two steps: (1) determining the frame description; and (2) extracting data. The algorithm for this process is described in Fig. 4.18. In the first step, the frame description for the raw frame is searched by examining every frame structure in the list and comparing its type and subtype (if applied) value to those of the raw frame until a match is found. In the second step, the frame structure is used as a blueprint to extract the needed data from the raw frame. It can be seen from the algorithm shown in Fig. 4.18 that after determining the type of frame, the method for extracting data is called to process the raw data. There are three different methods for processing the raw frames corresponding to three types of frames (*ExtractSimpleFrame* for simple frame; *ExtractDataTableFrame* for data table frame; and *ExtractComplexFrame* for complex frame). The details of these methods are described in Fig. 4.19, Fig. 4.20, and Fig. 4.21 respectively.

Perhaps processing the simple raw frame is the simple one. As described in Fig. 4.19, this process comprises a loop through all fields of the frame structure. With every field, its value is extracted from the raw frame. This value is combined with the field name (i.e., the value of the *name* attribute of the field) to form a key-value pair separated by a colon. All the extracted key-value pairs combined with the name of frame structure (i.e., the value of the *name* attribute of the frame structure) to form a JSON message. Finally, this JSON message is sent as the data of the event raised by STDL engine.

```
void RawFrameAnalysis(stdlFrameList, rawFrame)
  /* Search the frame description for a raw frame */
  Foreach (stdlFrame € stdlFrameList)
  {
    typeInStdlFrame = getFrameType(stdlFrame)
    subtypeInStdlFrame = getFrameSubtype(stdlFrame)
    typeInRawFrame = getFrameType(stdlFrame, rawFrame)
    subtypeInRawFrame = getFrameSubtype(stdlFrame, rawFrame)
    if (typeInStdlFrame == typeInRawFrame)
    {
      if ((subtypeInStdlFrame ==0) ||
         (subtypeInStdlFrame == subtypeInRawFrame))
      {
        If (IsSimpleFrame(stdlFrame))
          ExtractSimpleFrame(stdlFrame, rawFrame);
        Else if (IsDataTableFrame(stdlFrame))
          ExtractDataTableFrame(stdlFrame, rawFrame);
        Else
          ExtractComplexFrame(stdlFrame, rawFrame);
          break;
      }
    }
}
```

Fig. 4.18 The Analysis Process for Raw Frame

```
Void ExtractSimpleFrame(stdlFrame, rawFrame)
  /* format result using JSON syntax*/
  String data="{" + stdlFrame.Name+":[{"
  Foreach(field in stdlFrame.Fields)
  {
    Data+=field.name +":" + GetFieldData(field, rawFrame) + ",";
  }
  data.replace(data-Length-1,'}');
  data+="]}";
  FireDataFrameEvent(data);
```

Fig. 4.19 The Process of Analyzing Simple Frame

To illustrate how the JSON message looks like, let's see a simple example. Assuming the STDL engine receives a raw frame as shown in Fig. 4.5 and its corresponding STDL description is shown in Fig. 4.11. With the help of frame structure, the STDL engine can analyze the raw frame and extract the values 2, 50, and 64 for the fields *senderId*, *light*, and *temperature*, respectively. Combining these information with the *name* attribute in the frame structure (*light_temperature*), the STDL engine composes a JSON object message as follows: *{" light_temperature:[{ "senderId":2, "light":50, "temperature":64}]}*. It is worth noting that an array of objects is used even though there is only one object. The reason is that by using an array of objects one message format can be used for all events raised by the STDL engine.

The process of analyzing the data table frame is more complicated than that of the simple frame. The reason is that the list of fields in raw frame is repeated. As a result, the fields in the frame structure only describe the first instance of fields in raw frame. To deal with this problem, the analysis process separates the data in the raw frame into sub-frame and treats it individually. As shown in Fig. 4.20, the sub-frame is the part of the data that contains one instance of the repeated fields.

```
Void ExtractDataTableFrame(stdlFrame, rawFrame)
  String data="{" + stdlFrame.Name+":["
  Int itemLen=GetItemLength(stdlFrame)
  Byte[] item=new byte[itemLen]
  Int curPosition = stdlFrame.startOfFirstyte;
  While(curPosition + itemLen <= rawFrame.Length)
  {
    Item  = copy(rawFrame, curPosition, itemLen)
    Data+=ExtractListOfField(stdlFrame.Fields, item)+","
  }
  replace(data.Length-1,']')
  Data+='}');
  FireDataFrameEvent(data)

  /** Extract a list of field value from a byte array **/
  String ExtractListOfField(fields, bytes)
  String data="{"
  Foreach(field in fields)
  {
    Data+=field.name +":" + GetFieldData(field, bytes) + ","
  }
  Data.replace(data.Length-1,'}')
  Return data
```

Fig. 4.20 The Process of Analyzing Data Table Frame

It is not hard to process complex frames because it contains the frames of the other types. Consequently, processing this type of frame is simple, extracting its sub-frames and then calling the corresponding processing method. This process is described in Fig. 4.21.

```
Void ExtractComplexFrame(stdlFrame, rawFrame)
Int curPosition = 0;
STDLFrame stdlSubFrame
While(curPosition < rawFrame.Length)
{
   subFrame = getSubFrame(rawFrame, stdlFrame,
                         stdlFrameList, out stdlSubFrame)
   curPosition+=subFrame.Length
   if (IsSimpleFrame(stdlSubFrame))
     ExtractSimpleFrame(stdlSubFrame, subFrame)
   Else
     ExtractDataTableFrame(stdlSubFrame, subFrame)
}
```

Fig. 4.21 The Process of Analyzing Complex Frame

4.5 Prototype and Example Applications

4.5.1 Prototype

Besides the STDL and its engine, we developed a prototype for the proposed model. The currently implemented proxy supports two methods to communicate with WSNs: serial port and TCP/IP. For communication between the proxy and gateway the Web service technology is employed. The encoding formats for communication between them are JSON.

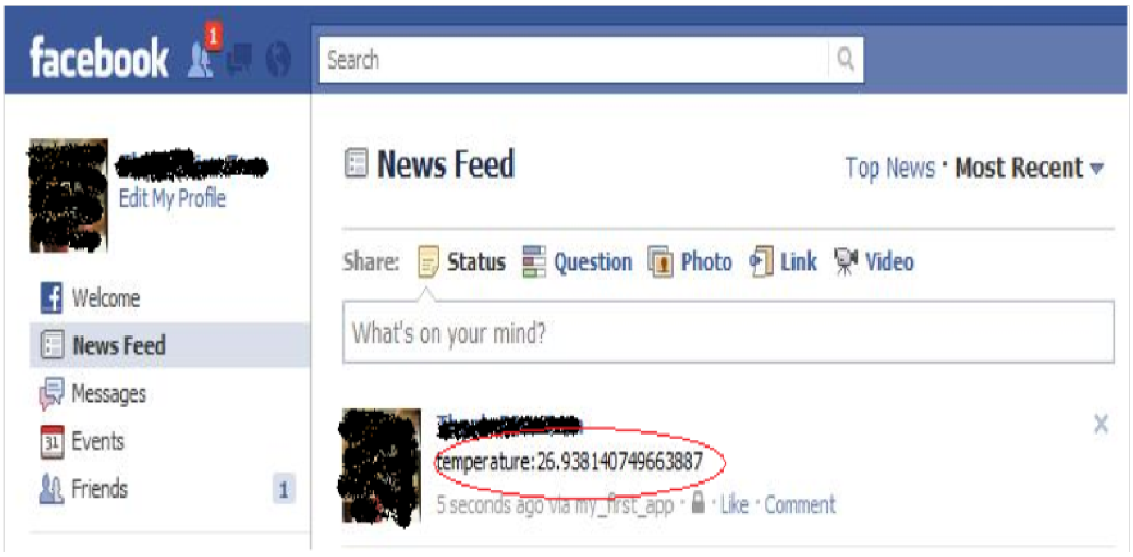
Similarly, the gateway middleware exposes the data and the functionalities of sensor networks through a set of services with JSON. In addition, the middleware also supports localization services based on RSSI. The localization services will be discussed in chapter 5.

We tested the prototype with MICAz, TelosB [47] and EWS Eneida [186] sensor nodes. The following section presents the example applications of the developed prototypes.

4.5.2 Example Applications

To illustrate how to use the proposed framework to integrate WSNs with other application environments, we set up a testbed with three computers and two sensor networks. Two computers act as proxies and collect data from the sensor networks; and the other one acts as the gateway. The communication between sensor networks and proxies is based on the serial port. In addition, FaceBook (FB) [181] social networking platform and Second Life (SL [182]) virtual world were selected for testing integration.

In the first application, the FB application Platform was employed as a front-end application to display sensor data. The FB was chosen since it is the most common and well-known social networking platform and it provides an API that allows for mashing up with other environments. In this simple demonstration, we publish the temperature of the monitored room in the wall of a FB account. This helps the account owner to instantly know the temperature of the room in order to act appropriately in case it unexpectedly changes. The result of this implementation is shown in Fig. 4.22.



[redacted]
temperature:26.938140749663887
5 seconds ago via my_first_app · Like · Comment

Fig. 4.22 Publishing Sensor Data on FaceBook

The second application that we implemented based on our model was a mashup of WSNs with the SL Virtual World. This application is similar to the first one but, instead of displaying sensor data as plain text, we used virtual objects. In this simple application, the temperature of the monitored target was represented by changing the color of an object attached to an avatar. For example, if the temperature was between 10 and 19 degrees Celsius, the color of the corresponding object would become green and if the temperature was greater or equal 50 degrees Celsius, the color would be red. Fig. 4.23 illustrates this process.

The above-mentioned applications show that sensor networks can become an integral part of the virtual environments. The diversity of representation tools in 3D virtual worlds and the sheer amount of users and social connections in social networks can open the door towards new types of applications as well as promote the wide-spreading of sensor networks and smart things and their integration with the Web.

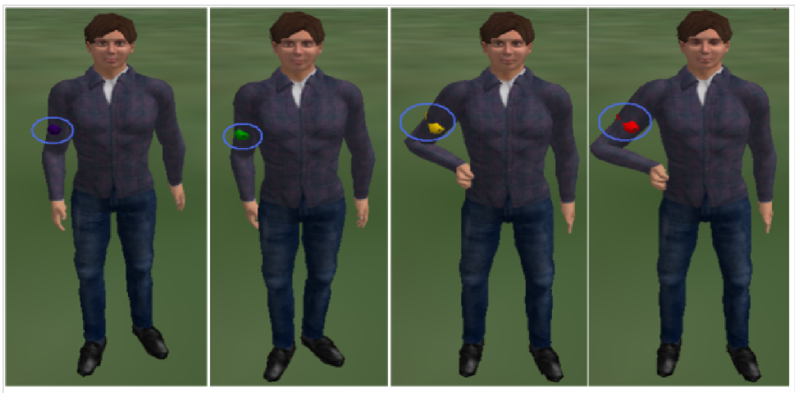

Different colors of attached object represent the different ranges of temperature of the monitoring target.

Fig. 4.23 Displaying Temperature Using Object Attached to Avatar in SL

Although our proposed model includes several layers, it is very fast and data coming from the sensor nodes quickly reaches the client applications. For single hop communications, it takes around 60 ms for data from the sensor nodes to reach the proxy. From there, it takes approximately another 26 ms for data to reach the gateway middleware and be available for the client applications. In the case of our mashup with the Facebook [181] platform, it takes a total of 581 ms for data from physical environments to be published and available to the users. During our tests, we could sometimes get the data from the sensor nodes to be posted on Facebook as fast as in 246 ms. An important note is that this time includes the processing time at the proxy and gateway.

The work in this chapter showed that a hybrid Proxy/Gateway is a suitable solution for mashing up physical resources with virtual environments. It preserves the major concepts of current research on sensor networks while providing an adaptable infrastructure for seamless integration and interoperability of wireless sensors with external applications.

4.6 Conclusion

An extensible, interoperable and adaptable model for interoperating between WSNs and application environments is an undeniable demand. The result of the research presented in this chapter shows that it is possible to make the integration infrastructure to be adaptable to the diversity of sensor networks by using STDL. In addition, the event-based approach is adopted to make it easy for adding new components to the framework. Furthermore, exposing data and functionalities of the WSNs as a set of web services makes the interoperability process transparent to other application environments.

The results of this study indicate that the framework can be adaptable to new applications and protocols of WSNs. In addition, it is possible to treat WSNs as a plug-and-play component of the Future Internet. This makes the development of applications for sensor networks easier and more flexible. Developers can employ existing applications to monitor, control, and visualize the sensor data and networks. This approach is also a good method for mashing up the physical world information with virtual worlds and other application environments.

5 Localization System for Wireless Sensor Networks

Summary

Determining the positions of sensor nodes, especially mobile nodes, in a WSN is crucial for many applications. It helps to identify the location of the collected data or of the node carriers such as the workers, patients or vehicles. It is a critical requirement for supporting the timely right decisions. This chapter presents a scalable localization system targeting controlled WSN in which a sensor network is divided into multiple zones and (maybe overlapped) subzones. In addition, multiple positioning methods were implemented and evaluated with real testbeds both in laboratory and industrial environments. The localization engine is implemented as a component of the gateway of the interoperability model presented in chapter 4.

5.1 Introduction

With the ability to wirelessly connect a large number of tiny and low cost nodes, WSNs have unlimited potential for useful applications. The nodes in a WSN can sense the target environment (e.g., temperature, humidity, pressure, radiation, PH, etc.), do some simple computation tasks and support wireless communications. Naturally, WSNs can be applied in most fields including military, industrial, health-care, environment and home monitoring. However, due to the constraints on the form, cost, and power consumption, the sensor nodes have small memory, low commuting power, and limited communication range. Consequently, there are many challenges related to the application development, deployment, and management of this type of networks. Among them, localization, i.e., determining the position of sensor nodes, is critical for many applications because data are meaningless without knowing the location in which it was obtained. In addition, the positions of the objects involved in the events are also essential for many important applications such as searching, rescue, target tracking and people health-care (e.g., workers in hazard environments, monitoring elderly or Alzheimer).

Localization is the process of determining the position of devices, objects, things or people in an area of interest. Location algorithms estimate the position of unknown objects (i.e., sensor nodes) by using inter-sensor measurements such as Received Signal Strength Indication (RSSI), Angle of Arrival (AoA), or propagation time. In addition, it requires the knowledge of the positions of some sensor nodes or devices called anchors, reference points or beacons. The localization problem has been studied since 1960s resulting in the most successful location system, which is widely in use today, GPS [23]. GPS based solutions are certainly a good choice for outdoors. Therefore, one desirable option when considering localization for WSNs is to embed GPS receiver in sensor nodes. TagSecure [187] is TagStone's location aware personnel tracking and safety management solution for hazardous environments. It is a GPS-based solution for active tags, complemented with Radio Frequency Identification (RFID) passive technology. Beyond the real-time GPS-based location, this location system also keeps the information on the last gate (RFID Reader) crossed by a tag. Because the GPS-based solution for sensor nodes is very high power consumption, the work in [24] tried to reduce it by offloading GPS processing to the cloud. However, the accuracy of this work is still low (35m). Hence, it is necessary to have alternative solutions for localization in WSNs.

One fundamental problem of localization in WSNs is that it is difficult to find an appropriate measurement (e.g. distance) between the unknown position nodes and anchors, considering the hardware and software restrictions, the requirements of accuracy, feasibility and the cost. This problem is even more severe in noisy industrial environments with a high degree of noise, interference and obstacles. As discussed in chapter 2, ToA is not a suitable measurement method for WSNs because it requires a very highly accurate clock and more complex algorithms to have the highly accurate synchronization, i.e., in ns. The reason is that the communication in WSNs is mainly very short distance while the travel speed of radio signal is very fast. Similarly, the round-trip time method also requires a very highly accurate clock, and it is difficult to calculate delay time at both sender and receiver. In addition, multiple messages exchanged between the sensor node and several beacons are needed to obtain information for estimating the position of the node. The AoA can produce more accurate distance estimation. However, it is costly because of an array of antennae. In addition, the accuracy of this method is severely affected by noise, interference, shadowing, multipath, obstacles, and other factors. The combination of RF and the ultra-sound reduces the complexity of antenna array. However, it requires the additional hardware, which is costly and energy inefficient. In addition, it is also has the same problem as those of AoA measurement method. Consequently, in spite of being unstable and having a high variance, RSSI measurement method is, in most cases, the only choice because of its availability.

The localization system presented in this chapter is based on the empirical measurement of the RSSI between the sensor nodes and the anchors. In addition, it includes the mechanisms for dealing with large-scale sensor networks while maintaining the performance of location estimate process. The implemented location system was evaluated in both laboratory and real critical industrial environment, the Soporcel paper mill of Portugal [188].

5.2 Related Work

The location algorithms for WSNs can be divided into two broad classes: one for ad-hoc (static or semi-static) sensor networks; and the other for controlled sensor networks. The former is based on the assumption that the nodes in WSNs are deployed randomly into the field and they rarely moved after deployment. In this case, the sensor network is almost static except when the nodes die or are added. The latter class is applied for the sensor networks that are carefully designed, using engineering methods. It is worth noting that a controlled sensor network comprises two main parts: the infrastructure and the mobile nodes. The infrastructure is usually well designed and includes a set of nodes with fixed known positions called anchors or beacons. On the other hand, the mobile nodes are usually attached to workers, patients, or vehicles to monitor the target environments or subjects. Consequently, determining the locations of these mobile nodes is essential for many types of applications. Because our localization system targets the controlled sensor networks, we focus our discussion on the localization approaches for this type of WSNs.

Perhaps the simplest algorithm to estimate the position of a sensor node is based on the "closest beacon" principle, i.e., the position of the node is the same as that of the closest anchor based on a measurement, e.g., RSSI. For example, if the measurement is RSSI then the position of the mobile node is also the position of the beacon that has the strongest signal strength. Active Badge [25], Cricket [26], and Identec [27] are examples of the positioning systems that employed this method. The advantage of this method is that it is very simple to implement. However, it only provides relative location such as in which room the node resides.

Another simple method is centroid algorithm [28] which computes the position of a mobile node by averaging the coordinates of involved anchors, i.e., anchors in the range of the node. In this method, the position of an unknown position node is determined by the arithmetic mean of the coordinates of all the beacons in its communication range. Similar to proximity method, this technique can only provide the relative location. In addition, it returns the same position for nodes that are in the range of the same set of anchors.

The second group of localization methods is based on the exploiting of the geometric characteristics of triangles, circles, spheres or hyperbolae to estimate the position of the unknown position nodes. In this approach, the localization problem is expressed as a system of ***n*** equations (e.g., circles, spheres, or hyperbolae). As a result, the position of a node is the solution of the equation system. Depending on the type of measurement the methods in this approach could be divided into two groups: lateration and angulation. Lateration method uses the distance measurement between a device and several anchors to model the problem as a system of circular (2D) or sphere (3D) equations, and when the number of equations is equal to 3 then it is also known as trilateration. With this method, the measurement method could be ToA, Round-trip Time of Flight or RSSI. However, because of the errors in measurement and estimation, the intersection of circles or spheres may not result in a single point but an area; or in some cases, it does not intersect at all. Consequently, instead of solving the system of equations, the linear or non-linear least square method [29], [30] is usually used. GPS [23] is the most well-known public localization service employs this algorithm. In addition, Bat [34] is the example of the lateration based location system for sensor networks. The accuracy of this system is in the range of centimeters. However, the use of a combination of ultrasound and RF makes this system more costly. In addition, it is very susceptible to noise, obstacles, and non-LOS environments. The recent work in [24] proposed a low power GPS-based solution for sensor nodes. This work tried to reduce power consumption for sensor nodes by only getting the raw signals from satellites and then forwarding them to the location service on the cloud for the offline computation. The position of a node is computed by combining the information from the raw signals obtained by the node itself and other sources. The current accuracy of this system is still low (35m) [24].

In cases where the distances cannot be directly measured or estimated but instead the differences of the arrival times of the signal at different anchors, a system of hyperbolic equations can be formed and used to estimate the location of the node. One method for finding the solution for the intersection of hyperbolas is to linearize the equations through the use of Taylor-series expansion and to solve it using the iterative algorithm [141]. Another method is to use correlation techniques with the cross-correlation function of the signals [142]. The main disadvantage of this method is that it requires that all anchors must be precisely synchronized.

Similar to lateration, angulation also bases on a system of equations for the localization problem. However, instead of using distance measurements, it uses the Angle of Arrival (AoA) of the transmitted signal at several anchors. In 2D space, the location of the object is computed by the intersection of a pairs of direction lines. In 3D space, it is possible to use these techniques for localization if the measurement of azimuth is available. Ubisense system [189] is a location system which employed AoA and Ultra-Wideband (UWB) to estimate the location. The accuracy of this method is very good (in rang of cm). However, its cost is high because it requires directional antennae. In addition, its accuracy is also severely affected by noise, obstacles, and non-LOS environments.

With regard to finding the best estimate for the localization problem that are expressed as an over-determined system of equations, Kalman filter [122] can be used. Kalman filter is a recursively optimization estimator and it is widely used in almost every fields including localization. It employs the prior knowledge of noise characteristics to account for and filter out the noises. In fact, Kalman filter can be used as an optimal tool in other localization methods such as lateration or angulation. The research in [31], [32], [33] employs Kalman filters for localization of sensor nodes, and claimed that its accuracy is very good (less than 1 meter). However, the testbeds in these researches were too small to assure the reliability of the accuracy. In fact, in our experiments with trilateration method using RSSI measurement, employing Kalman filter, the location error is much higher because of the error and instability of distance estimation using RSSI.

As it is difficult to find an appropriate, accurate and reliable method for measuring the distances between the mobile nodes and anchors, recent studies try to employ algorithms in machine learning field for localization problem for WSNs. The localization methods in this group are also known as pattern matching or learning-based, fingerprinting or scene analysis. The methods in this category comprise three main phases: (1) feature(s) collection, (2) training, and (3) location estimation. The objective of the first phase is to collect the necessary data from the deployment environment. The most common measurement collected for localization is RSSI because it is available in almost all wireless networks. In the second phase, the collected data are then used to train the algorithms to create the model and/or the necessary parameters. The final phase uses the model or parameters computed in the second phase to estimate the location of the unknown position objects by matching the new measurements with the created model. The first two phases are done offline, while the last one is carried out in real time. There are several localization algorithms in this approach including K-Nearest Neighbors (KNN), Probability-based, Artificial Neural Network (ANN), and Support Vector Machine (SVM).

KNN [148] is a common algorithm in machine learning and data mining for classification. To determine the class for a test object, the KNN works as follows. First, k records that are similar to the test object, based on some measurement, are searched from the training dataset. Then, the class of the test object is that of the majority of k selected records. KNN can be used for estimating the location of unknown position nodes by first searching the fingerprint dataset to find k records that are closest matched with the new observed data according to a distance function, e.g., Euclidean distance. By averaging the coordinates of these k records, then, an estimated position of the object is obtained. We could use the distances as the weights when averaging the coordinates of k records; and in this case it is called weighted KNN. RADAR [35], MoteTrack [38], and LADMARC

[37] are examples of localization systems that employed KNN. With the RADAR system, it is possible to achieve 90th percentile of location error around 5.97m.

MoteTrack [38] adds the distributed ability to the system, by implementing the localization algorithm on the sensor nodes. In addition, to improve the accuracy and robustness, it requires that the sensor nodes have to listen on multiple channels to collect data from multiple power levels. As stated in the paper, the accuracy of this system is very good: with data from 16 channels the 80th percentile of distance error is lower than 1.6m and with data from one channel the 80th percentile of distance error is 3.5m. Although MoteTrack [38] achieved an impressive accuracy, there are several problems with this approach. First, it requires the sensor nodes to wait a rather long time in order to acquire enough data for computing its location. Thus, it is not appropriate for highly moving nodes. Second, because the beacons have to continue to broadcast messages on multiple channels and power levels, it has very high power consumption. Third, because the localization algorithm is implemented on the sensor nodes, it cannot apply for the large sensor network having hundred or thousand anchors.

LANDMARC [37] is another KNN based location system. However, instead of manually collecting data from the deployment environment, this system employs a set of reference tags for this purpose. The main advantage of this approach is that the first step, i.e., collect feature(s), is not needed. In addition, the training dataset is always updated. With a testbed in which reference tags are positioned at distance 2m x 1m, the LANDMARC [37] achieved the 50th percentile of location error is about 1m and the 75th percentile of error is about 1.2m. However, in order to obtain good accuracy, a high density of reference tags, e.g., one tag every two meters is required. The high density of reference tags leads to the high interference and thus it severely affected the performance of the system. Moreover, the cost of this system is also high and it is not appropriate for use in many real environments.

Another machine learning method that can be used for localization is based on probabilistic theory. This method is similar to KNN, but instead of using the distance to measure the "similarity" between the new observed data and the records in the training dataset, the probability-based methods use the likelihood estimation to determine the similarity between them. A common method is to use Bayes' rule [149] to calculate the probabilities that the new observed data matches the records in training dataset. Horus [39], [150] was a probability-based location system for WLAN that had the 90th percentile of errors was about 1.43m. However, in order to obtain this accuracy the density of Access Points (APs) is high (average 6 APs per location). In addition, it requires multiple samples for each location estimate. Moreover, because the system is implemented on the client devices, it may be not appropriate for sensor nodes. Elnahrawy et al. [151] was another study on using probabilistic approach for localization in WLAN. They proposed Area-Based probability (ABP) to estimate the area in which a mobile node resides. In this study, the authors also characterized the limits of using RSSI for localization. The results from this study showed that using the RSSI for estimating location has an expected bound for performance with the median of distance error is about 3m and the 97th percentile of distance error is 9.15m [151]. This is a reasonable conclusion because of the high variance and instability of RSSI values.

It is interesting to note that the ANN, which is inspired on the operation of the human brain, can be used to solve many real world problems in different domains, including pattern recognition, classification and regression. ANNs can also be used to solve the localization problem in WSNs as research done in [42], [44], [153], [154]. The study in [42] used the Cricket sensors [26] in its experiments and showed that the performance of the neural network based solutions were better than those of the Kalman Filter [31]. However, the testbeds in this experiment was too small to evaluate the performance of ANN-based localization. On the other hand, the experiments of the study in [154] were only done using simulation, whose results are rarely trusted for evaluating the accuracy of localization methods. A more practical study in [44] showed that ANN based localization for WLAN achieved the 90th percentile of distance error was less than 5.4m. The advantage of this method is that it is very fast to estimate the location (online stage). However, the training stage takes very long time and needs experienced professional or empirical study to choose the good structure for ANN. In addition, it cannot work well if the training dataset has many non-separable records, resulting in significantly reducing the accuracy.

SVMs, also called kernel machines, are “maximum margin methods that allow the model to be written as a sum of the influences of a subset of training instances” [149]. In SVM method, the model is a class of kernel functions; and the training process tries to find the best parameters for the kernel functions to make the margin (i.e., the distance from the function to the nearest records of a class) as large as possible. SVM can also be used for localization in wireless network as shown in [44]. The work in this paper showed that SVM achieved the 90th percentile of distance error was about 5.12m. In addition, with the same environment, its performance was a little better than other learning based methods (Weighted KNN: 5.16m; Bayesian: 5.61m; and NN: 5.40m) [44].

Every solution has its own merits and drawbacks, making it appropriate for different applications' requirements. The proximity and centroid methods are simple (i.e., easy to implement and low memory computation demand) but their accuracy is very low, i.e., they only give a relative location such as in which room the node is. Similarly, lateration and angulation approach also have a low memory and computation requirements. However, their localization accuracy is dependent on a high accuracy and reliability of the measurements, which are very difficult to achieve in WSN. Consequently, these approaches usually give a very low accuracy in WSNs with RSSI measurement. On the other hand, the machine learning based methods are complex in implementation and require high memory and computation demand. However, the significant point to note is that learning based methods are appropriate for controlled WSNs and are more accurate than the others.

In this work, we proposed and implemented a localization system that is able to adapt to the growth of the sensor network. More important, we evaluated the localization methods for controlled WSNs in real critical industrial environments in order to find the most appropriate method(s). The next section presents the targeted application scenarios for our localization system.

5.3 The Application Scenarios

This section presents the application scenarios for which the localization system is designed. In critical environments such as refinery, chemical plant, paper mill, etc, determining the position of people (e.g., workers) or moving devices is very important in order to have instantaneously appropriate responses. In these environments, the sensor nodes are attached to the humans or vehicles, to monitor people's current health (e.g., heart rate or blood pressure), the environment conditions (e.g., temperature, humidity or air pressure), as well as their positions. By experiential working in critical industrial environments such as oil refinery, paper mill and chemical plant, we found that these environments have a lot of obstacles. Fig. 5.1, a part of a refinery, is an example of such an environment with machineries, tubes, and tanks present everywhere. For these reasons, using GPS may not be a good choice due to its low accuracy or unfeasibility when used in such a scenario with so many obstacles and interferences. In addition, high power consumption and additional hardware costs also prevent using GPS in sensor networks.

Although mobile devices and wireless networks are limited in the refineries, the noise and interference still exists. Our study presented in [190] shows that whereas there are no other wireless networks that interfere with the IEEE 802.15.4 based WSNs within the refinery, there is still a considerable amount of signal noise caused by several types of machineries, pumps, etc., that operate 24h a day. In addition, the effects of noise are different between radio channels. Moreover, the noise and interference severely affect the performance of the IEEE 802.15.4 based sensor networks in terms of delay and packet loss as shown in [191]. Consequently it is necessary to have a suitable localization for such scenarios. This means that the localization solution should work well in noisy environments with a lot of obstacles, but with low power consumption.

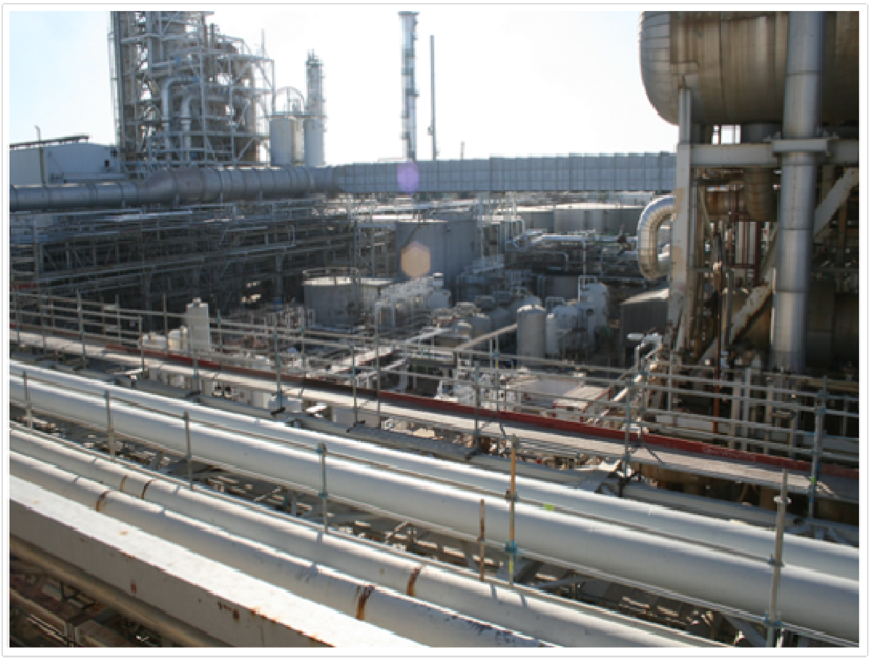


Fig. 5.1 A Typical Part of an Oil Refinery

It is important to note that in these application scenarios the mobile nodes do not usually care about their own positions but the monitoring or controlling applications (e.g., the *Supervisory Control and Data Acquisition - SCADA)* have to somehow locate the position of these mobile nodes. This means that the position can be calculated by the mobile nodes or by a central server, depending on which place is more appropriate. However, in the case where the location is estimated by the mobile node itself, this information has to be sent to the central servers, which host SCADA software, for further processing. In our approach, to reduce the power consumption as well as the computation burden of the sensor nodes, we decided to develop a central localization system in which the positions of mobile nodes are estimated. The proposed localization system implements multiple localization methods in order to allow users to select the most appropriate one for a specific deployment environment. The next section presents the proposed model.

5.4 Scalable Localization System

In order to create a positioning system that can respond to a large number of concurrently requests, we employed a multi-layered software architecture for the localization system. In addition, we also use the service-oriented principles for the system, i.e., the communication between layers is based on web services. The general model of the system is described in the following sub-section.

5.4.1 General Model of the System

The general model of the system is described in chapter 4 and this section only briefly summarizes it. The main goal of this model is to provide a method for exposing the data and functionalities of sensor networks and to allow an easy interoperability between the WSNs and external environments including enterprise applications, web 2.0, virtual worlds (e.g., Second Life [182]), and other applications. In addition, the model should be also flexible enough to easily add infrastructure services (e.g., localization and mobility) for WSNs. Moreover, it should be also scalable to apply for large sensor networks. Consequently, we adopted a multi-layered architecture for the software system. As shown in Fig. 4.1 in chapter 4, the model employs the proxies and gateways as the mediate layers for interoperability between sensor networks and the applications that monitor and control them. To support the scalability for sensor networks, there may be more than one proxy associated with one gateway. Moreover, there can be more than one gateway in the system. The details of these two components are described in chapter 4. This section only discusses how they support for realizing localization function.

The gateway, also called web service gateway, hosts localization engine, which implements the localization algorithms. The localization engine accepts the localization requests from the proxies, computes the position of the unknown position nodes, and returns the results back to the proxies. More important, the location results are also stored on the storage on the gateway (or a database server) for use by other applications such as the visual application or SCADA via a web service interface. The main advantage of the web service gateway is that it isolates the services from their consumers. In addition, any changes to the middleware will not affect the applications consuming the services provided that its interfaces are kept intact. Moreover, the security mechanisms such as authentication, authorization, and encryption can be implemented at the gateway.

The proxy is responsible for obtaining, analyzing and forwarding the data from the sensor network to the gateway. As discussed in previous chapter, the proxy is designed to use an event-based principle, i.e., developers can register the listeners that capture events of interest that happen in the network to add new component. In particular, to support localization, the *Localization Requester* component registers to the ”*data frame arrival”* event of the proxy to get the data from the sensor nodes. When having enough data for a location request, it will compose the request and send it to the localization engine on the gateway. This event-based model allows the system to be easily extensible.

In order to make the seamless interoperability between the layers, web services are employed in our software system. This means that the communication between proxies and the gateway, as well as the communication between the gateway and users' application, are based on web services. However, to reduce unnecessary overhead, the communication between the sensor networks and proxy is serial port or IP based.

5.4.2 Localization Middleware

The localization middleware comprises several localization methods to estimate the position of the sensor nodes when requested with appropriate data. The general components of the location engine are shown in Fig. 5.2. As shown in this figure, besides a list of implemented localization algorithms, the localization middleware also includes methods for the proxies to request the positioning service. When receiving a request, the localization engine will use the provided data, the model or training dataset, and a localization algorithm to estimate the position of the node in the request. The resultant position is then sent back to the proxy and stored in the database of the gateway at the same time.

The position results stored on the gateway can be accessed and used by the monitoring and controlling software or other applications. There are two methods for applications to get location data from the gateway: polling and publisher-subscriber model. For the former method, the applications periodically send request to the gateway to get the last location data, while for the latter, the application subscribes the location request to the gateway and when there is a new location result the location engine will raise an event to inform the application about the new data. All of these functionalities are provided by the gateway via web service interfaces.

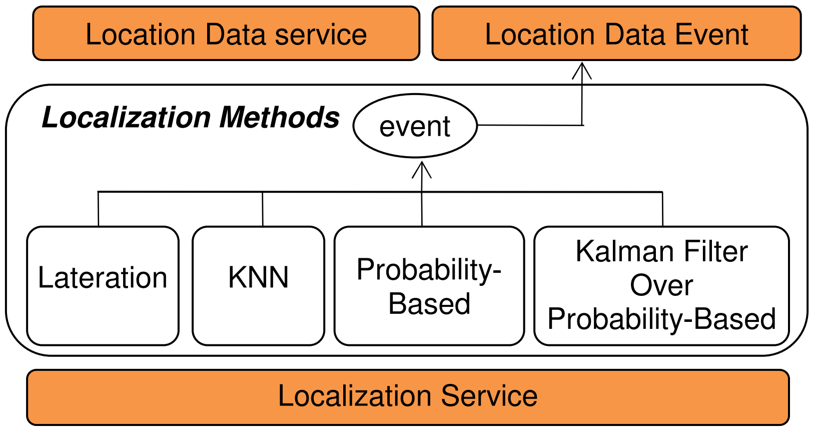


Fig. 5.2 Localization Middleware

5.4.3 Localization Methods

In order to be able to evaluate and select the appropriate method for different sensor networks, we implemented the following localization methods: Lateration, KNN [148], Probability-based (Bayesian theorem) [149] and Kalman filter [122] over probability-based. In the following discussion, RSSI measurement is used as the main input for our localization methods because it is available in almost all WSNs and our current location methods are also based on it. In addition, for the machine learning based methods, it is assumed that the training dataset of the deployment environment is already collected.

The first algorithm implemented in our localization engine was Lateration. This algorithm comprises two steps: (1) measuring or estimating the distance between a tag and some anchors; and (2) computing the position of the tag using the intersection of circles or spheres based on the measured (or estimated) distances obtained in step 1. Newton's method for nonlinear least square [29] was implemented in the location engine to solve the over-determined system of equations to obtain an estimation of the position of the unknown nodes. In addition, in order to estimate the distance from a tag to an anchor, we also implemented several methods for converting RSSI value to distance. The details of these conversion methods are presented in following section.

The second localization method implemented is KNN, which is based on the principle " similar input will have similar output". This method is called lazy learning algorithm because the training dataset is used as is. In this approach, the KNN algorithm uses the observed RSSI vector (a list of pairs of anchor and RSSI value) to search for k "closest" records in the training dataset according to some distance measurement (e.g., mean square errors of Euclidean distance). Then, the position of the unknown position node is computed by averaging the coordinates of these k records. In addition, the distances can be used as the weights when computing the average of coordinates; and KNN becomes the weighted KNN.

The third localization algorithm we implemented is based on the Bayesian decision theory [149] and it is called Probability-based. Instead of finding K-nearest records using the Euclidean distance, as KNN does, the Bayesian theorem is used to calculate the probability of the entries in the training set, in order to find k highest probability records for the observed RSSI vector. Then, the location of the unknown node is the (weighted) average of the coordinates of the k highest probability records.

The final localization method implemented in our localization engine is Kalman filter [122] over probability-based. In this implementation we combined two algorithms: (1) Probability-Based; and (2) Kalman filter. This method first estimates the position of a node using the probability-based method mentioned previously. Then the resultant position is used as input for the Kalman filter. Because we do not have a rigorous mathematical model for this case, we assume that the estimation of the current position is linearly related to previous estimated position, the current measurement and the noise. Consequently, our model for Kalman filter is as follows:

$$\begin{cases} x_k = x_{k-1} + w_{k-1} \\ z_k = x_k + v_{k-1} \end{cases}$$

In which, z_k is the position given by the probability-based method; x_k is the tag position; w_{k-1} and v_{k-1} are the process and measurement noise, respectively.

In our implementation, we assumed that the noise does not change over time. This means that $w_k=w_{k-1}=\ldots=w_1$ and $v_k=v_{k-1}=\ldots=v_1$. Consequently, the process and measurement noise matrixes were computed once and based on the errors of the probability-based method.

5.4.4 Scalable Mechanisms

The above localization methods work well for sensor networks with limited number of anchors. However, they will have some problems when used with sensor networks that have a large number of anchors and cover a large region. First, the training dataset significantly grows if each record comprises all the anchors of the entire sensor network. In addition, the location estimation process is slower when the training dataset becomes larger. Moreover, because the range of each anchor is limited, only a small number of anchors have useful values in each record of the training dataset. As a result, it wastes a lot of system resources, i.e., memory and computation, and affects the performance of the location system. The problems are more severe for the KNN and Probability-based methods. The reason is that these two methods belong to the lazy machine learning algorithm type, i.e., instead of creating the model from the training dataset these algorithms use it as is during estimation process. Therefore, reducing the size of the training dataset used in position estimate process is one way to improve the performance of the location system. However, if we do this by taking fewer measurement positions, then the accuracy will be reduced. Consequently, we have to keep taking the same number of measurements as well as the interpolation but somehow to reduce the number of records used in the estimation process.

One possible method is to divide the entire network into different non-overlapped zones which in turn is further divided into smaller subzones. A zone is a physically separated area such as a site, a building, or a floor in a building. The objective of subzone is to improve the performance and the estimation for each request only works on the dataset of the subzone. In order to determine the subzone to be used on the estimate process, each subzone has one or more represented points. As a result, we come up with a two steps localization process: (1) subzone determination (2) localization estimation on the selected subzone.

Before being able to apply this two-step localization process method, some preparation steps are needed. First, we have to define a set of zones sand subzones. Then, we have to process the collected data to create the training dataset for each subzone. These preparation steps need to be done only once. Dividing a WSN into zones is simple because it is based only the physical separated area. For the subzones, there are two possible methods: (1) beacon-based and (2) area-based. For the former method, the subzones are determined based on a list of anchors. Consequently, each subzone is represented by a list of unique beacons. In this case, to determine a subzone for estimating the position of a node, the location system uses the anchors' ID from the input data. It is important to note that subzones may be overlapped, i.e., they may cover common areas and thus have some common anchors. Consequently, it is possible that the list of anchors in an input data belongs to two or more subzones. In this case, the subzone with the greatest number of matched anchors wins and a tie is broken by randomly choosing a zone.

For the latter method, each zone is divided into smaller areas called subzones. The division can be simply based on the size of the area or it can also be based on the physical conditions such as obstacles, shapes, or terrains. It is important to note that the subzones might have the same list of anchors. Consequently, it is necessary to have an appropriate method to select the subzone. Our solution for this problem is to use the representative record(s) for each subzone. This means that for every subzone we select a position, e.g., at the centre of the subzone's area, as the representative point. Then, the data collected at the representative position serves as the representative record. It is possible to have more than one representative record for each subzone by choosing multiple representative positions. To select a subzone for a location estimate, the engine computes the similarity (e.g., distance) between the input data and the representative data of the subzones. The closest subzone is chosen to use for the second step, i.e., for the localization process, which is the same as the one presented in previous section, but with the subzone dataset.

The current implementation of our location system employs the second method to organize the subzones, i.e., area-based. Fig. 5.4 shows an example of a simple subzone division in which a subzone is an entire floor. However, in the real environment, a subzone can be a part of a floor. With this division, the entire training data set will be divided into multiple data sets (one data set for each subzone). The training data set for each subzone is reduced and only comprises data collected in an area covered by the corresponding subzone. By organizing training data this way, the performance of the location estimate is significantly improved. In fact, the location computation time remains the same regardless how large the sensor network is.

To further improve the accuracy as well as the performance, we employ a two-step method in the selecting subzone process. In the first step, some readers with the strongest RSSI values are used to limit the possible area of the tag. The result of this step is a list of subzones which have the areas overlapped with the region limiting by the position of these readers. In the second step, one subzone is selected by computing the similarity between the new observed values and representations of the subzone list selected in the first step.

It is important to note that the data collecting phase is the same as that applies to the entire network. This process comprises three main steps. First, determining the positions where data will be collected. Second, collecting feature(s) by putting the sensor nodes at the chosen positions to get the signal strength and/or other data if applicable. Finally, the collected data are processed to create a training dataset for using in the localization process. The next section presents our testbed environments and the experimental results done with our localization system.

5.5 The Testbeds

This section presents testbeds that are used in the experiments. The objectives of the testbeds are to evaluate and to compare the performance of different localization methods.

5.5.1 Sensor Platform

Because industrial plants are characterized by having huge metal structures and pipes everywhere, and some with concrete walls or platforms, the LOS communication cannot be considered in this system. In order get more range in distance, and communication robustness in such scenarios, the 433MHz based sensor networks are used. The testbeds in these experiments used the sensor hardware developed by Eneida [186], an engineering company specialized in Instrumentation, Energy and Communications and dedicated to the process industries. The equipments used in our testbed include: (1) the smart active tags (EWS µ433M and EWS µ433M1Ex), which broadcasts its own ID; (2) the wireless communication devices (also called readers) (EWS G433M and EWS G433M1Ex), which receive the data from the tags, obtain the RSSI, and forward them to the gateway devices; and (3) the communication gateway devices (EWS GIP or EWS GIPW), which accept the data from the readers and forward them to the central servers for further processing. The gateway devices get messages through CAN bus [192] or wireless, and then delivery them to the server via Ethernet or Wifi communication [186].

The radio component of this sensor system is based on the CC1101 radio transceiver from Texas Instruments (TI) [193]. This module is able to operate in the sub GHz ISM bands of 433MHz, 866MHz, and 902MHz and has features like low power consumption, automatic packet handling or serial asynchronous communication and channel hopping capabilities. The communication stack used in this implementation was the SimpliciTI from TI [193]. It is a royalty free stack and provides basic point to point or tree topology networks. It has built in encryption capabilities (XTEA algorithm [194]) and provides a MAC layer with Carrier Sense for medium access. One possible topology of this type of sensor net work is depicted in Fig. 5.3. The communication between readers and the gateway can also be wireless.

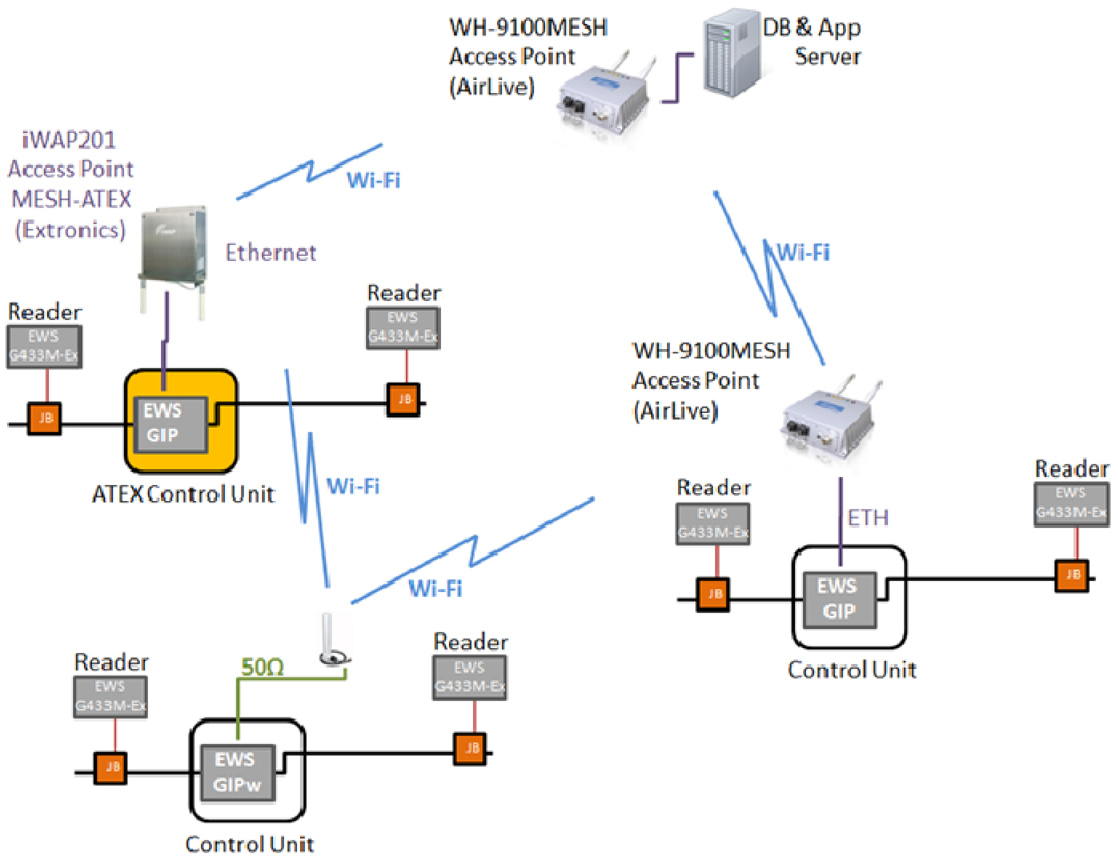


Fig. 5.3 EWS Sensor Network Topology

5.5.2 Testbed Environments

To evaluate the performance of the location system with different environments, we set up and did the experiments with two testbeds. The first one consists of two sites: the first one is at the Instituto Pedro Nunes (IPN) building in which Eneida Company is situated and the second one is at the fire department of Coimbra, Portugal which is about 300m from the IPN building. The first location is a two-story building where readers were deployed in both floors, creating two different zones. Consequently, the entire sensor network is divided into 3 zones: *zone 1* is located at the 1st floor of IPN, *zone 2* is the 2nd floor of IPN building and *zone 3* is the fire department. The layout of the test-bed is shown in Fig. 5.4. In this scenario the localization system is implemented on one server and placed at the 2nd floor of the IPN building.

The second testbed was set up at the Soporcel [188] paper mill, Portugal. In this experiment the test-bed was installed in the recovery boiler for power production building. This is a very hazardous and critical environment. There were 11 readers installed on the floor 4, 5, and 6 of the 18 story building. The area of each floor is about 990 square meters (33 m x 30 m).

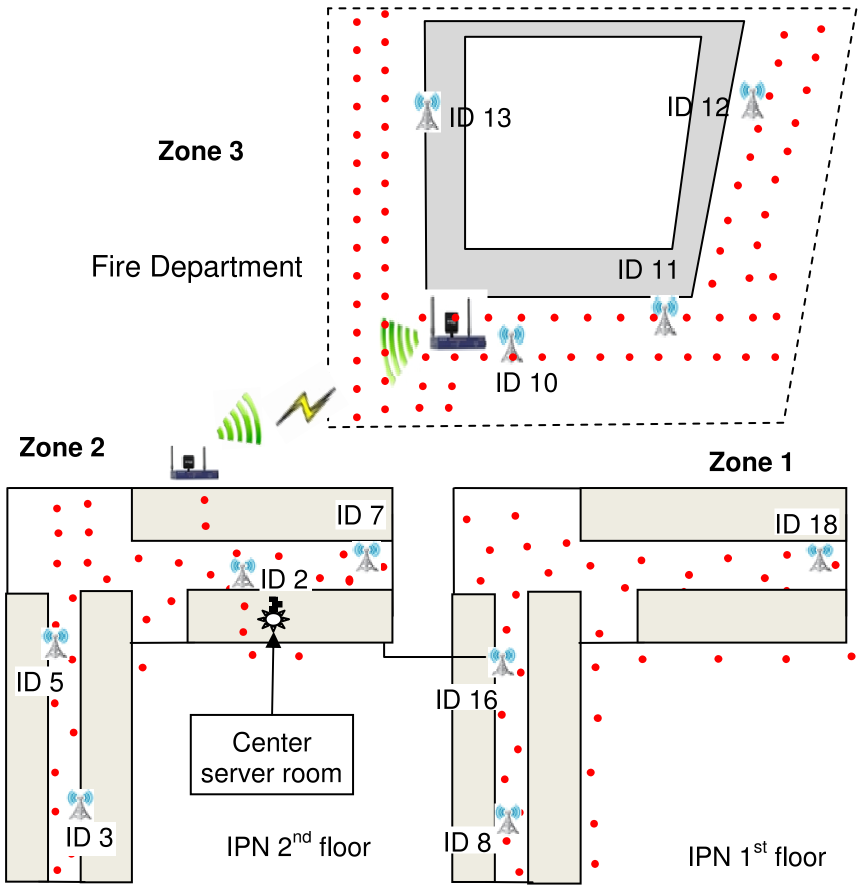


Fig. 5.4 Testbed at IPN Building and Fire Department

5.6 Experimental Results

With the installed test-beds we did numerous experiments with different configurations and objectives. The following sub-sections present the experimental results obtained from both laboratory and real critical industrial environments, Soporcel [188] paper mill, and the comparison of the performance between the different environments. Before presenting the location methods, we did numerous analyses to find ways to improve the accuracy and robustness of the location methods

5.6.1 RSSI Calibration

The lateration localization method requires the distances from the sensor node to several anchors. In most cases, however, the only feasible measurement in a WSN is the RSSI value. Thus, it is necessary to have a method to convert RSSI value to the distance. In order to find a good correlation between RSSI value and distance, we evaluated four possible conversion methods: (1) Mean RSSI value; (2) linear regression; (3) Friis Transmission Equation [195]; and (4) kernel smoother algorithm [149].

In the first method, the correspondence between RSSI value and the distance is computed using the arithmetic mean of the measured RSSI values at each distance. The result of this computation is a mapping table of pairs of distance and RSSI value. For the second method, we tried to find the values for the parameters *a* and *b* of the straight line *distance = a.rssi + b* that fit the collected data with minimum errors. The third method is to use the collected data to infer the values for the parameters of the Friis transmission equation [195]:

$$RSSI(dBm) = -(10.n.log(d) + A)$$

$$=> \ d = 10^{-\frac{RSSI+A}{10.n}}$$

In which *A* is the absolute value of RSSI within 1m distance; the signal propagation coefficient *n* shows the damping of the signal. Both parameters are determined empirically.

The final method is called the kernel smoother [149], which uses nonparametric regression to estimate the distance from RSSI value. Its principle is that close input (x) will have close output g(x) value. Assuming that the training dataset is $X = \{ x^t, r^t\}$, $r^t \in R$, this method can be expressed as follow.

$$g(x) = \frac{\sum k(\frac{x-x^t}{h})r^t}{\sum k(\frac{x-x^t}{h})}$$

In the equation *h* is the width and *k* is the kernel function. One common used kernel function is the Gaussian kernel as follows [149].

$$k(u) = \frac{1}{\sqrt{2\pi}\,\sigma} e^{-\frac{(u-\mu)^2}{2\sigma^2}} \ ; \ \mu = 0, \sigma = 1$$

To evaluate these methods, the RSSI values at different distances are needed. In this experiment, we collected RSSI values between a tag and a reader at different distances from 1 to 40 meters with 1 meter a step. At each distance one hundred RSSI values were collected. After this step, we obtained a list of RSSI value-distance pair.

The experimental results with these methods are depicted in Table 5.1 and Fig. 5.5. It can be seen from Table 5.1 that the kernel smoother is more stable (smallest standard deviation - SD) than the others. In addition, this method also has the better accuracy with 90th percentile of errors lower 8.26m. For most methods, except the Friis equation, the average error is around 5m. We can see from Fig. 5.5 that the mean RSSI and linear regression methods also have an average and median of errors similar to those obtained from the kernel smoother method. However, they have the larger SDs and have more outliers. Although the Kernel Smoother is better than the other methods, its error rate is also very high with the average error is about 5.16m.

Table 5.1 The Errors in Converting RSSI Value to Distance

	Average of RSSI	Linear regression	Friis Equation	Kernel Smoother
Min (m)	0.0143	0.0036	0.1696	0.0710
Max (m)	27.3752	34.6658	65.5842	19.4342
Average (m)	5.3921	5.2609	11.8823	5.1630
Q1 (m)	0.9825	1.9356	6.7932	2.9290
Median (m)	3.7320	3.8384	11.0021	4.7163
Q3 (m)	6.7032	7.0644	16.5340	6.8309
SD	5.0713	4.9184	6.7579	3.5497
90 percentile	12.0368	10.8615	18.4647	8.2612

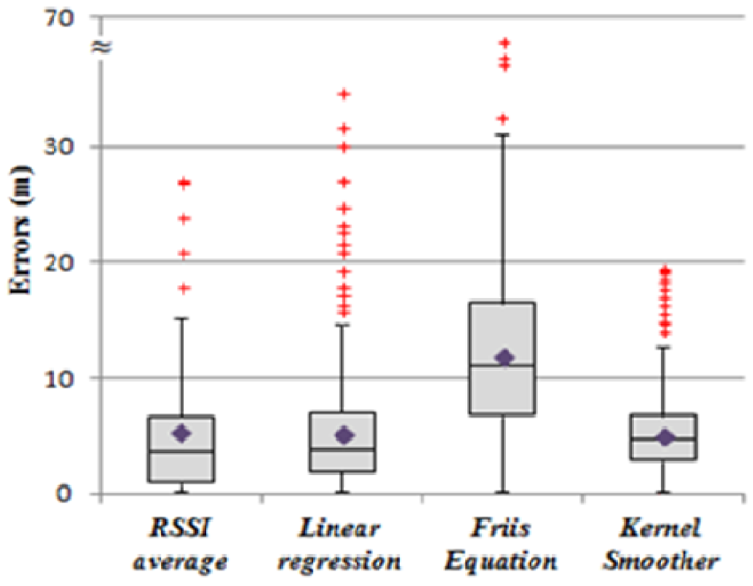


Fig. 5.5 The Errors in Converting RSSI Value and Distance

5.6.2 The Spread and Distribution of RSSI Values

Finding the spread of RSSI is also important because it provides information about how stable (or unstable) the RSSI is. In addition, it is worth noting that the probability-based localization methods assumed that the distribution of RSSI values is normal. Consequently, it is necessary to have an empirical study to see whether or not this assumption is acceptable. In order to evaluate the spread and distribution of RSSI values, we put a tag and a reader at fixed positions and measured the RSSI values received at the reader. To avoid the interference caused my people moving around, we did the experiments during the night in a room with the door closed. We totally collected 58978 RSSI values. The histogram in Fig. 5.6 indicates that, in this case, the spread of RSSI value, i.e., the range between the maximum and minimum, is 29.

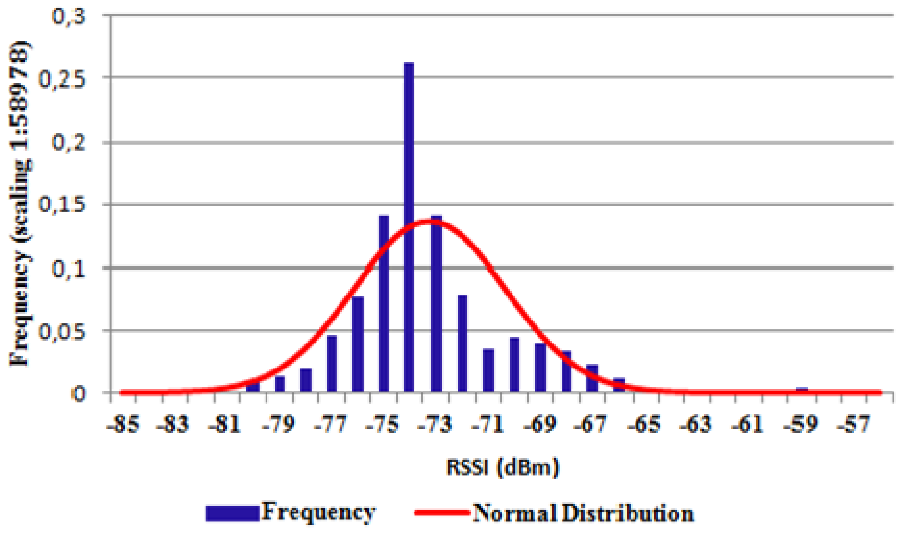


Fig. 5.6 The Distribution of RSSI Values

In order to see whether or not the RSSI values from this experiment obey the normal distribution, we also calculated the average and SD of the collected data. The red line in Fig. 5.6 shows the graph of normal distribution using the computed average and SD over the scaled histogram of the real data. Although these two graphs are not totally matched with each other, the distribution of the RSSI values is approximate to the normal distribution. This result allows us to use the normal distribution in the probabilistic-based localization algorithm.

Another relevant point top note is that combining this result and that of previous section, we can conclude that the RSSI values are unstable. The reasons for this conclusion are that with a fixed position, the measured RSSI values have a very high range and large SD.

5.5.3 Training Dataset

In order to estimate the position of a node, the machine learning based localization methods need to have a training dataset. The dataset consists of a list of records; each comprises the features collected at a specific position in the deployment environment. In addition, to compute the matching likelihood between a new observed data and a record in the training dataset, the probabilistic methods need SD of the RSSI of each anchor. Analyzing the collected data, we recognize that the SDs for each anchor varies from position to position. Therefore, it is more appropriate to use the SDs computed at each collected position in computing matching likelihood. Consequently, each entry in the training dataset is a tuple with the following information:

$$<x,y,z, rssiAvg_1, rssiStd_1,\ldots, rssiAvg_n, rssiStd_n>$$

In which:

x, y, z are the coordinates of the position where the data is collected;

$rssiAvg_i$ is the average of RSSI values from the anchor i^{th};

$rssiStd_i$ is the SD of the RSSI values of anchor i^{th} at position *x, z, y*.

Because collecting data is very time-consuming, we cannot collect the data in very fine-grained positions (e.g., 1 or 2 square meters each). Therefore, we applied a method similar to that used in [151], i.e., we collected RSSI values at the distance about 3-5 square meters and then did an interpolation to create a fine-grained dataset for training the localization algorithms. To make the testing of the accuracy more reliable, we independently collected two datasets: one for training and the other for testing. As an example, the red points in the Fig. 5.4 are the positions in which the data were collected for the first testbed. With the collected data being from 30 to 80 positions for each zone, the interpolation process produced about more than 1000 entries for the training dataset, each entry representing a point (or a tile) in a zone. The collected datasets were used to evaluate the localization methods in the following sections.

5.6.4 Evaluating the Lateration Localization Methods

As previously discussed, the accuracy of lateration algorithm depends on the precision of the distance measurement or estimate between the tag and the anchors. However, the results obtained from the experiments showed that the conversion between RSSI values and distance has a very high error (Table 5.1). In addition, it can be seen from

Fig. 5.6 that the RSSI is also unstable, with a high variance. These factors affect the accuracy of lateration method. In fact, by using the Kernel Smoother method for conversion between RSSI value and distance, the lateration method produced a very low accuracy. In addition, observing the results of this experiment, we saw that the error in distance measurements has a significant effect on the error estimation of the height (z coordinate). In most cases, the estimation error of z coordinate is unacceptable. Furthermore, without taking into account the estimation error of z coordinate, the error of this method is also very high; the majority of errors were greater than 10 meters. Consequently, in the following sections this method will not be involved in the evaluation.

5.6.5 Evaluating the Localization Methods with the Laboratory Testbed

This section presents the experimental results of three localization methods (KNN, probability-based and Kalman Filter over Probability-based) with the testbed installed at IPN building. The distance errors of these localization algorithms are depicted in Table 5.2 and Fig. 5.7.

Table 5.2 The Distance Errors of Localization Algorithms in Laboratory Environment

	KNN	Probability-Based	Kalman Filter Over Probability-Based
Min (cm)	6.64	0	6.02
Max (cm)	1809.87	1602.53	1456.09
Average (cm)	379.46	337.20	332.96
Median (cm)	231.31	199.92	205.99
75 Percentile (cm)	510.56	435.49	420.68
80 Percentile (cm)	609.24	534.56	508.64
SD (cm)	201.40	178.31	158.24

Comparing to lateration, the accuracy of these methods is significantly improved. As shown in Table 5.2 , it is possible to obtain the average distance error less than 3.8m. In addition, the Probability-based and Kalman filter over Probability-based methods produce a better accuracy (lower average distance errors) and are more stable (smaller standard deviation) than KNN. Comparing to KNN, it can be seen that the average error of the probabilistic method are improved about 11.12% (from 3.79m to 3.37m). Similarly, the average accuracy of Kalman filter over Probability-based method is also better than KNN about 14.89% (3.79m and 3.33m, respectively). Equally important, as shown in Fig. 5.7, the 80th percentile of distance errors is reduced from 6m (KNN) to about 5m (other methods).

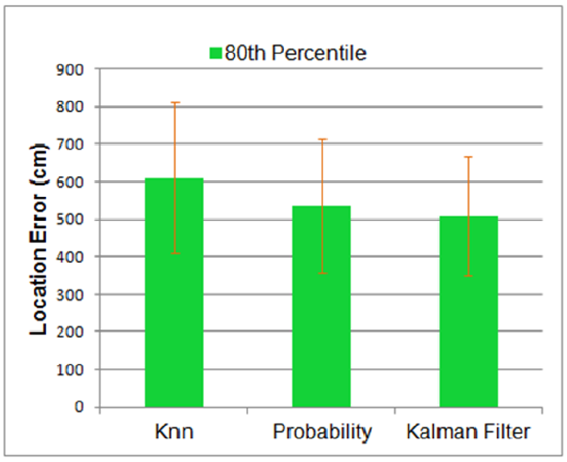


Fig. 5.7 The Distance Errors of Localization Algorithms With IPN Testbed

5.6.6 Evaluating the Localization Methods with the Testbed in industrial Environment

To evaluate the performance of the implemented location algorithms in a real critical industrial environment, we installed a testbed in a recovery boiler for power production building, located in Soporcel paper mill [188]. With this testbed, we did numerous experiments with different configurations and objectives. The Table 5.3 and Fig. 5.8 present the results of experiments with a testbed comprising 11 readers installed on 3 floors (4, 5, and 6) of this building.

Table 5.3 The Distance Errors of Localization Algorithms with the Testbed installed at Soporcel Paper Mill

	KNN	Probability-Based	Kalman Filter Over Probability-Based
Min (cm)	1.58	0	0
ax (cm)	2049.18	1968.72	1904.23
Average (cm)	449.15	431.98	434.31
Median (cm)	187.04	122.47	338.88
75 Percentile (cm)	753.27	755.99	718.63
80 Percentile (cm)	861.91	867.43	806.71
SD (cm)	251.77	257.45	225.51

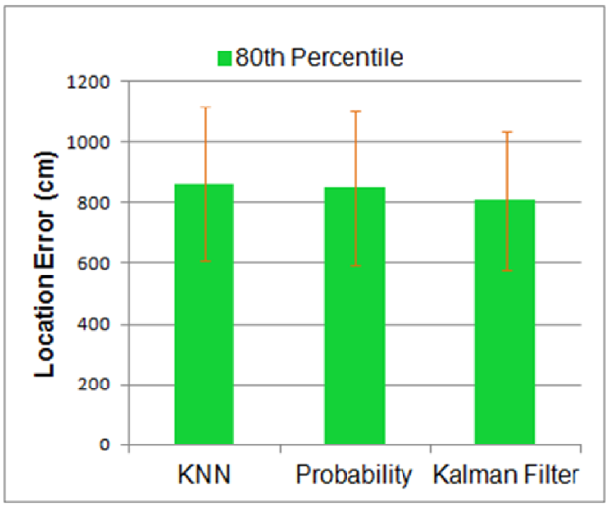


Fig. 5.8 The Distance Errors of the Localization Algorithms at Soporcel

Comparing with the results of the experiments done at the IPN building, it can be seen that the accuracy in this environment is significantly reduced. In particular, the average distance error of KNN is increased from 3.79m to 4.49m (15.52%) and those of Probability-based and Kalman Filter over Probability-based methods are increased from 3.37m to 4.32m (21.94%) and from 3.23m to 4.34m (25.64%), respectively. There are several possible explanations for this result. First, the second testbed was installed on a very noisy environment with a lot of motors, pumps, and other machineries. In addition, the obstacle and the heating from the recovery boiler may also affect the stability of RSSI and thus the accuracy of the location estimate. Moreover, the position of the readers is also a factor that influences the performance of the location system.

It is also important to note that when compared to KNN, in terms of location estimate accuracy, the performance of the other two methods is also a little bit better. However, the differences are not as substantial as those obtained in the first testbed.

With the collected data, we also analyze the accuracy of the location system at different areas in the real environment. The objective of this study is to find out the positions that had good accuracy and why they are better than the others. In this study, the floors 4, 5, and 6 are divided into 9, 7, 7 subzones, respectively. From the results of the experiments, we find out that among these 23 subzones, 9 of them (39.13%) have the average distance errors less than 2.23 meters with 80th percentile of errors are less than 4.4 meters. Table 5.4 and Fig. 5.9 describe the location errors of these subzones.

By observing the locations of these best subzones, we recognize that all of them are located in the boundaries of at least three readers. In addition, the communication between the readers and the tag in these subzones is rather clear. This is not necessarily a line of sight communication, but the obstacles between the reader and tag are not too big. Moreover, the distance between the readers also contributes to the accuracy, as in these best subzones the distance between readers is about 15 meters.

Table 5.4 The Distance Errors of Best Subzones at Soporcel Testbed

subzone	1	2	3	4	5	6	7	8	9
Min	0	0	0	0	0	0	0	0	0
Average	207.50	116.42	41.76	131.65	202.31	222.56	143.10	218.10	193.89
median	17.98	19.60	0	16.90	19.07	45.91	5.85	16.31	28.51
75 Percentile	145.92	41.71	14.00	94.00	339.80	319.22	181.71	341.56	345.62
80 percentile	425.77	50.26	73.80	359.87	411.26	424.28	424.57	440.51	432.72
90 percentile	604.74	592.80	146.94	480.17	504.97	521.33	526.69	587.88	601.33
Max	1066.47	812.10	958.29	928.78	1037.63	1052.33	1094.45	1088.58	923.15
Std, Dev	178.94	113.38	75.05	109.16	134.63	139.10	122.36	179.87	143.52

Unit: cm

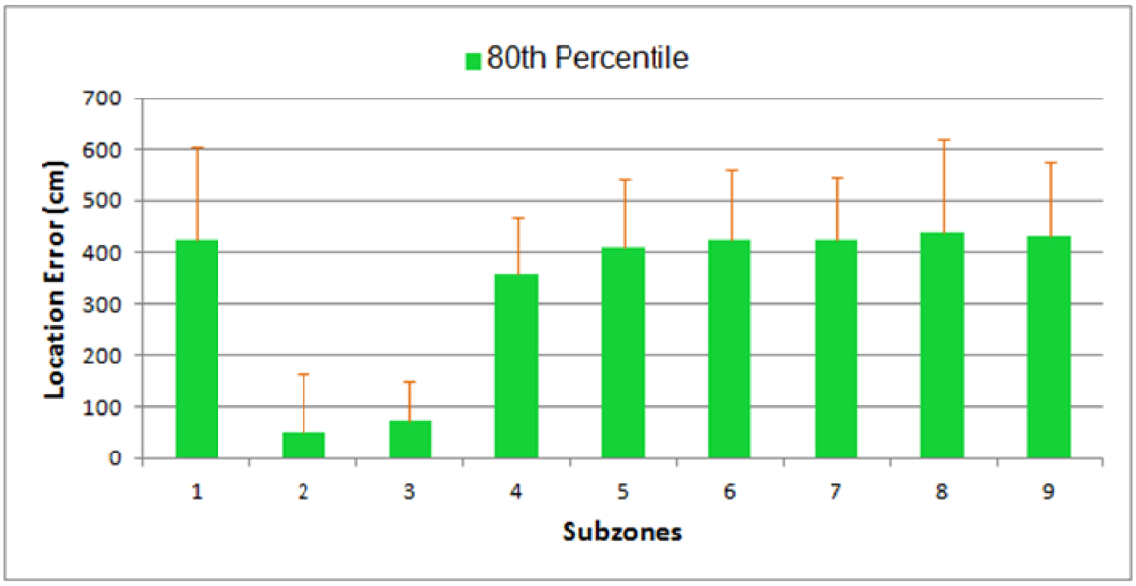


Fig. 5.9 The Distance Errors of the Best Subzones at Soporcel

The implication of this study allows us to design and deploy a location system with different levels of accuracy for different zones. For instance, we should deploy more readers for the high critical zones and fewer readers for other less important zones.

From the results of our experiments and those of other authors, e.g., [151], we can conclude that by using only RSSI values we cannot make more improvement on the accuracy of localization than those obtained in our experiments. The fundamental problem is not from the localization algorithms but from measurements, i.e., instability of the RSSI values. However, the accuracy and precision provided by KNN, probability-based (Bayesian theory) and Kalman Filter over Probability-based localization methods, are sufficient for many real world applications.

5.7 Summary

In this chapter, we present our model for localization system that can be applied for large-scale sensor networks. The localization engine implements numerous localization methods. We also did several experiments with two testbeds, one in the normal environment, and the other in a critical industrial environment, to evaluate the accuracy of the implemented localization methods.

The results from experiments show that RSSI values are unstable with high variance. As a result, lateration is not good in terms of accuracy when using RSSI values as the only measurement. On the other hand, pattern matching based methods such as KNN, probability-based and Kalman Filter over Probability-based produce a sufficient accuracy for many application scenarios. With these methods, it is possible to achieve a mean error less than 4m and 80th percent of errors is less than 6m. More important, by carefully engineering the positions of readers, it is possible to obtain an average distance error of about 2.2m.

6 Conclusion and Future work

Summary

WSNs have been being deployed for the real industrial environments, especially critical ones such as refineries, industrial plants (e.g., chemical processes, paper mills), and mining. Developers of WSNs for such environments face numerous challenges in designing, developing, deploying, and maintaining such as energy efficient protocols, reliable communication, localization, and integration. This thesis aims at creating the infrastructure for facilitating the development, deployment, and maintenance of WSNs in critical environments. In particular, it deals with the reliable communication, integration, and localization problems of sensor networks. The work in this thesis consists of three main separated but closely related topics. The first topic is about reliability in communication at low level of the network protocol stack, i.e., MAC layer. The second one targets at the infrastructure for interoperability between physical and digital worlds. Especially, it focuses on the adaptability issue for the diversity and heterogeneity of sensors and sensor systems. The final topic is about the supporting service for locating the unknown position nodes in controlled WSNs. This chapter summarizes the work done in this thesis, its main results and some future work.

6.1 Conclusion

The aim of the work in this thesis is to facilitate the development, deployment, and maintenance of WSNs in critical and industrial environments. To achieve this, the proposed solutions focused on three important areas of the WSNs: reliability, integration, and localization. The proposed solutions were implemented and evaluated using real testbeds installed in different environments. The following paragraphs summarize the work done in the context of this thesis.

The first issue of concern was to study the characteristics of different channels of IEEE 802.15.4 compliant sensor networks. The motivation of this work was from the problem we encountered when deploying the WSNs at Galp Energias refinery, Portugal. During the deployment of WSNs, we found that this hazardous and noisy environment greatly influenced our networks performance, e.g., when operating on a default channel (channel 26), the sensor network sometimes stopped working. This issue brought to our attention several questions: do the channels of IEEE 802.15.4 compliant sensor networks have the same quality? How are they affected by factors such as interference and noise? What is the quality of channels like in different environments? In order to answer these questions, numerous empirical experiments were done with the testbeds in different environments. The results showed that the quality of channels of IEEE 802.15.4 based sensor networks is different from place to place and it varies from time to time. From these studies we also recognized that interference, from other wireless networks, has significantly impacted on the performance of the communication channels. Equally important, it is clear from the study at the oil refinery that noises from machineries, pumps, etc., severely affects the quality of the radio channels. Consequently, it is very difficult or even impossible to predict the quality of different channels of IEEE 802.15.4 based sensor networks deployed in a specific environment without an experimental study.

As noise and interference have severe impacts on the performance of WSNs and they are present almost everywhere, it is necessary to have a mechanism for WSNs to continue working in such environments. This means that the sensor networks can work well in the environments in which there are other wireless networks and noise sources. This problem is referred to as the coexistence problem and the potential mechanism to deal with it is called cognitive radio (CR). However, fully employing CR for WSN may be difficult or inefficient. In order to allow WSNs to reliably operate in noisy and interference environments, we propose a MAC protocol named Dynamic MAC (DynMAC). This MAC protocol is based on CR principles to allow the network to dynamically select the best channel during its operation time. The best channel is selected by the cooperating between nodes in the networks. In addition, it also employs some mechanisms to improve the resilience and reliability of the network including packet loss rate monitoring, loss link detection, and channel rescanning.

A prototype of DynMAC based on the GinMAC [69] has been implemented. The current version of DynMAC was evaluated on both simulations, i.e., COOJA [172], and real testbed. The results from the testbed showed that it is very fast to establish the network during the boot time. In addition, the normal nodes can easily and quickly scan the channel of the network and join it. Moreover, the network can also switch to a better channel if the current channel becomes worse for some reason, e.g., a new installed wireless network interferes with the sensor network. Furthermore, the nodes in a DynMAC-based WSN can detect loss link and reestablish the connection.

Another relevant point is that the sensed data from the sensor networks need to be processed, presented and visualized by suitable tools to make them meaningful. To facilitate the interoperation between WSNs and external environments, we propose a proxy and gateway–based integration framework. In this framework, the data and functionalities of the WSNs are exposed using REST-based web services. This model allows sensed data to be easily accessed from the Internet, and to be able to be mashed up with web environments. More important, STDL language proposed in this thesis helps the integration framework adaptable with diversity and heterogeneity of sensor networks. The data frames in sensor network are described using STDL in order for the proxy to extract the needed information. Consequently, the framework can be used for any sensor networks if the structure of the frames are known and described by using STDL. A prototype of this framework was implemented and evaluated with sensor networks that run the contikiOS [95], TinyOS [94] and SimplicitI [193]. In addition, its interoperability was also tested by integrating WSNs with FaceBook [181] and SecondLife [182].

It is worth noting that locating mobile bodies, e.g., workers, patients, children, etc, has many potential applications, especially in critical and industrial environments. The position information helps to monitor the workers working in hazard environments. In this thesis, localization system with multiple algorithms was implemented. In addition, mechanisms for the localization system to be able to apply for large-scale sensor networks were proposed. Several experiments were done with two testbeds, one in the normal environment, and the other in a critical industrial environment, to evaluate the accuracy of the implemented localization methods. The experimental results showed that although the RSSI values are unstable, the learning based localization methods can produce a sufficient accuracy for many application scenarios.

6.2 Future Work

This thesis has achieved some interesting results; however, there are still aspects that need further investigation. The first one is the limitation of the DynMAC protocol. Currently, its implementation is based on GinMAC [69]. This means that it has the same scalability problem of GinMAC i.e., 25 nodes per tree. In addition, the experiments were only done in the laboratory. As a future work, it is necessary to do experiments with DynMAC in different environments to evaluate its performance as well as the ability to adapt to different environments or conditions. In addition, it is useful to improve the scalability when applying the mechanism used in DynMAC principles to other MAC such as X-MAC or T-MAC.

Concerning the STDL, we need to investigate the formats of the data frame from other sensor systems and operating systems for sensor networks to test its adaptable capability. This help to find out the limitation of STDL and to improve it.

Another limitation is that the localization system is only tested on the testbeds with maximum three zones and 16 anchors. It is important to test the positioning system with a larger testbed. As a future work, we will develop a simulation system to evaluate the scalability of the localization system. This simulation will help to estimate the appropriate hardware configuration for real application environments.

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APPENDIX A: STDL Grammar

A.1 The syntax of the STDL in Extended Backus-Naur Form (EBNF)

frames ="<frames>" frame {frame} "</frame>"
frame = "<frame " frameAttributes ">" frameDescription "</frame>"

frameAttributes= idAtrr nameAtrr typeAtrr subtypeAtrr lengthAtrr lengthPositionAtrr
idAtrr = "id" "=" nonNegativeInteger
nameAtrr = "name" "=" identifier
typeAtrr = "type" "=" nonNegativeInteger
subtypeAtrr = "subtype" "=" nonNegativeInteger
lengthAtrr = "length" "=" nonNegativeInteger
lengthPositionAtrr = "lengthPosition" "=" nonNegativeInteger

frameDescription = header content
header = "<header>" frameHeader "</header>"
frameHeader = startOfFrame typeField lengthField subtypeField sender destination gateway startOfFrame = "<startOfFrame" numberOfBitAttr ">" binaryOrHexa "</startOfFrame>"
typeField = fieldPosition
lengthField = fieldPosition
subtypeField = fieldPosition
sender = fieldPosition
destination = fieldPosition
gateway = fieldPosition

content = "<content>" frameContent "</content>"
frameContent = simpleFrame | dataTable | complexFrame

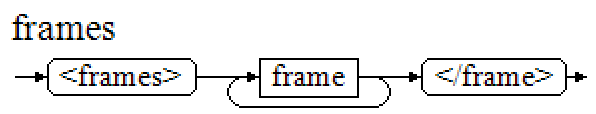
simpleFrame = "<simpleFrame>" field {field} "</simpleFrame>"

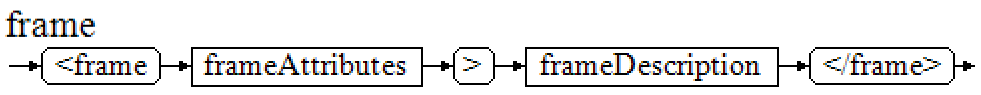
dataTable = "<dataTable>" nonRepeatedField repeatedField "</dataTable>"

```
nonRepeatedField = "<nonRepeatedField>" [dataLength]
                                     startPositionOfData {field} "</nonRepeatedField>"
repeatedField = "<repeatedField>" field {field} "</repeatedField>"
dataLength = field
startPositionOfData = field

complexFrame = "<complexFrame>" subframe Description "</complexFrame>"
subframe = "<subframe" "frameId " "="   nonNegativeInteger "/>"
Description =  "<Description>" {field} "</Description>"

field = field_nameAttr unitAttr fieldPosition
field_nameAttr = "field_name" "=" identifier
unitAttr = "unit" "=" string
fieldPosition = dataTypeAttr startPositionAttr numberOfBitAttr byte_orderAttr
dataTypeAttr = "dataType" "=" fieldDataType
startPositionAttr = "start_position" "=" nonNegativeInteger
numberOfBitAttr =  "number_of_bit" "=" nonNegativeInteger
byteOrderAttr = "byte_order" "=" byteOrder

identifier = (lowerLetter | upperLetter ) {lowerLetter | upperLetter | digit | "_"}
nonNegativeInteger = "0" | nonZeroDigit {digit}
digit =  "0" | nonZeroDigit
nonZeroDigit =   "1" | "2" | "3" | "4" | "5" | "6" | "7" | "8" | "9"
fieldDataType = "uint8" | "int8" |  "uint16" | "int16" | "uint32" | "int32" | "ulong" | "long"   |
"string"
binaryOrHexa = binaryNumber | hexaDecimalList
binaryNumber = ("0" | "1") {"0" | "1" }
hexaDecimalList = hexaDecimal {hexaDecimal}
hexaDecimal = "0x" (digit | "A" | "B" | "C" | "D" | "E" | "F" | "a"|"b"|"c"|"d"|"e"|"f" ) {2}
byteOrder = "little_endian" | "big_endian"
string = { lowerLetter | upperLetter | digit | “%” }
letter = lowerletter | upperLetter
lowerletter = "a" | "b" | “…” | "z"
upperLetter =  "A" | "B" | "…" | "Z"
```

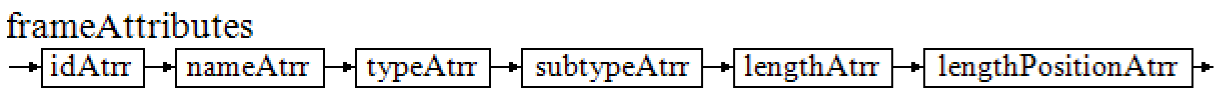
A.2 The syntax graphs of the STDL.

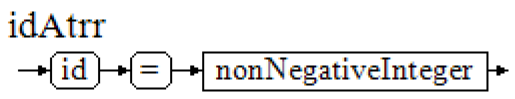
A.2.1 Frame Structure

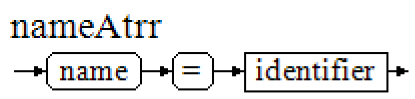


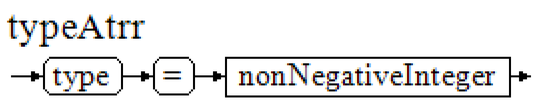


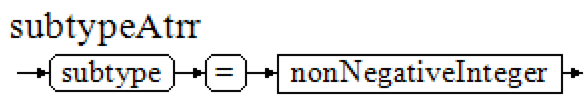
A.2.2 Frame Attributes

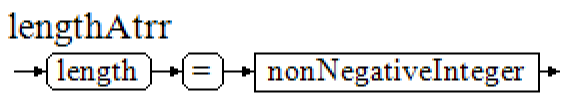


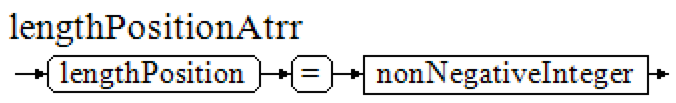




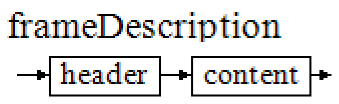


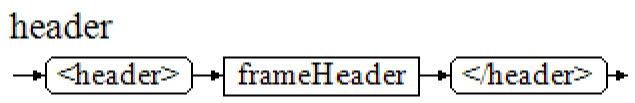


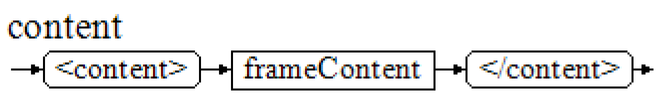




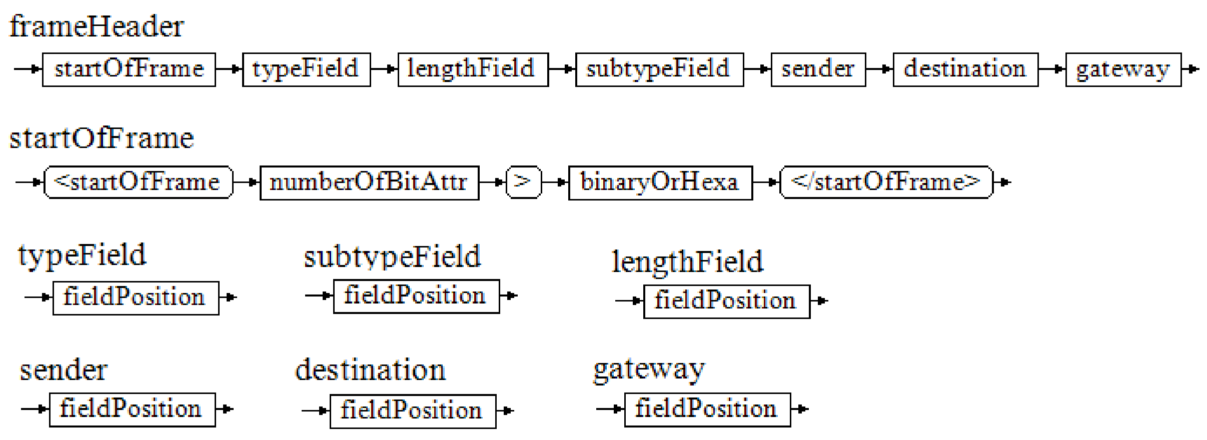
A.2.3 Frame Description



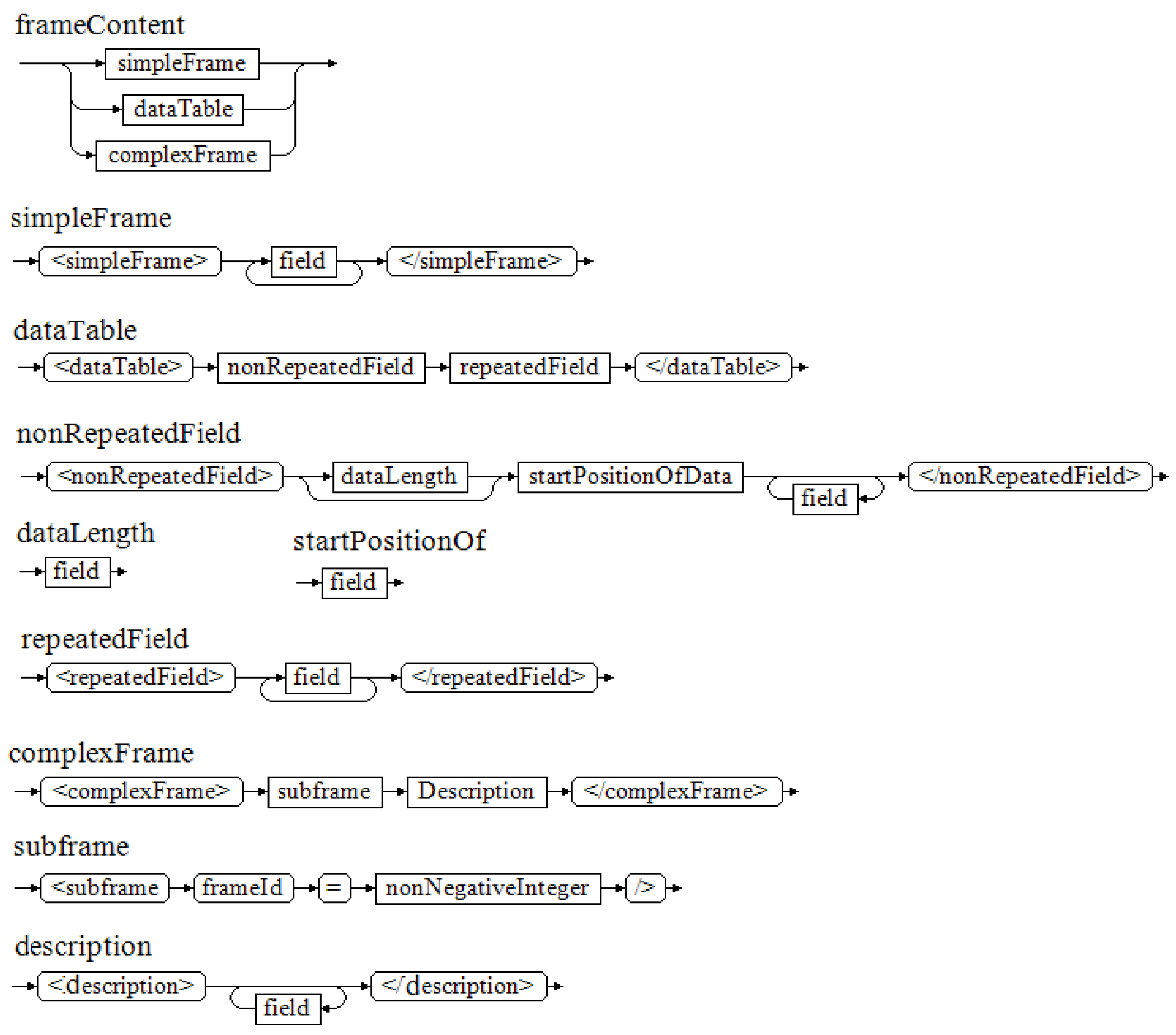




A.2.3.1 Frame Header Description

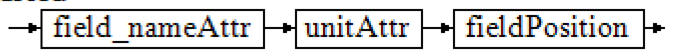


A.2.3.2 Frame Content Description

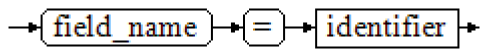


A.2.4 Data Type

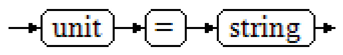
field



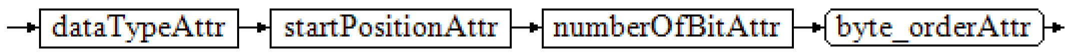
field_nameAttr



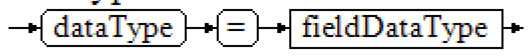
unitAttr



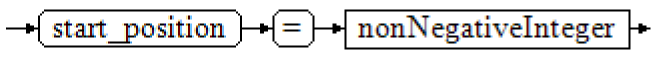
fieldPosition



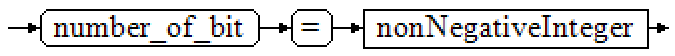
dataTypeAttr



startPositionAttr



numberOfBitAttr



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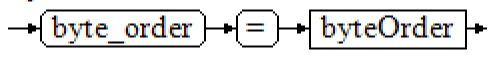

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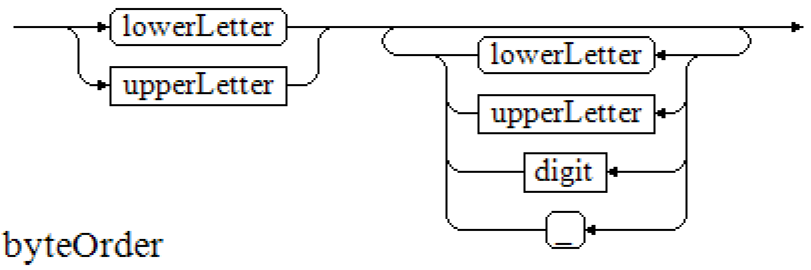

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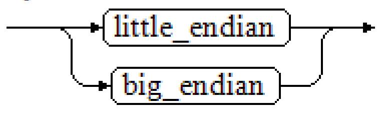

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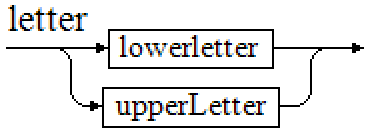

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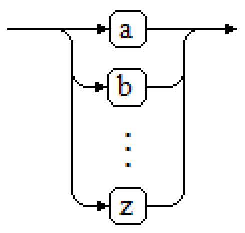

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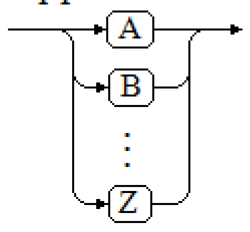

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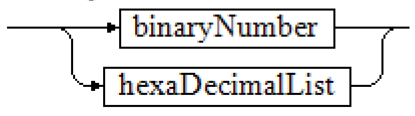

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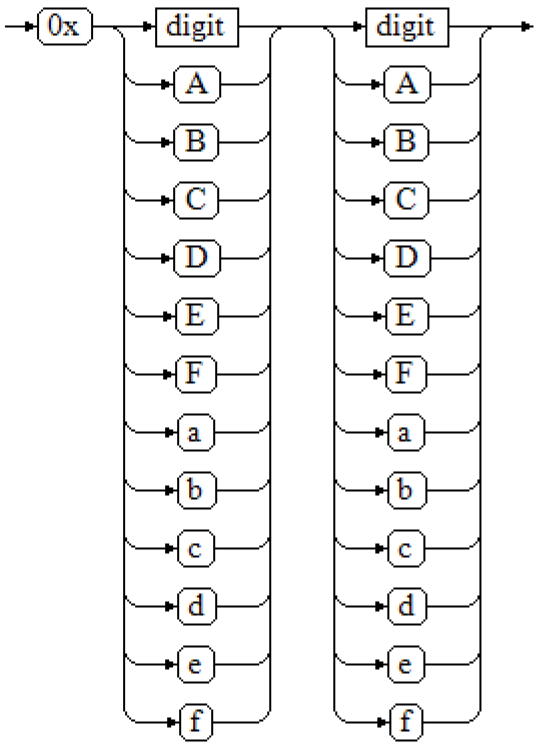

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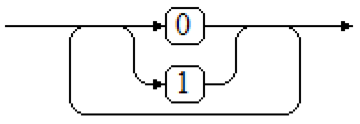

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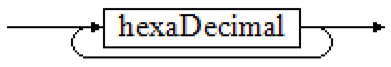

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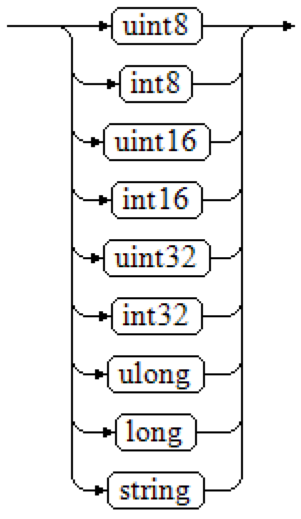

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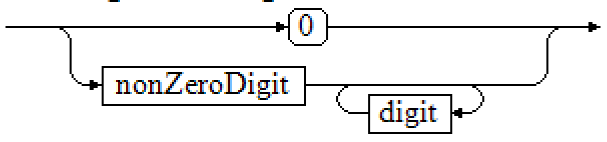

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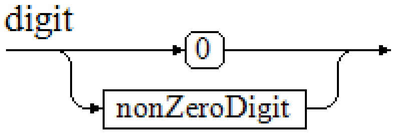

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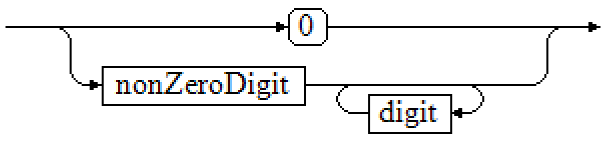
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