Ecole Doctorale EDITE

Thèse présentée pour l'obtention du diplôme de
Docteur de Télécom & Management SudParis

Doctorat conjoint Télécom & Management SudParis et Université Pierre et Marie Curie

Spécialité :
Informatique

Localisation en Intérieur et Gestion de la Mobilité dans les Réseaux Sans Fils Hétérogènes Emergents

Par
Apostolia Papapostolou

Soutenue le 31 janvier 2011 à TSP devant le jury composé de :

Mr. André Luc BEYLOT	**Professeur à l'université INPT Toulouse**	**Rapporteur**
Mr. David SIMPLOT	**Professeur à l'Université de Lille1**	**Rapporteur**
Mr. Jean Marie BONNIN	**Professeur à Telecom Bretagne**	**Examinateur**
Mr. Marcelo DIAS DE AMORIM	**Chargé de Recherche CNRS**	**Examinateur**
Mr. Mischa DOHLER	**Directeur de Recherche CTTC Barcelone**	**Examinateur**
Mr. Sébastien TIXEUIL	**Professeur à l'UPMC**	**Examinateur**
Mme Hakima CHAOUCHI	**Maître de Conférence-HDR TSP**	**Directeur de thèse**

Thèse n° 2011TELE0003

Thèse de Doctorat
Télécom & Management SudParis et l'université Pierre et Marie Curie (Paris VI)

Spécialité

Systèmes Informatiques

présentée par

Mlle. Apostolia Papapostolou

pour obtenir le grade de

Docteur
conjoint de Télécom & Management SudParis et l'université Pierre et Marie Curie

Localisation en Intérieur et Gestion de la Mobilité dans les Réseaux Sans Fils Hétérogènes Émergents

Soutenance prévue le 31 janvier 2011 devant le jury composé de

Jury

André Luc BEYLOT	**Rapporteur**	**Prof. à l'université INPT Toulouse**
David SIMPLOT-RYL	**Rapporteur**	**Directeur de Recherche Université Lille1**
Mischa DOHLER	**Examinateur**	**Directeur de recherche CTTC Barcelone**
Sébastien TIXEUIL	**Président du jury**	**Prof. à l'université Pierre et Marie Curie**
Marcelo DIAS DE AMORIM	**Examinateur**	**Chargé de Recherche CNRS**
Jean Marie BONNIN	**Examinateur**	**Prof. à Telecom Bretagne**
Hakima CHAOUCHI	**Directrice**	**Maître de Conférence à Telecom Sudparis**

Thèse de Doctorat
Télécom & Management SudParis et
l'université Pierre et Marie Curie (Paris VI)

Spécialité

SYSTÈMES INFORMATIQUES

présentée par

Mlle. Apostolia PAPAPOSTOLOU

pour obtenir le grade de

DOCTEUR
conjoint de Télécom & Management SudParis et l'université Pierre et Marie Curie

Localisation en Intérieur et Gestion de la Mobilité dans les Réseaux Sans Fils Hétérogènes Émergents

Soutenance prévue le 31 janvier 2011 devant le jury composé de

Jury

André Luc BEYLOT	**Rapporteur**	**Prof. à l'université INPT Toulouse**
David SIMPLOT-RYL	**Rapporteur**	**Directeur de Recherche Université Lille1**
Mischa DOHLER	**Examinateur**	**Directeur de recherche CTTC Barcelone**
Sébastien TIXEUIL	**Président du jury**	**Prof. à l'université Pierre et Marie Curie**
Marcelo DIAS DE AMORIM	**Examinateur**	**Chargé de Recherche CNRS**
Jean Marie BONNIN	**Examinateur**	**Prof. à Telecom Bretagne**
Hakima CHAOUCHI	**Directrice**	**Maître de Conférence à Telecom Sudparis**

Doctor of Science Thesis
Telecom & Management SudParis and
Pierre & Marie Curie University (Paris VI)

Specialization

COMPUTER SCIENCE

presented by

Miss Apostolia PAPAPOSTOLOU

Submitted in partial satisfaction of the requirements for the degree of

DOCTOR OF SCIENCE
Telecom & Management SudParis and Pierre & Marie Curie University

Indoor Localization and Mobility Management in the Emerging Heterogeneous Wireless Networks

Commitee in charge:

André Luc BEYLOT	**Reviewer**	**Prof. at INPT Toulouse**
David SIMPLOT-RYL	**Reviewer**	**University Lille1 Research Director**
Mischa DOHLER	**Examinator**	**CTTC Barcelone Research Director**
Sébastien TIXEUIL	**President**	**Prof. at Pierre and Marie Curie University**
Marcelo DIAS DE AMORIM	**Examinator**	**CNRS Researcher**
Jean Marie BONNIN	**Examinateur**	**Prof. at Telecom Bretagne**
Hakima CHAOUCHI	**Advisor**	**Lecturer at Telecom Sudparis**

To my parents.

Résumé

Au cours de ces dernières décennies, nous avons été témoins d'une évolution considérable dans l'informatique mobile, réseaux sans fil et des appareils portatifs. Dans les réseaux de communication à venir, les utilisateurs devraient être encore plus mobiles exigeant une connectivité omniprésente à différentes applications qui seront de préférence au courant de leur contexte. Certes, les informations de localisation dans le cadre de leur contexte est d'une importance primordiale à la fois la demande et les perspectives du réseau. De point de vu de l'application ou l'utilisateur, la provision de services peuvent mettre à jour si l'adaptation au contexte de l'utilisateur est activée. Du point de vue du réseau, des fonctionnalités telles que le routage, la gestion de handoff, l'allocation des ressources et d'autres peuvent également bénéficier si l'emplacement de l'utilisateur peuvent être suivis ou même prédit.

Dans ce contexte, nous nous concentrons notre attention sur la localisation à l'intérieur et de la prévision de handoff qui sont des composants indispensables à la réussite ultime de l'ère de la communication omniprésente envisagé. Alors que les systèmes de positionnement en plein air ont déjà prouvé leur potentiel dans un large éventail d'applications commerciales, le chemin vers un système de localisation réussi à l'intérieur est reconnu pour être beaucoup plus difficile, principalement en raison des caractéristiques difficiles liées à l'intérieur et l'exigence d'une plus grande précision. De même, la gestion de handoff dans des réseaux hétérogènes sans fil de futur est beaucoup plus difficile que dans les réseaux traditionnels homogènes. La procédure de handoff doit être transparente pour satisfaire la qualité de service requise par les applications de futur et leurs fonctionnalités, cela ne doit pas dépendre de la caractéristique de l'opération des technologies différentes. En outre, les décisions de handoff devraient être suffisamment souples pour tenir compte aux préférences des utilisateurs d'un large éventail de critères proposés par toutes les technologies.

L'objectif principal de cette thèse est de mettre au point précis, le temps et l'emplacement de puissance efficaces et la gestion de handoff afin de mieux satisfaire les applications sensible des utilisateurs en dépendent au contexte dans lequel les utilisateur se trouvent. Pour obtenir une localisation à l'intérieur, le potentiel de réseau sans fil local (WLAN) et Radio Frequency Identification (RFID) comme une technologie autonome pour détection de location sont d'abord ont été étudiés par des expérimentations de plusieurs algorithmes et paramètres dans des plateformes réels ou par de nombreuses simulations, alors que leurs lacunes ont également été identifiés. Leur intégration dans une architecture commune est alors proposée afin de combiner leurs principaux avantages et surmonter leurs limitations. La supériorité des performances du système de synergie a été validée par des analyses profondes sur leur performance si elles fonctionnent d'une manière automne (sans intégration). En ce qui concerne la tâche de gestion de handoff, nous identifions que la sensibilité au contexte peut aussi améliorer la fonctionnalité du réseau. En conséquence, deux types de systèmes qui utilisent l'information obtenue à partir des systèmes de localisation one été proposées. Le premier schéma repose sur un déploiement tag RFID, comme notre architecture de positionnement RFID, et en suivant la scène WLAN analyse du concept de positionnement, prédit l'emplacement réseau de la prochaine couche, c'est à dire le prochain point de fixation sur le réseau. La deuxième méthode repose sur une approche intégrée RFID et réseaux de capteurs / actionneur Network (WSAN) de déploiement pour la localisation physique des utilisateurs et par la suite pour prédire leur prochaine point de handoff aux niveaux des couches de liaison et le réseau. Etre indépendant de la technologie d'accès sans fil sous-jacent, les deux régimes peuvent être facilement mises en oeuvre dans des réseaux hétérogènes.

L'évaluation de la performance démontre les avantages de nos méthodes proposées par rapport aux protocoles standards concernant l'exactitude de prévision, le temps de latence et l'économie d' énergie. Les mots clés : mobilité, localisation, gestion de handoff, communication des réseaux sans fil, architecture des réseaux hétérogènes, analyse de performance, WLAN, RFID, WSAN.

Mots-clés :

localisation, mobilité, gestion de la handoff, communications sans fil, hétérogénéité, conception d'architecture réseau, analyse de performance, WLAN, RFID, WSAN.

Abstract

Over the last few decades, we have been witnessing a tremendous evolution in mobile computing, wireless networking and hand-held devices. In the future communication networks, users are anticipated to become even more mobile demanding for ubiquitous connectivity to different applications which will be preferably aware of their context. Admittedly, location information as part of their context is of paramount importance from both application and network perspectives. From application or user point of view, service provision can upgrade if adaptation to the user's context is enabled. From network point of view, functionalities such as routing, handoff management, resource allocation and others can also benefit if user's location can be tracked or even predicted.

Within this context, we focus our attention on indoor localization and handoff prediction which are indispensable components towards the ultimate success of the envisioned pervasive communication era. While outdoor positioning systems have already proven their potential in a wide range of commercial applications, the path towards a successful indoor location system is recognized to be much more difficult, mainly due to the harsh indoor characteristics and requirement for higher accuracy. Similarly, handoff management in the future heterogeneous wireless networks is much more challenging than in traditional homogeneous networks. Handoff schemes must be seamless for meeting strict Quality of Service (QoS) requirements of the future applications and functional despite the diversity of operation features of the different technologies. In addition, handoff decisions should be flexible enough to accommodate user preferences from a wide range of criteria offered by all technologies.

The main objective of this thesis is to devise accurate, time and power efficient location and handoff management systems in order to satisfy better context-aware and mobile applications. For indoor localization, the potential of Wireless Local Area Network (WLAN) and Radio Frequency Identification (RFID) technologies as standalone location sensing technologies are first studied by testing several algorithms and metrics in a real experimental testbed or by extensive simulations, while their shortcomings are also identified. Their integration in a common architecture is then proposed in order to combine their key benefits and overcome their limitations. The performance superiority of the synergetic system over the stand alone counterparts is validated via extensive analysis.

Regarding the handoff management task, we pinpoint that context awareness can also enhance the network functionality. Consequently, two such schemes which utilize information obtained from localization systems are proposed. The first scheme relies on a RFID tag deployment, alike our RFID positioning architecture, and by following the WLAN scene analysis positioning concept, predicts the next network layer location, i.e. the next point of attachment to the network. The second scheme relies on an integrated RFID and Wireless Sensor/Actuator Network (WSAN) deployment for tracking the users' physical location and subsequently for predicting next their handoff point at both link and network layers. Being independent of the underlying principle wireless access technology, both schemes can be easily implemented in heterogenous networks. Performance evaluation results demonstrate the advantages of the proposed schemes over the standard protocols regarding prediction accuracy, time latency and energy savings.

Key Words:

localization, mobility, handoff management, wireless communications, heterogeneity, network architecture design, performance analysis, WLAN, RFID, WSAN.

Table of contents

Chapter 1

Introduction

With the rapid growth of wireless communication and networking technologies, the great advances in mobile computing and handheld devices, and the overwhelming success of Internet, a revolutionary pervasive and mobile communication era is emerging as the natural successor of current mobile communication systems. The goal of this pervasive or ubiquitous computing vision is to create ambient intelligence with core concept the interaction between human with its environment and ultimate goal the enhancement of the user experience from the network. To that aim, an increasingly large numbers of everyday objects scattered throughout the surrounding environment will become smart by having some kind of simple computation and communication technology embedded into them, which will allow them to be connected to each other within local networks and, ultimately, connected to the Internet. Users will become even more mobile demanding to experience unobtrusive connectivity and ubiquitous access to different applications anywhere, anytime, by using the best technology from a plethora of interfaces available at the future multi-mode mobile terminals, and without the need for explicit awareness of the underlying communication and computing technology.

For the realization of such ubiquitous environments, location awareness and efficient mobility, in terms of handoff, management are two core concepts. Furthermore, a strong correlation exists between them. The continuous need for determining the unknown location of an entity stems from its mobility capability. Simultaneously, dealing with issues raised due to mobility can benefit if location information is available. This thesis targets at improving both the localization and handoff processes and proposes taking advantage of the availability of several wireless technologies for tackling more effectively the objectives of future communication networks. In the following, the main objectives, challenges and our approaches for achieving that goal are described.

1.1 Objectives and Challenges

Indoor location information is valuable for facilitating the interaction between a user and its environment and consequently the development of location based services (LBS) or more generally speaking context-aware applications where location is a key element of the user's context. Such applications adapt their functionality depending on the user's context and they span from applications in users' everyday life, working environment, commercial and industrial sectors to functions which aim at the performance enhancement of the wireless network functionality. Some typical examples of location-aided applications are:

≤ **Ambient Assisted Living:** Accurate positioning information is critical for the success of the Ambient Assisted Living (AAL) project [1] which aims at enhancing the everyday life of elderly users and people suffering from disabilities, through the use of Information and Communication Technologies (ICT).

≤ **Person and Asset Tracking:** Tracking of people inside buildings is critical in emergency situations such as fires, earthquakes, or other disasters. Moreover, indoor location systems are useful in hospitals for tracking staff members at any time without their intervention, in museums or schools for keeping track of children location [2].

Tracking of objects or assets is useful for finding the whereabouts of hospital equipment in a hospital, finding books inside a library or products inside a warehouse. The location of various physical resources such as printers, projects, and copiers also enables resource discovery applications [3].

≤ **Navigation:** Indoor location information can be used to build navigating tools in unfamiliar buildings [4], such as airports, train stations, museums, campuses, commercial department stores or big office buildings.

≤ **Location-Based Advertising and Social Networking:** Location methods can be used for selective and targeted advertising [5] and for providing product information inside retail stores [6].

On the other hand, location based social networking may further enhance the Internet based social networking services such as Facebook, Friendsters, MySpace, etc. by allowing users forming groups based on their social preference and interest.

≤ **Network performance improvement** User location information can be also exploited to enhance the functionality and the QoS in wireless networks. Such methods have been proposed for location-based access control [7], location-based handoff and in ad hoc networks in order to optimize routing algorithms and network self configuration [8]. One step further, combining positioning data with user profiles could significantly facilitate network planning, load balancing, caching of information closer to the user, radio resource management and design of other performance enhancement methods [9].

For the success of the above applications, the design of an accurate and reliable location determination system is essential. Wireless localization, i.e. location estimation by using radio signals (RS), has attracted considerable attention in the fields of telecommunication and navigation. The most well known positioning system is the Global Positioning System (GPS) [10], which is satellite-based and is successful for tracking users in outdoor environments. However, the inability of satellite signals to penetrate buildings cause the complete failure of GPS in indoor environments. For indoor location sensing a number of alternative wireless technologies have been proposed, such as infrared (IR), ultrasound, Wireless LAN (WLAN), UltraWideBand (UWB), Radio Frequency Identification (RFID), Bluetooth, wireless sensor networks (WSNs) [11]. However, the indoor radio propagation channel is characterized as site specific, exhibiting severe multipath effects and low probability of line-of-sight (LOS) signal propagation between the transmitter and receiver [12], making accurate indoor positioning very challenging. Moreover, compared to outdoor systems, determining the location of a user or device inside a building is much more difficult not only due to its harsh nature but also due to the requirement of indoor services for higher and more precise accuracy.

Handoff management is the process for keeping active the connection of the mobile user while changing its point of attachment to the network due to mobility. In the future pervasive networks, several heterogeneous wireless technologies will be available and users will demand ubiquitous access and ”always best” connectivity to a wide range of applications while on the move. For the harmonized integration of these different technologies under a common framework, the design of intelligent mobility management schemes is required in order to enable mobile users to experience uninterrupted service continuity anywhere, anytime, regardless their underlying access technology. Furthermore, mobility management schemes should be able to satisfy the requirements of emerging applications which are becoming more and more demanding regarding their QoS constraints.

However, the latency during the handoff processes leads to performance degradation. For the case of IEEE 802.11 WLAN wireless access, the handoff process requires from the mobile node to search periodically for better access points to associate with, by scanning all WLAN channels. However this process is power consuming and introduces packet loss, since during scanning the mobile node is not able to be served by its current AP. Mobile IP [13] is a network layer mobility management scheme for IP-based networks. It forwards packets to mobile users that are away from their home networks using IP-in-IP tunnels. Mobile IP handoff is composed of a sequence of stages, one of which includes the detection of a mobile node's movement to the new network. However, when the mobile node undergoes movement detection, it is unable to receive IP packets, resulting in further performance degradation.

1.2 Thesis Overview

Admittedly, location awareness of users and objects or devices in an indoor environment and their mobility management across heterogeneous networks are considered as key milestones towards the realization of future mobile communication networks. Furthermore, the strong correlation between these tasks mandates investigating their aspects in parallel, instead of considering them as two independent processes.

This thesis targets the development of location and mobility management schemes with main design goals:

≤ **Accuracy**. Knowing exactly where someone or something is or moves towards can improve user experience by personalized service delivery and also enhance the network functionality.

≤ **Fast time response**. Emerging applications will be more demanding in terms of QoS requirements, impelling for fast localization and handoff schemes.

≤ **Scalability**. The presence of many users should not degrade the system performance.

≤ **Generic handoff**. The co-existence of heterogeneous networks within which the user can roam, make technology-independent handoffs the most viable solutions.

≤ **Energy-awareness**. Since mobile devices are battery constrained, energy consumption issues should be taken into account as well.

Future communication systems are envisioned to be heterogeneous offering ubiquitous connectivity, whereby mobile users will be surrounded by diverse but complementary technologies capturing their different needs and requirements. Motivated by this observation, exploring possible synergies and interactions among several technologies was our main approach in order to tackle more effectively our goals.

For indoor location sensing, we focused our attention on two wireless technologies; WLAN and RFID. WLANs, such as IEEE 802.11, is considered as a promising one for offering a low-cost and reliable solution due to its availability in most indoor environments and capability for coordinated communication when in infrastructure mode. However, its accuracy is highly affected in the presence of severe multipath and environmental changes. More recently, RFID has emerged as an attractive technology for accurate location sensing due to the low cost of passive tags, the fast reading of multiple tags, the non Line of Sight (LOS) requirement, the less sensitivity in user orientation. However, the main shortcoming of RFID is considered the interference problem among its components, mainly due to the limited capabilities of the passive tags and the inability for direct communication between readers [14]. In order to overcome the limitations of both technologies we proposed an integration architecture for improving the localization performance.

Regarding the mobility management problem, we focused on the handoff component and we explored the potential of two popular pervasive technologies: RFID and WSAN, for providing fast handoff solution in the case of IP-based mobility over a WLAN access network. However, our proposed schemes can be applied for different link and network level mobility scenarios, making them viable solutions in heterogeneous networks.

1.3 Workflow and Contributions

For achieving the goals and objectives of this thesis the succeeding steps were followed in a chronological order:

≤ Initially, we focused on the case of WLAN fingerprinting positioning approach which is considered as the most popular for low-cost indoor localization. Considering both its deterministic and probabilistic variants, we proposed some simple techniques in order to improve the localization accuracy without increasing considerably the complexity and hardware requirements. Reference papers[1] include:

- *C1* A. Papapostolou and H. Chaouchi, *WIFE: Wireless Indoor positioning based on Fingerprint Evaluation*, in Proceeding of the 8th IFIP NETWORKING conference, Aachen, Germany, March 2009 [15].
- *C2* A. Papapostolou and H. Chaouchi, *Orientation - Based Radio Map Extensions for Improving Positioning System Accuracy*, in Proceeding of the 6th ACM International Wireless Communications and Mobile Computing Conference (ACM IWCMC), Leipzig, Germany, June 2009 [16].
- *J1* A. Papapostolou and H. Chaouchi, *Scene Analysis Indoor Positioning Enhancements*, Annals of Telecommunications journal, October 2010 [17].

≤ RFID positioning is considered as another attractive solution for location sensing with higher accuracy than WLAN systems. However, not much attention has been given to the collision problem, as far as positioning is concerned, which is the Achilles' heel of RFID technology. Therefore, we studied extensively the performance of the most popular RFID positioning algorithms in the presence of multiple users. Reference papers include:

- *C3* A. Papapostolou and H. Chaouchi, *Considerations for RFID-based Indoor Simultaneous Tracking*, in Proceedings of the 2nd Joint IFIP Wireless and Mobile Networking Conference, Gdansk, Polland, September 2009 [18].
- *J2* A. Papapostolou and H. Chaouchi, *RFID-assisted Indoor Localization and the Impact of Interference on its Performance*, in the SI on RFID Technology, Systems, and Applications of the Journal of Network and Computer Applications (Elsevier), April 2010 [19].

≤ Motivated by the benefits but also the limitations of the stand alone solutions, as identified in the previous steps, an integration architecture combining both WLAN and RFID technologies was then proposed. The main idea is to take advantage of the localization accuracy offered by the RFID deployment and the coordination capability of the WLAN infrastructure for minimizing the collision problem on the RFID channel

[1] In the enumeration list, the symbols C, J, B stand for publications in Conferences, Journals and Book Chapters, respectively.

with ultimate goal to enhance the localization accuracy in a time-efficient manner. Reference papers include:

- *C4* A. Papapostolou and H. Chaouchi, *Simulation-based Analysis for a Heterogeneous Indoor Localization Scheme*, in Proceedings of the 7th IEEE Consumer Communication and Networking Conference (IEEE CCNC), Las Vegas, Nevada, January 2010 [20].
- *C5* A. Papapostolou and H. Chaouchi,*Exploiting Multi-modality and Diversity for Localization Enhancement: WiFi and RFID usecase*, in Proceedings of the 20th IEEE International symposium on Personal Indoor and Mobile Radio Communications (IEEE PIMRC), Tokyo, Japan, September 2009 [21].

≤ Our next step was motivated by the observation that the joint WLAN and RFID architecture could be also used for the purpose of mobility management. Targeting the network layer handoff improvement, we proposed utilizing the RFID deployment in order to minimize the delay of the movement detection phase in the WiFi channel of the IP mobility management process. However, it is worthy mentioning that the proposed architecture is also valid in other mobility networks. Reference papers include:

- *C6* A. Papapostolou and H. Chaouchi, *RFID-assisted Movement Detection Improvement in IP Mobility*, in Proceedings of the 3rd IFIP International Conference on New Technologies, Mobility and Security (IFIP NTMS), Cairo, Egypt, December, 2009 [22].
- *C7* A. Papapostolou and H. Chaouchi, *Handoff Management relying on RFID Technology*, in Proceedings of the IEEE Wireless Communication and Networking Conference (IEEE WCNC), Sydney, Australia, April 2010 [23].

≤ In the sequence the unified system architecture for both localization and mobility management was designed and analyzed in:

- *B1* A. Papapostolou and H. Chaouchi, *RFID Deployment for Location and Mobility Management on the Internet*, in H. Chaouchi (ed), The Internet of Things: Connecting Objects, Wiley, John & Sons, May 2010 [24].

- *J3* A. Papapostolou and H. Chaouchi, *Integrating RFID and WLAN for Indoor Positioning and IP Movement Detection* journal of Wireless Networks (Springer), submitted in November 2009.

≤ Finally, in order to complete the viability of our proposed schemes, we tried to take into account their accompanied energy consumption. Motivated by this, we proposed a scheme combining the benefits of RFID and WSAN technologies for handoff improvement with respect to latency and energy consumption. Reference papers include:

- *C8* A. Papapostolou and H. Chaouchi, *Deploying Wireless Sensor/Actuator Networks and RFID for Handoff Enhancement* in Proceeding of the International Conference on Ambient Systems, Networks and Technologies (ACM ANT), Paris, France, November 2010 [25].
- *J4* A. Papapostolou and H. Chaouchi, *Handoff Management Schemes in Future Pervasive Environments*, submitted to the journal of Mobile Networks (Springer), *SI on Future Internet for Green and Pervasive Media of the journal of Mobile Networks and Applications (Springer)*, submitted in December 2010.

1.4 Organization of the Thesis

The rest of this thesis is organized as follows. In order to facilitate its presentation, we divided it into two parts: part I is devoted to localization, whereas part II focuses on mobility management aspects. The first chapter of both parts, i.e. chapters 2 and 6, include background and related work essential for the comprehension and highlighting of our contributions. Chapter 3 describes our proposed methods for improving the WLAN fingerprinting localization accuracy, chapter 4 studies the performance of RFID when the collision problem comes into place and chapter 5 ends part I by describing a heterogenous system which combines the benefits of both technologies. Chapter 7 describes and compares the two schemes we propose for mobility management. The first scheme relies on the RFID technology for reducing the network layer handoff latency, while the second scheme utilizes key properties of both RFID and WSAN technologies for handoff latency reduction but also energy saving. Finally chapter 8 summarizes our main conclusions, achievements and open issues for future research.

Part I

Indoor Localization

Chapter 2

Indoor Localization

Location awareness is one of the main concepts for the realization of ubiquitous and context-aware communications in the envisioned future wireless networks. From application point of view, location information is essential for enabling Location Based Services (LBS) in commercial, health-care, public safety and military domains [26]. From network perspective, location awareness can be utilized for enhancing mobility management functionalities such as routing, mobility prediction, handoff management for quality of service provisioning [7]. Moreover, position information can assist the self-organization, self-configuration of ad-hoc and sensor networks in the future communication networks [8].

Indoor positioning is a complex engineering problem that has been approached by many computing communities: networking, robotics, vision, and signal processing. The wide success and penetration of wireless networks in the realm of consumer applications attracted the attention of most of the research and industry communities for the development of wireless positioning systems, whereby location tracking is achieved with the aid of received radio signal properties. The most well known positioning system is the Global Positioning System (GPS) [10], which is satellite-based and is successful for tracking users in outdoor environments. However, the inability of satellite signals to penetrate buildings cause the complete failure of GPS in indoor environments. Thus, for indoor location sensing a number of alternative wireless technologies have been proposed, such as Cellular, wireless LAN, infrared, ultrasound, ultra-wideband (UWB), RFID, sensor networks [11].

Even though location estimation have been investigated extensively in the last few decades, there is still no absolute solution satisfying all performance requirements. This is because, the indoor radio propagation channel is characterized as site specific, exhibiting severe multipath effects and low probability of line-of-sight (LOS) signal propagation between the transmitter and receiver [12], making accurate indoor positioning very challenging.

The aim of this chapter is to provide essential background regarding positioning principles in conjunction with the relevant state-of-the-art. The rest of this chapter is organized as follows: in section 2.1 we first outline the principle aims and requirements a positioning system should satisfy. Sections 2.2, 2.3 and 2.4 describe the most outstanding signal metrics, positioning techniques and sensing technologies, respectively, that are employed by the majority of the current state-of-the-art indoor location systems. Finally, section 2.5 provides the chapter summary along with our research directions for indoor positioning.

2.1 Positioning Aims and Requirements

The localization problem is defined as the process of determining the current position of a mobile node or an object within a specific region, indoor or outdoor. The position can be expressed in several ways, depending on the application requirements or the positioning system specifications. For instance, absolute coordinates, relative or symbolic locations are possible formats.

The general framework of a wireless positioning system is illustrated in Figure 2.1. The key concept is to utilize properties of Received Radio Signal (RRS) measurements from several Fixed Reference Points (FRPs) in order to infer the unknown location of the receiver. Initially, radio signals transmitted by the FRPs (such as Access Points or Base Stations) are sensed/measured by the RRS-sensing devices of the receiver and then converted to location-related *signal metrics*. The reported signal metrics are then processed by the positioning algorithm for estimating the unknown location of the receiver, which is finally utilized by the application. The accuracy of the signal metrics and the complexity of the positioning algorithm define the accuracy of the estimated location.

For evaluating the efficiency of localization schemes the major performance objectives are summarized in the following [11],

- ≤ *Accuracy* is the most important requirement a location system should satisfy. Its most common metric is the mean distance error, defined as the average of the Euclidean distances between the actual and the estimated locations.

- ≤ *Precision* is a metric for evaluating the consistency or reliability of the system over many trials. It is defined as the standard deviation of the distribution of the distance

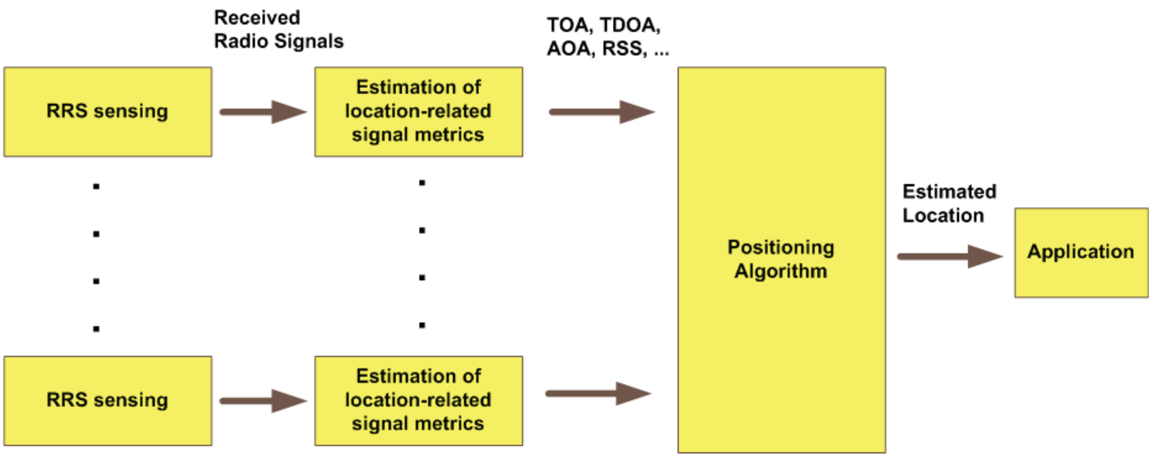


Figure 2.1: Wireless Positioning System.

errors or the cumulative probability function.

≤ *Complexity* involves the *computational* and *communication* requirements of the system. The computational complexity refers to the processing operations of the positioning algorithm, whereas the communication complexity refers to the positioning message exchange overhead. These factors mainly affect the *time response* and/or lifetime of the system.

≤ *Scalability* refers to the number of nodes that can be simultaneously tracked or the scale of the target area, e.g. metropolitan, campus-wide, within a building, etc.

≤ *Deployment and maintenance cost* refers to the hardware requirements and labor effort for installing, setting up and maintaining the positioning system.

≤ *Power consumption* is also an important aspect especially when the positioning process is performed by energy-constrained terminals.

≤ *Fault tolerance* or *robustness* refer to the ability of the positioning system to perform well even under harsh conditions such as the failure of a positioning component.

The wide range of applicability of location information and the diversity of performance requirements drove the research over several directions, resulting in a vast variety of proposed positioning systems. Consequently, a classification among them is essential for assisting their differentiation and evaluation. Several classification criteria can be applied with the most prevalent ones being the type of *metric* of the received radio signal measurements, the *positioning technique* and the *wireless sensing technology*.

2.2 Received Radio Signal Metrics

The most traditional received radio signal metrics are the Time of Arrival (ToA), Time Difference of Arrival (TDoA), Received Signal Strength (RSS), Signal to Noise Ratio (SNR), Angle of Arrival (AoA) or combinations of more than one of these metrics [27], [28], [29]. In the following, a more detailed description of these most commonly used signal metrics is provided, followed by a discussion comparing their main advantages and limitations.

2.2.1 Time of Arrival (ToA)

Times of Arrival (ToA) refers to the time needed for a signal to travel from one node to another which indicates their separation distance. Thus, in TOA-based systems, the propagation time of a signal from a FRP to the target node is measured in order to calculate their distance. In order to measure the ToA parameter for a signal traveling between two nodes, these nodes must be timely synchronized and the transmitted signal must be timestamped.

Let $s(t)$ denote the signal transmitted from a node to another at time t. Then, the received signal is expressed as

$$r(t) = s(t \quad \tau) + n(t), \tag{2.1}$$

where τ represents the ToA and $n(t)$ is white Gaussian noise with zero mean and a spectral density of $N_o/2$.

The most well-known methods for performing ToA estimations are considered to be the correlator or Matched Filter (MF) receivers [30]. According to the correlator-based approach the received signal is correlated with a local template $s(t \quad \hat{\tau})$ for various delays $\hat{\tau}$ in order to calculate the delay corresponding to the correlation peak. Similarly, the MF approach employs a filter that is matched to the transmitted signal and estimates the instant at which the filter output reaches its higher value. Both approaches are optimal in the maximum likelihood (ML) sense for the signal model in eq. (2.1).

However, in real environments, signal distortion due to multipath characteristics, affect the optimality of these conventional schemes.

2.2.2 Time Difference of Arrival (TDoA)

The TDoA approach is followed to replace the absolute synchronization requirement between the target node and the FRPs with the more moderate requirement for relative clock synchronization among the FRPs only. TDoA estimates the time difference between the arrival times of two signals traveling between the target node and two FRPs, which determines the position of the target node on a hyperbola, with foci at the two FRPs.

One approach for estimating TDoA is to first estimate ToA for each signal traveling between the target node and a FRP, and then to subtract the two estimates. Since the target node and the reference nodes are not synchronized, the ToA estimates include a timing offset, which is the same in all estimates as the reference points are synchronized, in addition to the time of flight. Therefore, the TDoA estimate can be obtained as

$$\tau_{TDoA} = \hat{\tau}_1 \quad \hat{\tau}_2, \tag{2.2}$$

where $\hat{\tau}_i$, for $i = 1, 2$, denotes the ToA estimate for the signal traveling between the target node and the ith reference point.

Another approach for TDOA estimation is to perform cross-correlations of the two signals traveling between the target node and the FRPs, and to calculate the delay corresponding to the largest cross-correlation value. The cross-correlation function of these signals is given by integrating the lag product of two received signals over a time period T

$$\hat{R}_{1,2}(\tau) = \frac{1}{T} \bigcup r_1(t) r_2(t + \tau) dt. \tag{2.3}$$

The TDOA is the value τ that maximizes $R_{1,2}(\tau)$, i.e. the range differences.

2.2.3 Angle of Arrival (AoA)

In AoA-based systems the position is calculated via goniometry. The location of the target node lies on the intersection of several pairs of angle direction lines, each formed by the circular radius from a FRP to the target node. The angle between two nodes can be determined by estimating the AoA parameter of a signal traveling between the nodes. AoA estimates are obtained with the aid of directional antennas based on the beamforming technique [31] or with the aid of antenna arrays based on the principle that differences in arrival times of an incoming signal at different antenna elements include the angle information if the array geometry is known [32].

For narrow-band signals, time differences can be represented as phase shifts. Therefore, the combinations of the phase shifted versions of received signals at different array elements can be tested in order to estimate the AOA. However, for wide-band systems, time delayed versions of received signals should be considered, since a time delay cannot be represented by a unique phase value for a wide-band signal.

2.2.4 Received Signal Strength (RSS)

Signal strength refers to the power or energy of the signal traveling between two nodes. RSS systems are based on propagation-loss equations which are indicative of the distance r between those nodes, due to signal attenuation as their distance increases. The free-space transmission loss, L_B, for instance, is proportional to $1/r^2$. Thus, if RSS measurement is used in combination with a path-loss and shadowing model a distance estimate can be obtained. In two-dimensional space, such signal measurement determines the location of one node on the circle centered at the other node with radius their estimated distance.

However, in practice, a signal traveling from one node to another experiences fast (multi-path) fading, shadowing and path-loss, resulting in non-deterministic radio propagation models [33]

$$PL(d) = PL(d_o) + 10n \log \left(\frac{d}{d_o} \right) + X_\sigma, \tag{2.4}$$

where $PL(d)$ the path loss for distance d between a FRP and the target node, $PL(d_o)$ the free space path loss at reference distance d_o, n the path loss exponent whose value depends on the frequency used, the surroundings and building type, and X_σ is a zero-mean Gaussian random variable in dB having a standard deviation of σ_{dB}. The variable X_σ is called the shadow fading and is used to model the random nature of indoor signal propagation due to the effect of various environmental factors such as multipath, obstruction, orientation, etc. This path loss model is used for calculating the distance d from each RP, based on its transmit power P_t, i.e. $RSS(d) = P_t \quad PL(d)$. Note that this model can be used in both line-of-sight (LOS) and non line-of-sight (NLOS) scenarios with an appropriate choice of channel parameters.

Some techniques measure SNR ratios although RSS is a stronger function of location as SNR is affected by random fluctuations in the noise process [34].

2.2.5 Range-free Metrics

All the above metrics belong to the category of *range-based* measurements. However, there is another type of metrics which do not rely on such ranging measurements and they are known as *range-free* or *anchor-based* metrics [35]. Usually, a heterogeneous network is considered which consists of two types of nodes: (i) *anchors* which are powerful nodes with established location information and beacon their position to their neighbors, and (ii) *blind* nodes which listen to such beacons in order to calculate their position.

In [36] the simple centroid algorithm is proposed for estimating the unknown location of a blind node based on the announced locations of the anchor nodes. In DV-HOP [37] anchors, instead of single hop broadcasts, flood their location throughout the network maintaining a running hop-count at each node along the way. Blind nodes calculate their position based on the received anchor locations, the hop-count from the corresponding anchor, and the average-distance per hop; a value obtained through anchor communication. Like DV-Hop, the Amorphous positioning algorithm proposed in [38] uses offline hop-distance estimations, improving location estimates through neighbor information exchange. In [35], an area-based scheme, called APIT, performs accurately location estimations with the irregular radio pattern and random node placement. The main idea of APIT is to divide the whole network into triangular regions among anchors, and then to determine the possible position of a blind node via the aggregation of the two distinct triangular regions. Consequently, the position of the node can be estimated by calculating the Center of Gravity (CoG) of the intersections of the triangles where the node resides.

2.2.6 Comparison

Both ToA and TDoA metrics require strict time synchronization, either between both target nodes and the FRPs or between the FRPs only, respectively. Thus, such metrics are most suited for cellular networks since the receiving nodes are typically synchronized to base stations.

Obtaining AoA measurements is more expensive in implementation compared to ToA and TDoA due to the utilization of special hardware such as antenna arrays, and complex transmission techniques such as beamforming. Moreover, it requires a minimum distance between the receivers which results in additional costs and larger node sizes. Furthermore, this technique is highly sensitive to multipath, NLOS conditions, and array precision.

The main advantages of RSS metric are its low cost and ease of obtaining such measurements for most of the receivers. Thus, obtaining RSS information is much simpler than applying signal processing techniques to extract the time or angle of arrival. Since RSS positioning is based on theoretical or empirical models in order to convert the received signal strength measurements to distance estimates its performance depends highly on the channel behavior and the accuracy of the employed radio propagation model. However, node mobility and unpredictable variations in channel behavior, which are even more intense in a complicated indoor space, can occasionally lead to large errors in distance evaluation. Also, this technique is very susceptible to noise and interference.

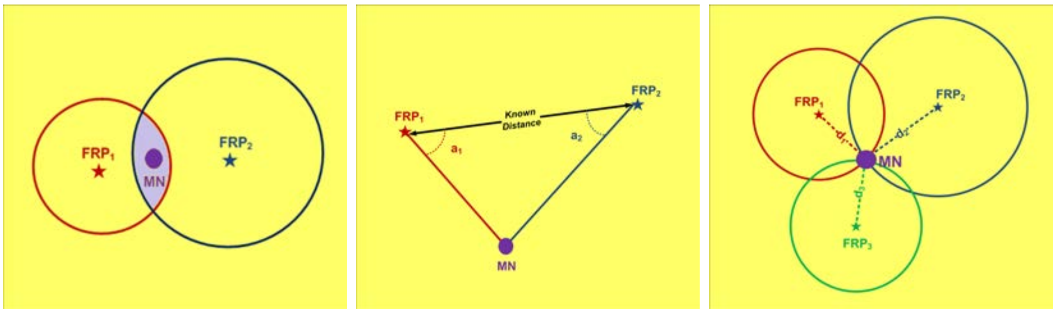
Finally, comparing *range-based* and *range-free* metrics, one would say that selecting the optimal one depends on the assumptions for the network. For instance, range-free metrics are considered as cost-effective solution and thus, more suitable for wireless sensor networks where sensor nodes have limited hardware capabilities. The performance of *range-free* metrics depends on the density of the anchor nodes and the complexity of the positioning algorithm.

2.3 Principle Location Estimation Techniques

Indoor location systems can be classified based on the principle approach followed by the positioning algorithm. [39] and [28] provide interesting surveys on the basic positioning techniques and taxonomies of localization systems based on them. There are three principle classes of positioning techniques, namely *proximity*, *triangulation*, either *lateration* or *angulation*, and *scene analysis*, which are employed either alone or in combination and in either their baseline or enhanced version by any location determination system. In the sequence, we describe the general mechanism, performance advantages and limitations of each approach.

2.3.1 Proximity

Proximity-based localization approaches provide symbolic relative location information and their key concept is the "nearness" to objects with known positions, as shown in Figure 2.2(a). Usually, proximity-based algorithms rely on a dense grid of antennas, each having a well-known position and employ *range-free* signal metrics where location-aware objects are considered as the *anchor* nodes. The identification of such objects such as credit card point of cell-ID, Cell of Origin (CoO) [40], topology or connectivity information [41] and physical



a ro imity b n ulation c ateration

Figure 2.2: Principle Positioning Techniques.

contact detection with the aid of sensors [42] are examples of proximity-based approaches that can be employed for retrieving location information.

In general, proximity methods are considered as simple techniques but with limited capabilities regarding their accuracy performance. For enhancing their accuracy, hardware-based solutions, such as a denser deployment of sensors or identifiable objects are required, resulting in higher cost for the development and maintenance of the positioning system.

2.3.2 Triangulation

Triangulation uses the geometric properties of triangles to estimate the target location. It has two derivations: *lateration* and *angulation* which differ in the method for obtaining range estimations between the target node and each of the fixed reference points.

2.3.2.1 Lateration

Lateration or *distance estimation* techniques determine the position of an object by measuring its distance from several fixed reference points. For a two dimensional space at least three such reference points are required which do not lie in the same line. In Figure 2.2(c), the estimated location is the intersection point of the cycles with centers the reference points and radius the corresponding estimated distances from each one of them. Lateration methods employ the *range-based* signal measurements of RSS, ToA, TDoA or combinations, and can be further classified accordingly.

Lateration systems require coverage from at least three reference points in order to provide a reliable location estimate. Moreover, the performance of a specific lateration approach shares the advantages and disadvantages of the corresponding signal measurements, i.e. RSS, ToA or TDoA metrics.

2.3.2.2 Angulation

Angulation techniques are very similar to lateration methods, with the difference that angles instead of distances are measured. For a two-dimensional space, two at least reference points are required which are equipped with directional antennas or support advanced transmission techniques such as beamforming. Based on the received angle of arrival (AoA) measurement of both transmitted signals, the known distance between the reference points and triangle properties, the unknown position of the receiver is calculated. Figure 2.2(b) illustrates this concept.

Angulation-based approaches are very accurate and precise. However, their dependency on advanced hardware and transmission techniques increases the cost and complexity of the positioning system and limits their adoption and incorporation for a low cost, simple and fast positioning solution.

2.3.3 Scene Analysis

The main concept of *scene analysis* methods, also known as *fingerprinting*, is that special features of the scene observed at a specific position are exploited for describing and subsequently identifying that position. Thus, the location of an unknown point can be inferred based on the similarity of such observed scene characteristics.

Figure 2.3 depicts the general mechanism of scene analysis localization. Such methods require an offline phase for learning the radio characteristics in a specific area under study. Such radio characteristics may correspond to any radio signal metrics, either *range-based* or *range-free*; RSS is though the commonly selected metric. This signal information is then stored in a database called *Radio Map*. During the online localization phase, the receiver's unknown location is inferred based on the similarity between the Radio Map entries and the real-time RSS measurements. The similarity in signal space can be based either on pattern matching techniques (*deterministic* schemes) or on probability distributions (*probabilistic* schemes). The type of these features and the way they are represented define the accuracy and complexity of this positioning method. In general, deterministic scene analysis compared to the probabilistic case is simpler but less accurate way for discriminating among different area positions.

The main advantage of these methods is that they do not rely on any theoretical model,

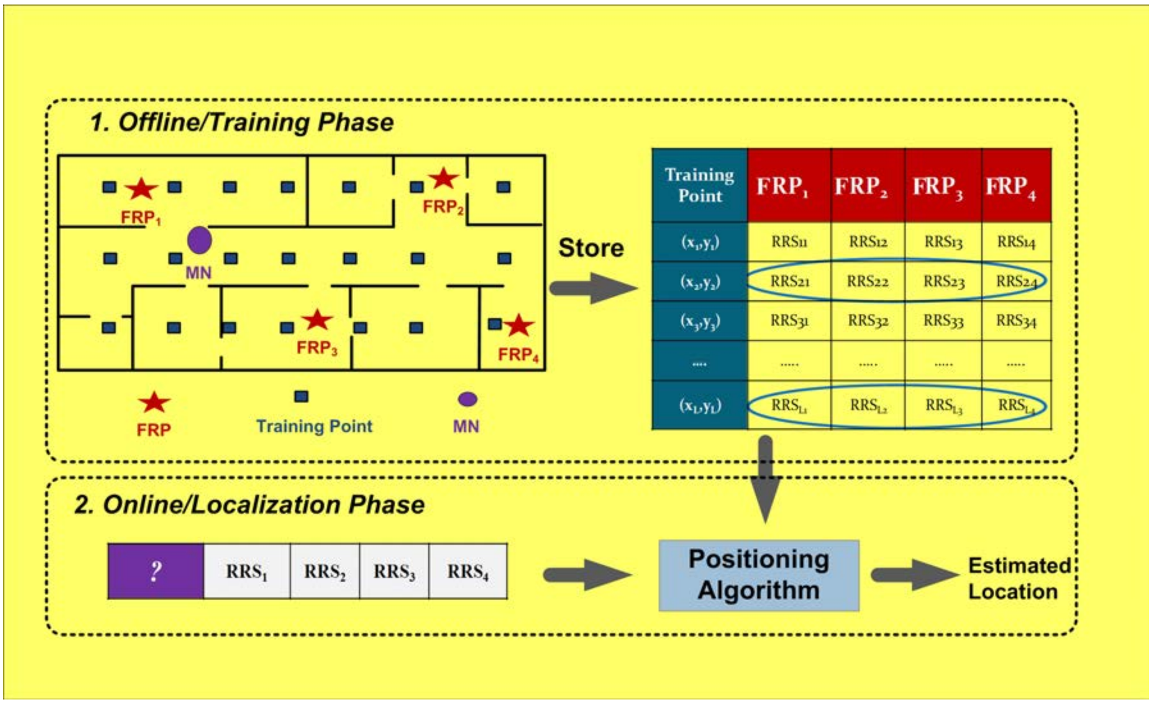


Figure 2.3: Scene Analysis Positioning Technique.

or specific hardware. Additionally, they are based on the passive observation of features which do not correspond to geometric distances or angles, the measurement of which compromises more power consumption. The main disadvantages of such methods are the requirement of a pre-phase for capturing these features and their higher dependency on environmental changes, which cause inconsistency of the signal behavior between the training phase and the time of the actual location determination phase.

2.4 Popular Location Sensing Technologies

All aforementioned positioning techniques can be based on any available technology by taking advantage of the characteristics of the corresponding emitted signals [11]. The most common technology types applied for positioning technologies are outlined in this section. Satellite signals are very successful for outdoor positioning with GPS [10] being the most famous system employing them. However, their inability to penetrate inside buildings cause their complete failure for indoor positioning and therefore are excluded from our relevant survey. This section also provides the current state-of-the art in location systems, classified based on their employed wireless technology. [11], [28] and [39] provide a more extensive survey of location systems.

2.4.1 Infrared (IR)

IR technology is attractive for indoor positioning systems because it is available on board of various, very common wired and wireless devices, such as TV, printer, mobile phones, PDAs, etc. The *Active Badge* location system [41] developed at AT & T Cambridge in 1990s is one of the first indoor badge sensing systems. It uses diffuse infrared technology and follows the proximity based positioning approach. Each person to be located wears an active badge which emits on demand a globally unique infrared signal every 10 seconds. Within each target area such as a room, one or more pre-build infrared sensors detect the emitted signals from the badges and forward this information to a central server to which they are connected via wired links. The server upon reception of this data, estimates the position of the detected badges and provides it to several location-aware applications.

However, an IR-based positioning system, which offers absolute position estimations, needs LOS communication between transmitters and receivers without strong light interference. Thus, the coverage range per infrastructure device is limited within a room. Furthermore, an IR signal is influenced by fluorescent light and sunlight. Finally, the wired links for connecting the sensors increase its deployment cost.

2.4.2 Ultrasound

Ultrasound positioning systems provide a kind of inexpensive positioning solutions. Usually the ultrasound signals used to locate objects need to be combined with RF signals, which perform synchronization and coordination in the system. These ultrasound positioning systems increase the system coverage area.

The *Active Bat* positioning system [43] also developed at AT & T Cambridge uses ultrasonic technology and follows the ToA-based *lateration* technique for determining the position of an *active bat*, which is a tag carried by a person or attached to an object. Sensor nodes are mounted on the ceiling of the target area in a grid fashion. A controller sends requests via short range to the bats and simultaneously a synchronized reset signal to the ceiling sensors using a wired serial network. In response to the request packets sent by the controller, each bat broadcasts a pulse of ultrasonic to the grid of the ceiling sensors. Each ceiling sensor measures the time interval from reset to ultrasonic pulse arrival and computes its distance from the Bat. The local controller then forwards the distance measurements to a central controller, which performs the lateration computation. The location estimation of the Active Bat is more accurate than Active Badge [41] and it can also provide orientation information. However, the performance of ultrasonic is influenced by the reflection and obstacles between tags and receivers, which degrades the system accuracy. Finally, the ceiling sensors need to be connected through cables which increases the deployment cost of the system.

The *Cricket* Location Support System [44] also uses ultrasound emitters as infrastructure and follows the ToA-based lateration. However, the computations are performed locally by the objects to be located for reducing the cost and ensuring more privacy. The emitters also transmit RF signals for synchronization of the ToA measurements and forwarding their location information in a decentralized fashion. Such location information is used for proximity based positioning in case of the failure of the lateration due to insufficient number of received ultrasonic beacons.

2.4.3 Cellular network

Indoor positioning based on mobile cellular network is possible if the building is covered by several base stations or one base station with strong RSS received by indoor mobile clients. Otsasen et al. presented a GSM-based indoor localization system in [45]. Their key idea that makes accurate GSM-based indoor localization possible is the use of wide signal-strength fingerprints. The wide fingerprint includes the six strongest GSM cells and readings of up to 29 additional GSM channels, most of which are strong enough to be detected but too weak to be used for efficient communication. The higher dimensionality introduced by the additional channel dramatically increases localization accuracy. They present results for experiments conducted on signal-strength fingerprints collected from three multi-floor buildings. The results show that their indoor localization system can differentiate between floors and achieve median within-floor accuracy as low as 2.5 m.

2.4.4 Wireless Local Area Network (WLAN)

WLAN-based indoor positioning is an example of low cost positioning technology. It uses the existing infrastructures in indoor environments since the 802.11 wireless technology is inexpensive and widely deployed on campuses, hospitals, airports, commercial environments etc. However, the accuracy of location estimations based on the WLAN signals is affected by the complex behavior of signal propagation [46], and by various elements in indoor environments such as movement and orientation of human body, the overlapping of APs, the nearby tracked mobile devices, walls, doors, etc.

The *Daedalus* project [47] developed a WLAN proximity-based system for coarse-grained user location. A mobile host estimates its location to be the same as the access point to which it is attached. Therefore, the accuracy of the system is limited by the access point density.

RADAR [48] proposed by Microsoft Research group is a deterministic fingerprinting system which uses RSS measurements from the existing WLAN. During an offline phase, the system builds a radio map for the RF signal strength from a fixed number of APs, either by calibrating the area or by applying a radio propagation model. During normal operation, the RF signal strength of the mobile client is measured by a set of fixed APs and is sent to a central controller. The central controller uses a k-Nearest Neighbor (k-NN) approach to determine the location from the radio map that best fits the collected signal strength information.

The *Aura* system proposed in [49] uses two techniques: Pattern Matching (PM) and Triangulation, Mapping and Interpolation (TMI). The PM approach is very similar to the RADAR approach. In the TMI technique, the physical position of all the access points in the area needs to be known and a function is also required to map signal strength onto distances. Based on this information, a set of training points at each trained position is generated. The interpolation of the training data allows the algorithm to use less training data than the PM approach. During the online phase, they use the approximate function they got from the training data to generate contours and they calculate the intersection between different contours yielding the signal space position of the user. The nearest set of mappings from the signal-space to the physical space is found by applying a weighted average, based on proximity, to the signal space position.

The *Horus* [50] is WLAN RSS fingerprinting localization system which defines the possible causes of variations in the received signal strength vector and devises techniques to overcome them, namely providing the correlation modeler, correlation handler, continuous space estimator, and small-space compensator modules. Moreover, it reduces the computational requirements of the location determination algorithm by applying location-clustering techniques.

The *Nibble* location system, from UCLA, is a WLAN-based scene analysis scheme which uses a Bayesian network to infer a user location [51]. Their Bayesian network model includes nodes to be localized, noise, and access points (sensors). The signal to noise ratio observed from an access point at a given location is taken as an indication of that location.

Ekahau [52] is a commercial real-time location system (RTLS) which also uses the WLAN infrastructure but combines site calibration and the RSS-based triangulation technique for determining the location of WiFi enabled devices.

2.4.5 Bluetooth

Bluetooth is a low-cost and low-power technology and many devices are already equipped with it. Thus, it can be used in location sensing. However, a disadvantage of Bluetooth-based positioning system is that the system can only provide accuracy from 2 to 3 m with the delay of about 20s. Furthermore, Bluetooth positioning systems suffer from the drawbacks of RF positioning technique in the complex and changing indoor situations. [53] is a bluetooth-based positioning system.

2.4.6 Radio Frequency Identification (RFID)

RFID is a means of storing and retrieving data through electromagnetic transmission to an RF compatible integrated circuit. Thus, it is not only for the indoor positioning applications, but also provides many potential services for the demands of users. The advantage of an RFID positioning system is that cheap, light and small tags can be taken by people to be tracked. The RFID system can uniquely identify equipments and persons tracked in the system. However, the proximity and absolute positioning techniques need numerous infrastructure components installed and maintained in the working area of an RFID positioning system.

SpotON [54] is RFID positioning system which uses RSS measurements to estimate the distance between a target tag and at least three readers and then applies trilateration on the estimated distances.

LANDMARC [55] employs also the RFID technology but follows a scene analysis approach by using readers with different power levels and reference tags placed at fixed, known locations as landmarks. Readers vary their read range to perform RSS measurements for all reference tags and for the target tag. The k nearest reference tags are then selected and their positions are averaged to estimate the location of the target tag.

WhereNet positioning system [56] offered by Zebra Technology company is another commercial RTLS based on RFID and follows a sophisticated TDOA algorithm for locating tagged items. Location antennas mounted at fixed positions on the ceiling receive the emitted IDs from the tags and forward this data to a location processor via coaxial cable.

2.4.7 Ultrawideband (UWB)

The UWB technology offers various advantages over other positioning technologies: no line-of-sight requirement, no multipath distortion, less interference, high penetration ability, etc. Thus, using UWB technology provides a higher accuracy. However, the high cost of UWB-enabled devices and infrastructure is an issue. [57] is a proprietary UWB-based positioning solution.

2.4.8 Wireless Sensor Networks (WSN)

Wireless localization techniques have also been explored for localization in sensor networks. Sensor networks are ad hoc networks of many autonomous nodes deployed to perform a variety of distributed sensing tasks, by sensing physical or environmental condition including sound, pressure, temperature, light, etc., and generating proportional outputs. Based on such measurements, a person or device can be located.

Georgia Tech's *Smart Floor* [58] is a proximity based location system. Embedded pressure sensors on the floor of the area capture footfalls and Hidden Markov Models recognize the users according to their profiles. The system has the disadvantages of poor scalability and high incremental cost, because the floor of each building in which Smart Floor is deployed must be physically altered to install the pressure sensor grids. [59] provides a survey for sensor-based positioning. ZigBee technology is a special case of such schemes and in [60] the authors enumerate and compare mechanisms based on this standard. In general, sensor-based positioning is cost effective due to the decreasing of the price and the size of sensors. However, their limited processing capability and battery power reduce the accuracy for real-time tracking.

2.5 Chapter Summary

Undoubtedly, accurate and cost effective acquisition of a user or service location information, as part of the more general term of context, is one of the major envisions for the realization of the next generation user-oriented wireless networks.

In this chapter the principle location methods and the most popular wireless technologies for location sensing were reviewed focusing on their advantages and limitations. It is generally accepted that there is still no single technique or technology offering a general solution satisfying all requirements, impelling for new approaches and research directions.

The insufficiency of stand-alone solutions in combination with the heterogeneity of available technologies in the future pervasive environments drove the research over synergetic approaches for solving more efficiently the challenges of indoor localization [61]. The SELective Fusion LOCation estimation (SELFLOC) [62] algorithm infers the user location by selectively fusing location information from multiple wireless technologies and/or multiple classical location algorithms in a theoretically optimal manner. The authors in [63] propose a fingerprinting method by combining the signal strength measurements from WiFi and bluetooth systems and report accuracy increase.

The promising research trend towards technology integration for tackling more effectively the problem of indoor location sensing is also adopted by us, as explained later in this thesis.

Chapter 3

WLAN Scene Analysis Localization

Wireless Local Area Networks (WLANs) are very common in most indoor environments for providing wireless communication in an infrastructure or ad hoc mode. Therefore, WLAN systems are considered as an attractive technology for performing indoor location sensing. For indoor positioning scene analysis, or fingerprinting, schemes are mostly preferred than triangulation schemes due to their independence on an indoor propagation radio model.

However, utilizing the WLAN technology for localization has a number of limitations. Since the main target of a WLAN is the communication between its components, the deployment of the APs is such that minimum overlapping is achieved, undesirable for localization purposes. Moreover, the inherent characteristics of the wireless medium, the so called propagation losses, and uncontrollable environmental changes cause undesirable variations of the signal properties, deteriorating the positioning process. Finally, the orientation of the user has also a strong impact on the power level of the received signal causing uncertainty in fingerprinting positioning techniques.

In this chapter, we focus on WLAN-based indoor positioning and study both its probabilistic and deterministic fingerprinting variants. In general, probabilistic approaches are more accurate but more complex than the deterministic ones. We first identify how the inherent impairments of the wireless medium and indoor characteristics implicate the positioning process and suggest ways to mitigate them by employing simple techniques with low processing requirements. More specifically, we firstly propose training the positioning system by obtaining several samples of Received Signal Strength (RSS) measurements for different locations and orientations from the Access Points (APs) within the studied indoor environment. A simple processing of these RSS samples is then suggested. This is to evaluate their quality and reliability before storing them to the radio map. During the real-time positioning process, techniques to further increase the system accuracy and reduce its time response are explored. More precisely, using the current user orientation information for reducing the number of candidate training points and a hierarchical searching algorithm for selecting these candidates are examined.

The remainder of this chapter is organized as follows: section 3.1 gives some background regarding WLAN fingerprinting positioning and systems. Section 3.2 describes its main challenging issues which motivated this study. Section 3.3 describes our proposed localization approaches and section 3.4 discusses some system design parameters. In section 3.5 we evaluate the performance of the proposed schemes and compare them with two other popular location systems for the same experimental testbed. Finally, section 3.6 summarizes the main points and contributions of this chapter.

3.1 WLAN Localization

This section gives an overview of the WLAN technology from the localization perspective and reviews two popular WLAN fingerprinting positioning systems which initiated our study.

3.1.1 WLAN Technology Overview

Wireless LAN (WLAN) is the most widely adopted wireless networking technology due to its low infrastructure cost, ease of deployment and high data rates, by utilizing the unlicensed and free spectrum. They are deployed in most indoor environment, such as airport, home, office, and campus environments. A typical WLAN consists of an Access Point (AP) and mobile Stations (STAs) connected to this AP. A STA can be connected to an AP by following an AP discovery process. An AP and its associated STAs form a Basic Service Set (BSS) communicating on the unlicensed Radio Frequency (RF) spectrum. A collection of APs, connected through some kind of backbone, called Distribution System (DS), can extend a BSS into an Extended Service Set (ESS).

There are two operating modes for enabling the communication among STAs: the infrastructure and ad-hoc mode. In the infrastructure mode, an AP acts as a fixed entity that bridges all data between the STAs associated to it. The ad-hoc is decentralized mode, whereby STAs recognize each other and establish a peer-to-peer communication directly without any existing infrastructure. The Institute of Electrical and Electronic Engineering (IEEE) 802.11 is the most prominent family of Standards specifying the WLAN physical (PHY) and Medium Access Control (MAC) layers [64]. The first series of standards by IEEE was ratified in 1999 but had relatively low data rates (1 or 2 Mbps). The next standard in the family, IEEE 802.11b [65], increases the data rate to 11 Mbps. With the introduction of newer standards, IEEE 802.11a [66] and IEEE 802.11g [67], the data rate increases to 54 Mbps per AP. For associating with an AP, the IEEE standard describes the AP discovery techniques, called scanning. The 802.11 network card of the STA tunes into each channel in turn, sends a PROBE REQUEST packet and logs any corresponding PROBE RESPONSE packets it receives. In this way, Received Signal Strength Indicator (RSSI) measurements from the surrounding APs are collected by the STA and usually, the AP from which the RSSI is higher, is considered as the best AP to which that STA should connect.

3.1.2 WLAN Positioning Systems

Although WLAN has not been designed for localization, the radio signal can be used for location estimation by exploiting the Received Signal Strength Indicator (RSSI) values. The scanning mechanism is a part of the 802.11 specification, and thus this functionality is readily available in the hardware device driver. Therefore, the availability of WLAN infrastructure, the ease of obtaining such measurements, the simplicity of storing and comparing numerical parameters and mainly the strong correlation between a specific location and the RSS levels from the surrounding APs, RSSI information enables location estimation.

WLAN positioning systems can follow either RSS-based triangulation or fingerprinting approaches. Indoor propagation modeling is not accurate due to the implicating indoor characteristics, degrading the performance of triangulations schemes whose performance relies mainly on the accuracy of the radio model. However, in location fingerprinting, instead of determining the distance between the user and the transmitting AP, the characterization of the signal propagation is determined by actually measuring the RSSI pattern at certain locations. This provides localization even in very complex environments, because it is not based on the signal propagation model, but on a database of real measurements. Therefore, we focus our attention on fingerprinting localization schemes.

Fingerprinting (or scene analysis) localization includes two main phases: offline and online. The offline is a training phase during which the area is calibrated by collecting RSSI measurements from the area APs at different locations. In this way, a database which correlates positions with RSSI fingerprints and referred as Radio Map is built. The online phase is the actual location determination phase during which the unknown location of a user holding a wireless device is inferred by testing the similarity in signal space between its current RSSI measurements and the stored Radio Map entries. Fingerprinting approaches can be either deterministic or probabilistic depending mainly on (i) the selected format for representing RSSI measurements as radio fingerprints during the offline Radio Map construction and (ii) the method for testing the similarity between the current radio characteristics and the stored radio map fingerprints during the online localization phase. In deterministic schemes, a scalar value of several RSSI sample measurements from a specific AP is stored in the Radio Map as radio information from that AP and a non-random metric is used for radio similarity check. Probabilistic schemes use probability distributions to characterize the signal behavior at each calibrated location and follow probability-based similarity tests for inferring the unknown user location. Deterministic schemes are considered simpler with less processing and storing requirements, lacking however the accuracy of probabilistic frameworks which include more detailed information regarding signal behavior.

Reviewing the literature, a plethora of fingerprinting localization schemes, either deterministic, probabilistic or combination, can be found. Providing a survey is out of the scope of this thesis. Interested readers are directed to [68], [28] for related studies. Our target is to develop a fingerprint-based WLAN localization scheme which achieves a good trade-off between accuracy and simplicity objectives. To that end, we focus our attention on two representative systems: RADAR [48] and COMPASS [69]. *RADAR* is a reference deterministic fingerprinting system which uses RSSI measurements from the existing WLAN. During the offline phase, the average of multiple RSSI measurement samples from all visible APs at each training location forms the signal vector to be stored as a radio map entry for that location. During the online phase, a pattern matching technique based on the Euclidean distance in signal space between the current RSS vector and all radio map fingerprints is followed in order to determine the most similar ones. Finally, the coordinates of the k nearest entries are averaged in order to estimate the unknown user location based on the k Nearest Neighbor (k-NN) algorithm. COMPASS, is a probabilistic scheme which stores the histogram of the RSSI samples from each AP in order to build the radio map.

Moreover, RSSI samples are collected not only for different locations but also for different orientations. During the online phase, only the radio map entries with orientation similar to that of the user are considered for comparison. The similarity between the current signal vector and the offline fingerprints is based on the Bayes' theorem such that they maximize the current RSS probability density function. Finally, the unknown location is estimated as the average of location coordinates of the k most likely radio map entries.

3.2 Our Motivation: WLAN Scene-Analysis Positioning Challenges

For scene-analysis based positioning, the scene characteristics that are selected for training the system and compared during the real-time localization process should satisfy two main objectives. Firstly, they must uniquely describe different locations and secondly their storage and processing requirements should remain low. Obviously, an inherent trade off exists between them.

The stability of the RSSI values at a specific point and their divergence for different points are two desirable factors for inferring accurately a location based on RSS information. However, inherent characteristics of the wireless medium at this band and the indoor environment cause RSS variations, fusing the system. In this section, these hindrances and their impact in the positioning performance are addressed. In parallel, we propose simple methods to compensate them without increasing considerably the processing and hardware requirements.

3.2.1 Multi-path and Shadowing

Multipath and shadowing are the main limiting factors for accurate indoor positioning. Multipath is related to the signal propagation losses such as reflection, scattering, diffraction, due to the existence of walls, obstacles and the indoor layout. For dealing with multipath, several radio propagation models have been proposed all of which try to incorporate the indoor characteristics, however none of them has managed to accurately model and predict the radio behavior, vital for accurate location estimation. Therefore, we choose to obtain real (empirical) RSS measurements during the offline training phase instead of assuming a theoretical model.

Shadowing is related to signal variations due to environmental changes, movement of people and rearrangement of objects. The received signal varies with respect to time and especially with respect to the relative position of the receiver and the transmitter. Shadowing makes indoor positioning even more complicated. The signal behavior at a specific location depends also on environmental characteristics that may change randomly in time. Thus, obtaining multiple samples of RSS measurements is essential, but still not sufficient. The consistency among these samples should also be considered. In [50], the authors observe high autocorrelation between successive samples and propose a first order autoregressive model in order to account for this high autocorrelation. In [70], sensors are used to sense environmental changes and the system is adapted accordingly.

We target at a more simplified solution, by not considering events of short duration. We believe that even though such short-time environmental changes are random, their impact in the sample space can be detected and alleviated. For instance, consider a set of samples (for a given point and a specific AP) most of which have absolute value higher than zero and some of them are almost zero valued. It is obvious, that since signal from this AP is received most of the time, this point is within the AP range and the almost zero-valued samples are most probably due to the instantaneous blocking effect of obstacles temporally placed during the sampling process. Thus, considering these incompatible samples may lead to RSS information distortion. Especially for the static schemes, where the mean value is used for summarizing the RSS, taking into account these samples reduces the correspondence with the real strength level. Moreover, the higher the strength of the signal the worse this distortion is, which is even more undesirable since high RSS values are more indicative and significant for the location estimation process. Based on this observation, in this work the incorporation of a sample filtering module in the positioning architecture is proposed and explained in section 3.3.

3.2.2 Orientation-dependency of the Radio Scene

It has already been identified that the power level of the signal received from an AP at a fixed location depends on the orientation of the user due to the blocking effect of the human body. For instance, consider the case when a user's orientation is such that his WiFi-receiver has direct line of sight with an AP but for the opposite orientation his body fully prevents a signal from being received from the same AP and the same physical position. Thus, the relation between a position and RSS level is not unique (1-1), but, in contrast, different RSS values correspond to the same position. In RADAR [48] the authors try to deal with this by sampling RSS for four different orientations and taking the maximum value as representative for this position. In COMPASS [69] the authors assume the existence of digital compasses during training and and run-times phases. The orientation of the user is detected and only training points with similar orientation are selected for RSS comparison during the online phase.

We claim that the orientation information should certainly be considered by the positioning system, at least during the training phase and possibly during the real-time process as well. Training points should differ regarding not only their location coordinates but also their orientation. In our proposal RSS measurements for different orientations at the same position are considered as new training points, in contrast with COMPASS where they are merged. During the online phase, we examine two cases as shown in section 3.3. In the first case, the user is not equipped with a digital compass and therefore RSS comparison is performed for all training points. In the second case, we assume the user is also equipped with a digital compass and therefore, only points with similar orientation are considered.

3.2.3 Location Ambiguity

Location ambiguity is a term used to describe the phenomenon when two or more positions even physically far apart are very similar in signal space. This is mainly because of the complex indoor propagation environment. Apparently, since our system is based on the similarity in RSS to infer the location, such ambiguity must be eliminated. In [71] considering the location history of the tracked user is proposed. Thus, if a point close in signal space is far away from the previous location of the user, it is not considered as a candidate for inferring the current position. Hardware-based solutions can provide the location system with a location approximate and thus points not within this range are excluded.

For eliminating or mitigating this phenomenon we propose giving more priority to information more sensitive to RSS variations. Since the RSS level depends more on the distance from APs rather than the specific orientation, we propose a *hierarchical* pattern matching approach according to which the first level patterns are only location dependent and the second level patterns include orientation information.

3.2.4 Operational Processing Time

In general, scene analysis methods are regarded as fast response solutions with the deterministic cases even more advantageous. However, adding the orientation-dependent information increases the number of candidates and thus jeopardizes the time efficiency factor. For dealing with this, the hierarchical pattern matching approach compensates this issue.

3.3 Proposed Enhanced Localization Approaches

In this section the architecture, the general methodology and the mechanism of the basic system components of our enhanced localization approaches are described.

3.3.1 General Architecture and Methodology Overview

WLAN-based location determination systems can be categorized into two classes from architectural point of view: network-based and user-based. In the former, a specific positioning component is required which measures the RSS of the mobile user devices within its range and estimates their location based on a specific positioning algorithm. In the user-based approach, each user device is responsible for measuring the RSS from the visible APs and in the sequence uses this RSS information and a positioning algorithm to infer its location. We assume a user-based architecture so no special component is required and therefore they can easily work with the available WLAN system. However, the limited resources of user devices impose the requirement for a positioning process with low processing overhead.

Figure 3.1 illustrates an overview of our proposed positioning methodology. It includes two main stages, namely the *offline* training stage and *online* location determination stage. During the *offline* phase, Joint Location and Orientation (JLO) - based calibration of the area under study is conducted, i.e. multiple RSSI samples measurements are obtained for different locations and orientations. These RSSI samples are processed by the RSS sample filter module, transformed to an appropriate format and finally stored in a database, called Radio Map (RM). Note that the offline phase is conducted only once and repeated only in the case of big environmental changes which may affect the RSS characteristics of this area. The *online* phase is actually the main phase of the positioning process. Initially, as in the offline phase, run-time RSSI sampling and filtering of these samples are performed. The

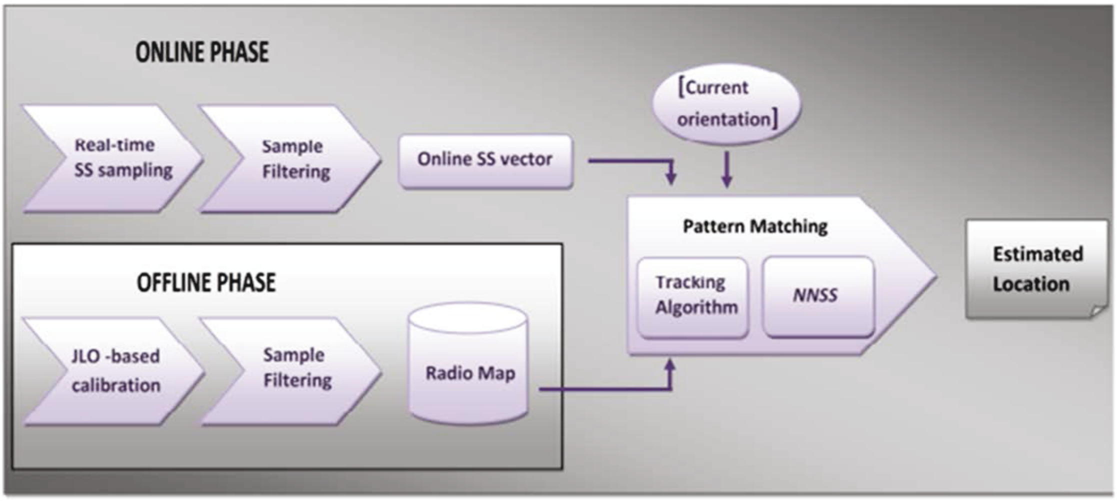


Figure 3.1: WLAN Fingerprinting Positioning Process Overview.

resulting online radio signal vector is compared with the RM entries based on a hierarchical pattern matching technique which is defined by the selected tracking algorithm and the algorithm for selecting the closest RM matches, called Nearest Neighbors in Signal Space (NNSS) algorithm.

In the following the system components are described in detail and modeled.

3.3.2 Joint Location and Orientation (JLO) based Calibration

During the offline phase the area under study is calibrated in the sense that a set of specific points within this area are selected and multiple RSSI sample measurements from the surrounding APs are obtained. The selection of these points is not only location- but also orientation-based, i.e. the selected points differ in their location and orientation. Assume and r physically distinct points within the building are selected for training the system and $i : i \,/\, \}1, \ldots, r|$ one of these with known location coordinates (x_i, y_i). Instead of ignoring the orientation at this point and simply sampling RSSI measurements from all n APs, we repeat the RSSI sampling process for eight different orientations, i.e. $\mathcal{C}\omega_j$ with $j = 1 \ldots 8$. Let

$$\mathbf{S}_i(\omega_j) = [\}SS_{i1}(\omega_j)|\,, \ldots, \}SS_{in}(\omega_j), \ldots|\,] \tag{3.1}$$

the RSS sample vector at position (x_i, y_i) and orientation ω_j, where $\}SS_{in}(\omega_j)|$ the set of RSS samples from AP_n.

3.3.3 Sample Processing

Uncontrollable environmental changes cause distortion of the RSS characteristics postulating for a simple, not hardware-dependent solution. To that aim, the incorporation of a *Sample Filtering* module after the RSSI sample calibration step is proposed. This additional module actually removes RSSI samples whose value is incompatible when compared with the majority of the measurement samples. More complicated filtering approaches, taking into account the frequency of the samples, add complexity without an accuracy improvement, at least for our experimental data.

3.3.4 Radio Map Representation and Current Orientation

Including orientation information entails differentiating the representation format of the the RM entries. This is actually the point where our approach mainly differs from COMPASS and this difference is also reflected to the online location determination process. Let $(x_i, y_i, \mathbf{S}_i)$ a RM entry, where $\mathbf{S}_i$ is called radio fingerprint of position (x_i, y_i), whose format should be such that the orientation factor is accounted. In COMPASS, the format of $\mathbf{S}_i$ depends on the current user orientation, ω_u, which implies that users need to be equipped with a compass. More precisely, the RSSI samples of the similar orientations of each calibrated point (x_i, y_i) are merged to finally describe the RSS fingerprint of the corresponding RM entry i, i.e. $\mathbf{S}_i = \sum_{j:|\omega_j-\omega_u|<\Omega} \mathbf{S}_i(\omega_j)$, where $\sum$ the merging operation and Ω an orientation threshold. In contrast, in our case, we do not require from users to know their orientation and construct the RM according to two possible formats,

$$\mathbf{S}_i^A = \mathop{\frown}\limits_{j=1,\ldots,8} \mathbf{S}_i(\omega_j), \mathcal{C}i \ / \ \}1, \ldots, r| \tag{3.2}$$

$$\mathbf{S}_i^B = [\mathbf{S}_i(\omega_1), \mathbf{S}_i(\omega_2), \ldots, \mathbf{S}_i(\omega_8)]^T, \mathcal{C}i \ / \ \}1, \ldots, r| \,, \tag{3.3}$$

where $\mathbf{S}_i(\omega_j)$ is given by eq. (3.1). In the first case the radio fingerprint $\mathbf{S}_i^A$ actually merges the radio fingerprints from all 8 orientations, whereas in the second case, $\mathbf{S}_i^B$, we differentiate among the radio fingerprints from the 8 different orientations and consider them as 8 individual RM entries, even though their physical location is identical.

Keeping the hardware requirements of users as low as possible is more desirable. However, assuming the availability of compasses during the online is also studied. In this case, the Radio Map takes the following format

$$\mathbf{S}_i^C = [\mathbf{S}_i(\omega_a), \mathbf{S}_i(\omega_b), \ldots, \mathbf{S}_i(\omega_d)]^T, \mathcal{C}i \ / \ \}1, \ldots, r| \, . \tag{3.4}$$

where $\omega_a, \ \omega_b, \ldots, \omega_d$ similar orientations with the current user orientation, i.e. $\omega_a \quad \omega_u < \Omega, \ \omega_b \quad \omega_u < \Omega, \ldots, \ \omega_d \quad \omega_u < \Omega$.

3.3.5 Positioning Algorithm

During the online phase, the online RSS vector of a user u, denoted as $\mathbf{S}_u$ is compared with the radio fingerprints, $\mathbf{S}_i, i \ / \ \}1, \ldots, r|$ [1] and the entries corresponding to the most similar ones are retrieved. The way for summarizing the RSS samples, $\}SS_{im}(\omega_j)|$, and the similarity metric between radio fingerprints are defined by the positioning algorithm. In general, the scene analysis positioning algorithms are categorized into two main types: namely, deterministic and probabilistic for the static and differential cases, respectively.

3.3.5.1 Deterministic

In the deterministic approach, a single scalar, usually the mean value of the measured RSS samples is selected for summarizing them, i.e. $SS_{im}(\omega_j) = \overline{\}SS_{im}(\omega_j)|}$, $\mathcal{C}i = 1 \ldots, r$, $\mathcal{C}m = 1, \ldots, n$ and $\mathcal{C}j = 1, \ldots 8$. Accordingly, the merging operation in eq. (3.2) is again the average. The metric for quantifying the similarity between them is their distance in signal space, i.e.

$$d_{ui} = \mathbf{S}_u \quad \mathbf{S}_i = \prod_{m=1}^{l} SS_{um} \quad SS_{im} \tag{3.5}$$

where l the number of considered APs[2], with $l \geq n$ and n the total number of APs in the area.

3.3.5.2 Probabilistic

In this case, the probability distribution of the sample values from each AP m is stored as the RSS information for each offline point i, i.e. $SS_{im}(\omega_j) = PDF\}SS_{im}(\omega_j)|$ and accordingly, the merging operation in eq. (3.2) is again the probability distribution of the

---
[1] $\mathbf{S}_i$ can be any of the $\mathbf{S}_i^A$, $\mathbf{S}_i^B$ or $\mathbf{S}_i^C$ RM representations

[2] A design parameter to be discussed in section 3.4.1

RSSI samples for all orientations. The similarity metric is based on the Bayes' theorem, such that given $\mathbf{S}_u$ we look for the offline points i which maximize the probability $P(i/\mathbf{S}_u)$, i.e. we want

$$\arg\max_i [P(i/\mathbf{S}_u)] = \arg\max_i [P(\mathbf{S}_u/i)] \tag{3.6}$$

where $P(\mathbf{S}_u/i)$ can be calculated by combining the individual probabilities, $P(SS_{um}/i)$ for each AP m, by either multiplying (prod) or adding (sum) them, i.e.

$$P(\mathbf{S}_u/i) := \begin{cases} \int_{m=1}^{l} P(SS_{um}/i), & \text{if prod} \\ \prod_{m=1}^{l} P(SS_{um}/i), & \text{if sum.} \end{cases} \tag{3.7}$$

Where l the number of the considered APs, with $l \geq n$.

3.3.6 NNSS Algorithm for Location Estimation

The basic idea of the location estimation process is the Nearest Neighbor in Signal Space (NNSS) concept, since the closeness in signal information is considered. According to this, the RM entry i with minimum d_{ui} or maximum probability $P(\mathbf{S}_u/i)$ is selected as the NN of the user u. If more than one closest matches need to be determined we have the k-NNSS positioning algorithm, where k is a parameter defining the number of these NNs. Two approaches for searching and finally selecting these k NNs from the available training RM entries are examined. The first one is hardware-dependent since user devices need to be equipped with a compass for determining their orientation. Based on this information the look up in the RM follows the representation (3.4). The second approach is a software-based solution. Actually, we propose a modified version of the k-NNSS positioning estimation which defines a different method for searching the NNs in the RM. Before giving the details of the proposed algorithm, we present the motivation behind it.

After the joint location-and-orientation-based calibration, an increased number of calibrated points is available, i.e. if r is the number of physically distinct points, a total number of $8 \pm r$ radio fingerprints is available. Including them individually in the RM, see eq. (3.3), and considering all of them during the online searching phase would on the one hand increase the probability of finding a closest match in RSS but on the other hand, a large search space would degrade the time response and the resource utilization performance. Furthermore, even though orientation is an important factor for RSS variations, the actual location still remains the main indicative one and thus, it should be prioritized during the RSS similarity testing. Finally, the phenomenon of location ambiguity, as addressed in section 3.2.3, would become more possible since the probability of two physically far located points having the same RSS characteristics would increase. In other words, both complexity and accuracy related reasons triggered us in proposing a two-level algorithm, called mk-NNSS,

1. Initially, we consider eq. (3.2) as the RM representation and the m closest matches are determined.

2. In the second level, we consider eq. (3.3) as the RM representation but only for the selected m candidates, leading to a search space of $8 \pm m$ points, and the k NNs are finally determined.

After having selected the k NNs of user u, their locations are utilized for estimating its unknown location $(\widetilde{x}_u, \widetilde{y}_u)$. Since some of the selected NNs may correspond to the identical physical location, we calculate the weighted average of the unique coordinates with weight the frequency of appearance of each distinct location,

$$(\widetilde{x}_u, \widetilde{y}_u) = \left(\frac{\prod_{i \in \mathcal{N}_u} w_i \times x_i}{k}, \frac{\prod_{i \in \mathcal{N}_u} w_i \times y_i}{k} \right) \tag{3.8}$$

where $\mathcal{P}_u$ the set of the physically distinct NNs of user u.

3.4 System Design Considerations

In this section, the impact of two design parameters on the system performance is discussed.

3.4.1 Number of Access Points

An important parameter is the number of APs from which RSS is measured and considered in the final format of the radio fingerprints. In general, it holds that the more the available information, the more accurate the final decision. However, this statement is not always valid. For the deterministic approach, the similarity between fingerprints is a single scalar which contains RSS information from all APs without discriminating among them (see eq. (3.5)). Thus, if many APs are considered there is high probability that two different fingerprints will have the same distance from the user's current RSS vector, and consequently fusing the system. For the probabilistic approach, when an AP m is not visible from the current user, then training points i also non visible from this AP are biased in (eq. 3.7) due to the RSS histogram for this AP $(PDF(\}SS_{im}|\,) = PDF(\}0, 0, \ldots = 0|\,) = 1)$. Finally, scanning signal entails power consumption which is undesirable. Therefore, the optimal number of APs that should be considered is a significant design parameter.

3.4.2 Number of Nearest Neighbors

In this section we explore the influence of the parameters m and k, of the mk-NNSS algorithm, on the system performance.

3.4.2.1 Parameter m

The parameter m defines how many closest matches are selected during the first level of the hierarchical RM look up and whose orientation-based fingerprints are considered during the second step of the search process. Obviously, higher values of m result in larger search space at the second level of the mk-NNSS and thus, the processing time and the consumed resources for performing more comparisons are increased. Its impact on the accuracy is not so obvious. A bigger search space increases the probability of finding a very similar point but also the location-based fingerprint lose their priority over the orientation-based fingerprints.

3.4.2.2 Parameter k

Parameter k defines how many NNs are finally selected for estimating the unknown location. Thus, the computational complexity is not affected by its value. However, it does affect the accuracy.

Intuitively, considering more points increases the accuracy but adding locations which are far from the real position may distort the final result. Thus, finding the optimal value is an issue. In most works which follow the k-NNSS method the value of k is fixed for all user-cases and is more related to the grid-geometry employed during the calibration phase. However, the implicating factors of an indoor environment make each case different from the others. Therefore, making the value of k adaptive for each user, i.e. k_u instead of a fixed $k\ \mathcal{C}u$, appears to be promising for increasing the accuracy.

For the deterministic case, the distance in RSS, d_{ui}, would maybe give a hint for the optimal value of k_u. Assuming a fixed value for k, we observed that for some users, k or more NNs had relatively small d_{ui} but for some other users only a subset of these k NNs had relatively small d_{ui}. Thus, adding or excluding NNs based on the relativity of their d_{ui} value can lead to the optimal value of k_u. Algorithm $adaptiveNN(Du, rlt)$, gives the details for estimating the optimal value of k_u for user u. The input D_u is a vector of RSS distances between u and the RM entries, sorted in ascending order and rlt is a parameter which defines the number of these distances that should be considered for defining a *relatively small* distance in RSS. The operations *mean* and *std* give the mean value and the standard deviation of the first rlt smallest distances, respectively, and their purpose is to define the *relatively small distance* ($RSdist$) and the *relatively small deviation* ($RSdev$). The main idea of the algorithm is: if the absolute difference between the distance in SS of a NN i and the $RSdist$ is smaller than the $RSdev$, then this NN should be considered as candidate for estimating the unknown location of user u.

Algorithm 1 $[k_u] = adaptiveNN(D_u, rlt)$

$RSdist = mean(D_u(1 : rlt))$
$RSdev = std(D_u(1 : rlt))$
$k_u = 1$
for all $i = 1 : length(D_u)$ **do**
  if $d(u, i) \quad RSdist < RSdev$ **then**
    $k_u = k_u + 1$
  end if
end for

3.5 Experimental Evaluation

For evaluating the performance of our systems we chose to use a real experimental scenario instead of simulating one. Also, instead of performing a new experiment we preferred to utilize the already available measurement results from [69] in order to provide a fair comparison between our schemas and other systems. In this section, we first briefly describe the experimental testbed we utilized. After defining the performance metrics, we depict the performance improvement achieved by our proposed schemes and finally we compare them with two other positioning systems for the same experimental scenario.

3.5.1 Experimental Testbed and Data

The testbed we used for deploying our positioning system corresponds to an office environment of $15 \pm 36\ m^2$. During the offline phase, 110 RSS measurements from all 17 802.11b and 802.11g APs and responding peers were sampled for 166 distinct physically points and for each of the 8 possible orientations, leading to 1328 points in the radio map. During the online phase, 60 random points were selected and 110 RSS samples were measured from all APs. For more technical details, refer to [69].

3.5.2 Performance Metrics

A user-based positioning system is successful when it can estimate the user current location accurately, fast and without wasting the limited user-device resources. As accuracy metric we choose the Mean Location Error (MLE) between the real and estimated locations, denoted as (x_u, y_u) and $(\widetilde{x}_u, \widetilde{y}_u)$, respectively, i.e.

$$MLE = \frac{1}{N} \prod_{u=1}^{N} \sqrt{(x_u \quad \widetilde{x}_u)^2 + (y_u \quad \widetilde{y}_u)^2} \tag{3.9}$$

where N the total number of users. For our data N=60.

For evaluating the time response of the system we use the Online Computation Time (OCT) metric, which is quantified by measuring the *number of comparisons* that need to be made during the online operational phase. It depends on the selected RM representation format and the NNSS approach. We adopt the following naming for the different tested scenarios,

≤ *Merged RM* is the case when orientation is not considered during the area calibration and thus (3.2) is used for the RM representation.

≤ *Flat RM* is the case when only eq. (3.3) is used, i.e. no priority given to the location- over the orientation-based fingerprints and the conventional k-NNSS is followed.

≤ *Hierarchical RM* is the case when both eq. (3.2) and eq. (3.3) are used and the mk-NNSS algorithm is followed.

≤ *userOrient RM* is the case when eq. (3.4) is adopted, i.e. a compass is assumed during the online phase also and γ is the number of RM entries with similar orientations.

Regarding their OCT we have,

$$OCT = \begin{cases} 166, & \text{if } \textit{Merged RM} \\ 8 \pm 166, & \text{if } \textit{Flat RM} \\ 166 + \mu \pm 8, & \text{if } \textit{Hierarchical RM} \\ \gamma \pm 166, & \text{if userOrient RM.} \end{cases} \tag{3.10}$$

3.5.3 Numerical Results

In this section, numerical results illustrate the impact of the proposed positioning enhancements and the various design parameters on the system performance. We study separately the probabilistic and deterministic cases and later a comparison among them is provided.

3.5.3.1 Probabilistic

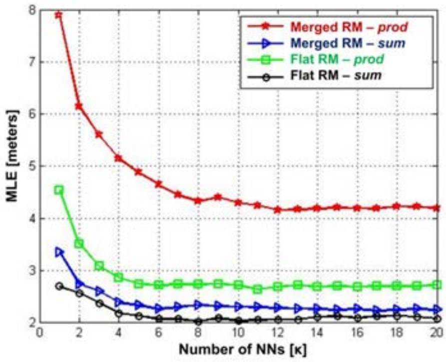
Figure 3.2(a) illustrates the performance advantage in terms of MLE if JLO - based calibration is employed. Both metrics, *prod* and *sum*, (see eq. (3.7)), are examined for different numbers of NNs. We observe that even though for the metric *prod* the error reduction is high, its performance remains worse than the case of the *sum* metric, with or without considering the orientation during calibration. The intuition behind this is that metric *sum* is less dependent on the individual contribution of each AP and thus less bias from each one of them is introduced. For the rest, we consider only the case of this metric with JLO - based calibration and try to further improve it.

In the sequence, we test if there is any benefit by filtering the incompatible samples. Figure 3.2(b) shows that the performance is worse. This is because probabilistic schemes are based on the statistics of the samples which give the appropriate information concerning the reliability of the samples, something not possible in the deterministic schemes.

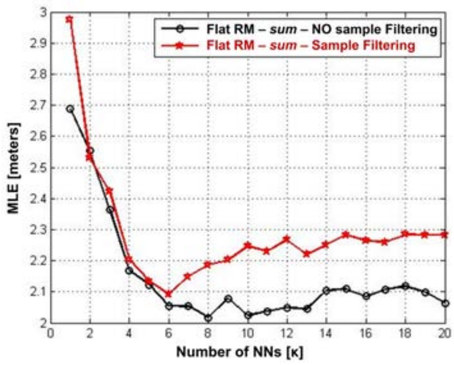
Finally, we assume the availability of digital compasses during the online phase as well and we examine if this additional information can further improve the accuracy of the system. Figure 3.2(c) shows that there is indeed improvement and the best accuracy (MLE = 1.93 meters) is achieved for threshold value $\Omega = 65^o$, which corresponds to $\gamma = 2$.

3.5.3.2 Deterministic

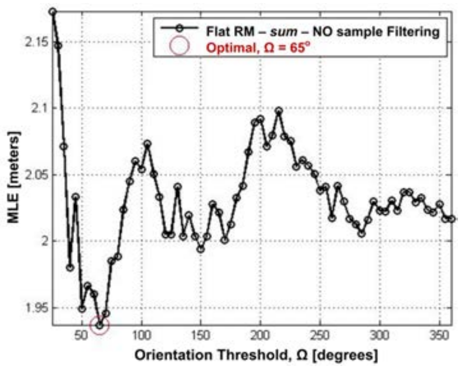
In Figure 3.3(a), the superiority of the Flat RM cases over the Merged RM cases illustrates the improvement in MLE after JLO-based calibration for the deterministic case



a Impact on the after J based calibration for the t o probabilistic in schemes.



b Impact on the after sample lter for the probabilistic scheme *sum*.



c versus orientation threshold for the probabilistic scheme *sum*. ptimal case hen ^{o}.

Figure 3.2: Performance Analysis of Probabilistic Fingerprinting.

as well. However, regarding the Sample Filtering module, if applied, now we observe that the MLE can be further decreased for both RM representations. This is due to the limitation of the simple average to include information regarding the reliability of the samples. Overall, the best accuracy (MLE = 1.75 meters) is achieved when we perform both enhancements and the coordinates of $k = 7$ 10 NNs are averaged.

In the sequence, we assume the availability of digital compasses during the online phase as well and we examine if this additional information can further improve the accuracy of the system. Figure 3.3(b) shows the MLE for different values of the orientation threshold, Ω. The minimum MLE is achieved for high values of Ω, therefore, there is no need for additional hardware equipment during the actual runtime of the system, in contrast with the probabilistic case.

Comparing the performance of our optimum probabilistic and deterministic schemes, an interesting remark can be made. Even though deterministic approaches are considered as less accurate, we observe that the accuracy of our optimum deterministic approach is better than its probabilistic counterpart, keeping at the same time the advantage of low processing and storage requirements. For that reason, in the sequence we focus our attention on the deterministic case only and attempt to further improve its performance in terms of accuracy and time response as well.

In Figure 3.3(c) we examine the impact of the number of APs, l, that should be considered in eq. (3.5). The x axis corresponds to the number of APs. Note that it is important not only how many APs but also which APs are considered. However, considering all possible AP combinations was not trivial due to the large number of the available APs. Thus, we decided to first consider only the mode-1 APs (real APs) and then include the mode-3 APs (peers in adhoc mode), since the former were more frequently scanned. We observe that the MLE is improving as l increases until it exceeds a certain value. This justifies our claim that more information improves the accuracy but at the same time the phenomenon of aliasing becomes more possible. The minimum MLE is achieved when $l = 10$ APs, which is also the average number of the visible APs from each position. Thus, a general conclusion that could be made after these observations is that, for each online user case u an AP m should be included in eq. (3.5) if it is visible by this user u, i.e. $SS_{um} \forall\!\!\neq 0$.

The main drawback of the Flat RM scheme is the large size of the resulting RM, which degrades the time response and resource utilization. The Hierarchical RM and the corresponding mk-NNSS algorithm were proposed for reducing the time for searching the candidate locations. In Figure 3.3(d) both the MLE and MLT are examined for the two cases of k, i.e. either equal to 7 or adaptive, as described in section 3.4.2. The main observation is that with the Hierarchical RM the achieved accuracy is better compared to Flat RM scheme and this justifies our motivation behind the mk-NNSS algorithm. Additionally, comparing the two cases of the parameter k, we remark that the adaptive case decreases not only the MLE but also the time response of the system since the minimum possible MLE is achieved for lower value of the parameter m.

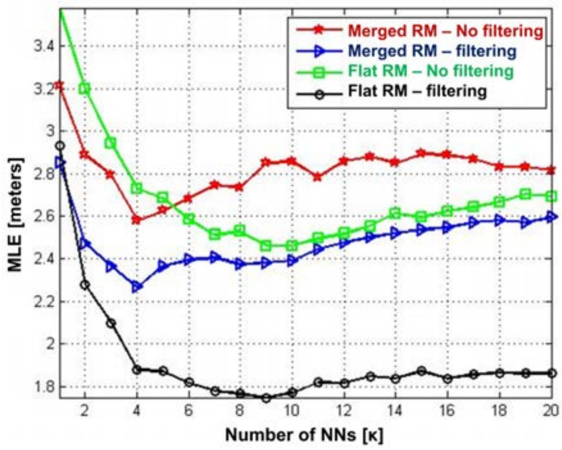
3.5.4 Comparison with other Systems

Finally, we compare the performance of the best deterministic and probabilistic schemes, with RADAR and COMPASS for the same experimental environment. For the deterministic case, optimal performance is achieved when JLO-based calibration and filtering are deployed and the hierarchical RM representation and pattern matching concepts are followed. We term this scheme as OPT-D. Additionally, we differentiate between the two cases regarding k. For the probabilistic case, the optimal performance is achieved with JLO-based calibration, the *sum* similarity metric and selection of RM points with similar to the user orientation. We term this scheme as OPT-P. Table 3.1 summarizes the main performance characteristics for all systems.

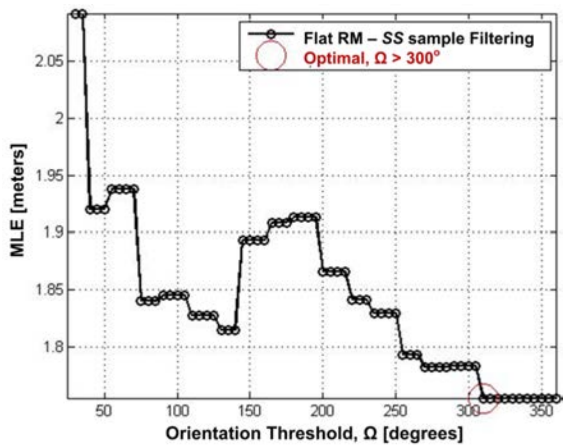
Regarding accuracy in terms of MLE, both OPT-D schemes are superior, with a slight increase when k value is adaptive. OPT-P is better compared to RADAR but less accurate than COMPASS. Regarding the Worst Error (WE), we achieved an impressive reduction for all of our schemes. Regarding the complexity and storage requirements for building the RM during the offline phase, deterministic approaches have less, since for each point only the mean values of the RSSI samples from all APs need to be measured and stored. On the contrary, for probabilistic schemes, the probability distributions of all RSSI sample values need to be calculated and stored.

Regarding the time response, for our deterministic schemes, we report an increase in the RM size. For the OPT-D and COMPASS the RM is less due to the selection only of $\gamma = 2$ RM entries with orientation similar to the user's.

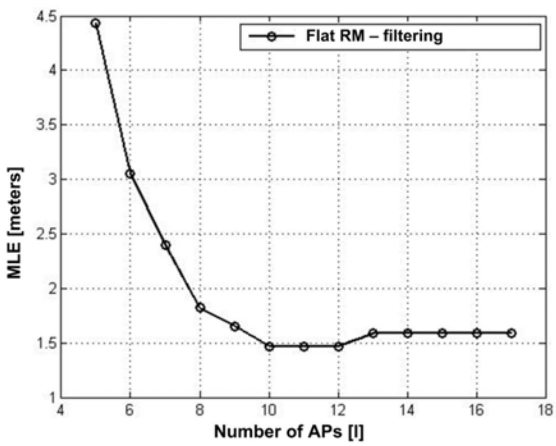
Finally, regarding the hardware requirements, RADAR does not rely on a digital compass, our deterministic schemes require it only during the offline phase, whereas both our probabilistic proposal and COMPASS have this additional requirement during the entire positioning process.



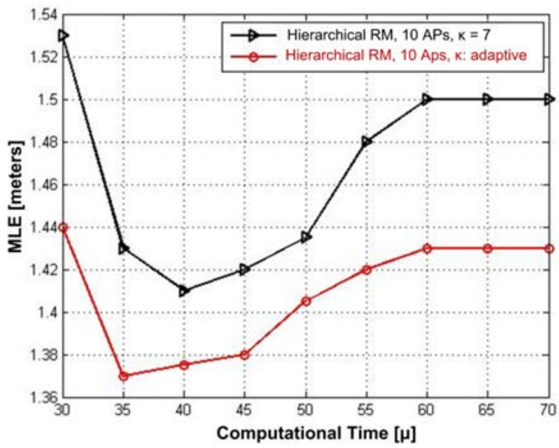
a Impact on the after J calibration and sample lterin for the deterministic scheme.



b versus orientation threshold for the deter ministic scheme. ptimal case hen > ^{o}.



c Impact on the of the number of considered s for the deterministic scheme.



d Impact on the and C after hierarchical pattern matchin for the t o deterministic schemes.

Figure 3.3: Performance Analysis of Deterministic Fingerprinting.

Table 3.1: Comparison with other systems

System	MLE	WE	OCT	Type	Compass	
					offline	online
OPT-D, $k = 7$	1.41	4.10	486	Det.	✓	
OPT-D, k : ad.	1.37	3.83	446	Det.	✓	
OPT-P, *sum*	1.94	3.93	332	Prob.	✓	✓
RADAR	2.26	15	166	Det.		
COMPASS	1.65	11	332	Prob.	✓	✓

3.6 Chapter Summary

This chapter focused on the case of indoor location determination based on the received signal intensity from the existing 802.11 wireless data network. Following the concept of fingerprinting technique, we studied both deterministic and probabilistic cases and proposed the incorporation of simple additional modules in the positioning mechanism for mitigating the shortcomings of WiFi-based localization. Our main contributions include: considering orientation information and filtering incompatible RSSI samples during the training or the entire operation and an hierarchical pattern matching algorithm for selecting candidate locations from the training set during the run-time process. Additionally, the impact of two design parameters was discussed. More precisely, we suggested including RSS information from less APs and adapting the number of candidate locations depending on each user RSS characteristics. Numerical results based on real experimental evaluation of our proposals showed accuracy enhancement, especially for the deterministic case, without sacrificing considerably the time-efficiency of the localization process.

Chapter 4

RFID Reader Localization

Radio Frequency Identification (RFID) is a rapidly developing wireless technology with key features which anticipate its outstanding position in the upcoming era of pervasive computing. Even though object identification is its primary objective, it is generally accepted that RFID systems can revolutionize various commercial applications. A RFID system consists of three basic component types, readers, tags (passive or active), and servers [72]. Key properties of RFID, such as low cost and indefinite lifetime of passive tags, non line of sight requirement, simultaneous and fast reading of multiple tag IDs, resilience to environmental changes, reduced sensitivity regarding user orientation motivated the research over RFID-based positioning schemes. Correlating tag IDs with their location coordinates is the principle concept for their realization.

Though RFID offers promising benefits for accurate and fast tracking, there are some technology challenges that need to be addressed and overcome in order to fully exploit its potential. Admittedly, the interference problem among its components and from non-conductive materials is the main shortcoming of RFID [14]. Actually, there are three main types of RFID interference. The first one is due to the concurrent responses of multiple tags to a single reader's query, the second is related to the queries of multiple readers to a single tag and finally, the third is due to the low signal power of weak tag responses compared to the stronger neighbor readers' transmissions. The first type affects the time response of the system, whereas the other two reduce the positioning accuracy. In addition, interference from non-conductive materials such as water or glass, imposes one more concern regarding the appropriateness of RFID for widespread deployment.

The main goal of this chapter is to explore the applicability of RFID for indoor location sensing. To that end, we study the impact of several interference types on its performance. Focusing on the case of determining the location of mobile terminals with reader extension by relying on a deployment of tags, we consider three RFID positioning schemes which are easily-implemented but differ in their memory and computation requirements. Mathematical models are derived for describing the main interference types and their influence on the accuracy and time response of these schemes. Finally, extensive simulation analysis is conducted for exploring the practicality and efficacy of RFID for the localization of single or multiple users under different levels of environmental harshness. Numerical results validate the potential of RFID in location sensing but also the requirement for careful design of RFID-based positioning systems.

The rest of this chapter is organized as follows: section 4.1 provides the essential background and related work for RFID localization while in section 4.2 we justify our motivation for conducting this study. In section 4.3 the conceptual framework of a RFID-based positioning system is described and section 4.4 provides its theoretical and simulation-based analysis. Finally, in section 4.5 we draw our main conclusions.

4.1 RFID Localization

This section gives an overview of the RFID technology from the localization perspective and reviews popular RFID positioning systems found in the literature.

4.1.1 RFID Technology Overview

RFID has a relatively long history of more than 50 years in the field of wireless communications, but only the last decade it has received a considerable attention for becoming a useful general purpose technology. Actually, RFID was initially developed as an automatic identification system consisting of three basic component types, readers, tags, and servers [72]. RFID tags are simple devices with main purposes storing their ID and transmitting it to a reader. Many types of RFID tags exist, but at the highest level, they can be divided into two classes: active and passive. Active tags require a power source such as an integrated battery. Passive tags do not need a battery to operate, they just backscatter the carrier signal received from a reader. This makes their lifetime large and cost negligible. Readers are responsible for communicating with tags and an application. To that end, they have two interfaces. The first one is a RF interface enabling them to read the IDs of tags with their vicinity by running a simple link-layer protocol over the wireless channel. The second one is a communication interface, such as IEEE 802.11, for enabling communication with servers. Servers are back-end entities responsible for receiving and processing the information sent from the readers.

Key benefits of RFID, such as low cost and indefinite lifetime of passive tags, non line of sight requirement, simultaneous and fast reading of multiple tag IDs, resilience to environmental changes, reduced sensitivity regarding user orientation, inspired the academia and industry for exploring its potentials in more intelligent applications, such as supply chain management, object or people tracking, real-time inventory, retail, anti-counterfeiting, baggage handling, and health-care [73] and more recently for indoor localization.

4.1.2 RFID Positioning and Systems

RFID positioning systems can be broadly divided into two classes: *tag* and *reader localization*, depending on the RFID component type of the target.

In *tag localization* schemes, readers and possibly tags are deployed as reference points within the area of interest and a positioning technique is applied for estimating the location of a tag. SpotON [54] uses RSS measurements to estimate the distance between a target tag and at least three readers and then applies trilateration on the estimated distances. LANDMARC [55] follows a scene analysis approach by using readers with different power levels and reference tags placed at fixed, known locations as landmarks. Readers vary their read range to perform RSS measurements for all reference tags and for the target tag. The k nearest reference tags are then selected and their positions are averaged to estimate the location of the target tag. Wang et al. [74] propose a 3-D positioning scheme which relies on a deployment of readers with different power levels on the floor and the ceiling of an indoor space and uses the Simplex optimization algorithm for estimating the location of multiple tags. LPM [75] uses reference tags to synchronize the readers. Then, TDoA principles and ToA measurements relative to the reference tags and the target tag are used to estimate the location of the target tag. In [76] RSS measurements from reference tags are collected to build a probabilistic radio map of the area and then, the Kalman filtering technique is iteratively applied to estimate the target's location.

If the target is a RFID reader, usually passive or active tags with known coordinates are deployed as reference points and their IDs are associated with their location information. In [77] passive tags are arranged on the floor at known locations in square pattern. The reader acquires all readable tag locations and estimates its location and orientation by

Table 4.1: RFID Localization systems.

System	Target	Deployment	Approach	Accuracy
SpotOn [54]	Tag	Readers	RSS trilateration	3 m
Landmarc [55]	Tag	Readers and Tags	RSS Scene Analysis	1 - 2 m
Simplex passive[74]	Tag	Readers and Tags	RSS proximity and optimization	0.3 - 3 ft
LPM [75]	Tag	Readers and Tags	TDoA weighted mean squares	-
Kalman [76]	Tag	Readers and Tags	RSS mean squares and Kalman filtering	0.5 - 5 m
Lee [77]	Reader	Tags (dense)	RSS Proximity	0.026 m
Han [78]	Reader	Tags (dense)	Training and RSS Proximity	0.016 m
SVM [79]	Reader	Tags	RSS Scene Analysis	80%
Bayesian [80]	Reader	Tags	Proximity and Bayesian Inference	1.5 m
Simplex active[74]	Reader	Tags	RSS proximity and optimization	0.2 - 0.5 ft

using weighted average method and Hough transform, respectively. Han et al. [78] arrange tags in triangular pattern so that the distance in x-direction is reduced. They show that the maximum estimation error is reduced about 18% from the error in the square pattern. Yanano et al. [79] utilize the received signal strength to determine the reader position by using machine learning technique. In the training phase, the reader acquires the RSS from every tag in various locations in order to build a Support Vector Machine (SVM). Since it is not possible to obtain the signal intensity from every location, they also propose a method to synthesize the RSS data from real RSS data acquired in the training phase. When the reader enters the area, it will pass the received signal intensity vector to the SVM to determine its position. A Bayesian approach is also proposed to predict the position of a moving object [80]. Having the posterior movement probability and the detected tags' locations, the reader location is determined by maximizing the posterior probability. Then, the reader position is calculated by averaging the inferred position from all tags. However, the accuracy of the algorithm depends on the movement probability model. Finally, [74] proposes also a reader localization scheme by employing the Simplex optimization method. Table 4.1 summarizes the main characteristics of the above systems.

4.2 Our Motivation: The Interference Problem in RFID

Selecting a best scheme is apparently not trivial since this depends on several factors such as deployment cost, processing requirements, time and power constraints, scalability issues etc. In this chapter, we focus on the second type of positioning schemes, i.e. *reader localization* systems, because they are easier to implement as low cost passive tags can be deployed in a large extent in most indoor environments. Additionally, it is anticipated that future mobile terminals will have a reader extension capability for gaining access at a wide range of innovative applications and services supported by RFID systems.

The goal of this chapter is definitely not proposing a novel positioning algorithm. Actually, our motivation stems from the lack in the literature of a research study regarding the impact of the interference problem, which is persistent in RFID, on the localization performance. Even though RFID is a promising technology for localization, the interference problem should be extensively studied before the development of RFID-based localizers. To that end, we have selected three positioning algorithms differing in their complexity level in order to investigate their behavior when multiple reader-enabled mobile nodes need to be localized simultaneously. We believe that examining this parameter is crucial for verifying the efficiency of employing RFID in general location sensing applications.

In the following we demonstrate and model the main RFID interference types and their impact on the localization performance. In addition, proposed mechanisms for dealing with each type are also outlined.

4.2.1 Multiple Tags-to-Reader Interference

When multiple tags are simultaneously energized by the same reader, they reflect simultaneously their respective signals back to the reader. Due to a mixture of scattered waves, the reader cannot differentiate individual IDs from the tags. This type of interference is known as multiple tags-to-reader interference or tag identification problem.

4.2.1.1 Anti-collision Algorithms

For resolving multiple tag responses an anti-collision mechanism is essential. Reviewing the literature, several anti-collision protocols have been proposed, such as time-division multiple or binary tree-based schemes [14]. For instance, the EPCglobal [81], an organization that recognized the potential of RFID early, proposed bit-based Binary Tree algorithm (deterministic) and Aloha-based algorithm (probabilistic). The International Standards Organization (ISO) as part of the ISO 18000 family proposed the Adaptive Protocol which is similar to the Aloha-based algorithm proposed by EPCglobal, and binary tree search algorithm. These protocols mainly differ in the number of tags that can be read per second, their power and processing requirements.

In this work, we selected the Pure and Slotted Aloha schemes [82] as basis for our analysis. Let $\mathcal{G}_u$ the set of tags simultaneously energized by the reader r_u. When reading starts, each tag transmits its ID irrespectively of the rest $\mathcal{G}_u \quad 1$ tags. The communications from a tag to the reader is modeled as a Poisson process [83]. Each tag responds on average λ times per second. The model requires independence among tag transmissions, which is supported by the lack of tag-to-tag communication capabilities. Since each tag's transmission is Poisson distributed, there is a mean delay of $1/\lambda$ between consecutive transmissions. This is referred to as the arrival delay [83]. Thus, on average each tag takes $\frac{1}{|\mathcal{D}_u|\lambda}$ time to transmit its ID for the first time. This is referred as arrival delay [83]. During collisions, colliding tags retransmits after a random time. In Aloha-based schemes, the retransmission time is divided into K time slots of equal duration s and each tag transmits its ID at random during one of the next time slots with probability $1/K$. This means tags will retransmit within a period of $K \pm s$ after experiencing a collision. On average, a tag will retransmit after a duration of $\frac{K+1}{2} \pm s = a$ slots. The number of collisions before a tag successfully responds is $e^{xG_A} \quad 1$, where e^{xG_A} denotes the average number of retransmission attempts made before a successful identification, where $G_A = \mathcal{G}_u \lambda s$ is the offered load and $x = 1$ for Pure Aloha (PA) and $x = 2$ for Slotted Aloha (SA). Since each collision is followed by a retransmission, the average delay before a successful response is $(e^{xG_A} \quad 1)a$, followed by a single successful transmission of duration s. In total, the average delay a tag takes to transmit its ID successfully is $\mathrm{t}_{TR} = (e^{xG_A} \quad 1)as + s + \frac{1}{|\mathcal{D}_u|\lambda}$. For non-saturated case, i.e. tags to be detected are less than the maximum number of tags that can be read per inventory round, the total time needed for reading successfully $\mathcal{G}_u$ tags follows the linear model

$$\mathrm{T}_{TR} = \mathcal{G}_u \pm \mathrm{t}_{TR} = \mathcal{G}_u \pm \Big\} s \Big] 1 + (e^{xG_A} \quad 1)a \Big(+ \frac{1}{\mathcal{G}_u \lambda} \Big(. \tag{4.1}$$

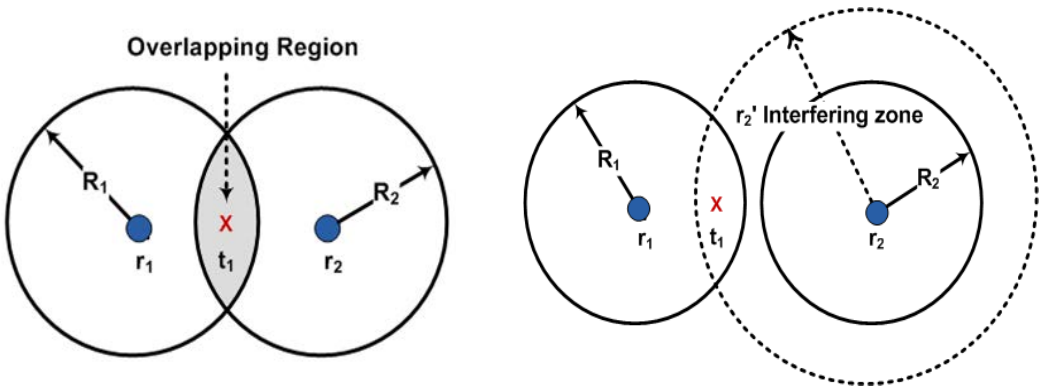
4.2.2 Multiple Readers-to-Tag Interference

Multiple readers-to-tag interference occurs when a tag is located at the intersection of two or more readers' interrogation range and the readers attempt to communicate with this tag simultaneously. Let R_i and R_j denote the read ranges of readers r_i and r_j and d_{ij} their distance. Apparently, if

$$R_i + R_j > d_{ij} \tag{4.2}$$

and r_i and r_j communicate at the same time, they will collide and the tags in the common area will not be detected.

Figure 4.1(a) depicts two readers r_1 and r_2 which transmit simultaneously query messages to a tag t_1 situated within their overlapping region. t_1 might not be able to read the query messages from neither r_1 nor r_2 due to interference.



a any eaders to a Interference. b eader to eader Interference.

Figure 4.1: Two types of interference in RFID.

4.2.2.1 Reader Collision Probability

The probability P_{ij}^C of such collision type between readers r_i and r_j, if equation (4.2) is satisfied, depends on the probabilities r_i and r_j are simultaneously trying to communicate with their common tag. For characterizing the probability of simultaneous reader communication, we assume that each reader is in a scanning mode with probability p^{scan}. Thus, P_{ij}^C depends on the probabilities r_i and r_j are in a scanning mode, p_i^{scan} and p_j^{scan}, respectively, i.e.

$$P_{ij}^C = p_i^{scan} \pm p_j^{scan}. \tag{4.3}$$

A mechanism coordinating reader transmissions as the one proposed in [21] can compensate this type of interference.

4.2.3 Reader-to-Reader Interference

Reader-to-reader interference is induced when a signal from one reader reaches other readers. This can happen even if there is no intersection among reader interrogation ranges ($R_i + R_j < d_{ij}$) but because a neighbor reader's strong signal interferes with the weak reflected signal from a tag. Figure 4.1(b) demonstrates an example of collision from reader r_2 to reader r_1 when the latter tries to retrieve data from tag t_1. Generally, signal strength of a reader is superior to that of a tag and therefore if the frequency channel occupied by r_2 is the same as that between t_1 and r_1, r_1 is no longer able to listen to t_1's response.

4.2.3.1 Read Range Reduction

Reader-to-reader interference affects the read range parameter. In equation (4.8) this factor had been neglected. However, when interfering readers exist, the actual interrogation range of the desired reader decreases to a circular region with radius R^I_{max}, which can be represented by

$$R^I_{max} = \arg\max_{d \in [0, R_{max}]} SIR(d) \approx TH, \quad (4.4)$$

where

$$SIR(d) = \frac{P_s(d)}{\bigcup_i I_i} \quad (4.5)$$

and I_i the interference from reader r_i.

The Class 1 Gen 2 Ultra High Frequency (UHF) standard ratified by EPCGlobal [81], separates the readers' from tags' transmissions spectrally such that tags collide only with tags and readers collide only with readers.

4.2.4 Interference from Nonconductive Materials

Since RFID technology uses electromagnetic waves for communication, interference from specific materials such as glass or water is unavoidable. This prevents tags being detected from a reader even though they are located with its zone. For incorporating this characteristic in the model, each reference tag t is assigned a probability p_t of not being detected. Obviously high values of p_t are assigned to tags which are mounted to such interfering materials.

4.3 Positioning Framework

In this section, we initially model a RFID system and the communication principles among its components and later we provide the architecture and processing details of the positioning schemes we consider.

4.3.1 RFID System and Communication Model

We model an indoor environment as a 2-D area with L and W denoting its length and width respectively. A set $\mathcal{U}$, of passive RFID tags with known coordinates (x_t, y_t), $\mathcal{C}t \ / \ \mathcal{U}$ are placed on the floor of this area such that a grid of *reference* tags is formed with inter-tag spacing δ. Within this area, we consider a set $\lceil$ of users with RFID reader-enabled terminals which are randomly located and an accurate and fast estimation of their position $(\widetilde{x}_u, \widetilde{y}_u), \mathcal{C}u \ / \ \lceil$ should be obtained.

The communication between a reader and a passive tag is done using either magnetic or electromagnetic coupling. Coupling is the transfer of energy from one medium to another medium, and tags use it to obtain power from the reader to transfer data. There are two main types of coupling, inductive and backscatter, depending on whether the tags are operating in the near-field or far-field of the interrogator, respectively. A key difference between them is that far-field communication has a longer read range compared to near field communication. RFID systems operate in the Industry, Scientific and Medical (ISM) frequency band that ranges from 100 KHz to 5.8 GHz but they are further subdivided into four categories according to their operating frequency: Low Frequency (LF), High Frequency (HF), Ultra-High Frequency (UHF) and Microwave. Tags operating at UHF and microwave frequencies use far-field and couple with the interrogator using backscatter. Recently, ultra-high frequency (UHF) passive RFID systems have received a great deal of attention and thus, we focus our research interest on these tag types.

The communication link between the main RFID components is half duplex, reader to tag and then tag to reader. In the forward link, the reader's transmitting antenna (transmitter) sends a modulated carrier to tags to power them up. In the return link, each tag receives the carrier for power supply and backscatters by changing the reflection coefficients of the antenna. In such a way, its ID is sent to the reader's receiving antenna (receiver). The path loss of this two way link may be expressed as

$$PL(d) = PL_o + 10N \log \left(\frac{d}{d_o} \right) + X_\sigma, \tag{4.6}$$

where d the distance between the reader and a tag, PL_o the path loss at reference distance d_o given by $PL_o = G_tG_r(g_t\Gamma g_r)\Big)\frac{\lambda}{4\pi d_o}\Big(^N$ and G_t, g_t, and G_r, g_r are the gains of the reader and tag transmit and receive antennas, respectively. Γ is a reflection coefficient of the tag and λ the wavelength. $N = 2n$, where n the path loss component of the one way link. The path loss model defines the received power $RSS(d)$ at the receiver given the transmit power P_t of the transmitter, i.e.

$$RSS(d) = P_t \quad PL(d). \tag{4.7}$$

In the absence of interference, the maximum read range a reader receiver can decode the backscattered signal is such that

$$R_{max} = \arg\max_{d \geq 0} RSS(d) \approx TH, \tag{4.8}$$

where TH represents a threshold value for successful decoding.

Ideally, it is assumed that the signal transmission from each reader forms a circle with radius R_{max} if omnidirectional antennas are considered. However, in practice this is not real due to different signal gains at different directions. To quantify this problem a Degree of Irregularity (DoI) has been proposed in [74], according to which if R_u and R_l the maximum and minimum values of a reader transmission range, then DoI is the maximum variation of the reader's transmission range per unit degree change.

4.3.2 Positioning System Architecture

Figure 4.2 depicts the positioning system architecture. The reader embedded at each user device queries for reference tags within its coverage in order to retrieve their IDs. Then, the list of the retrieved tag IDs with the corresponding RSS levels is forwarded to the *Location Server* within a TAG LIST message. Based on the received TAG LIST messages and a repository which correlates the IDs of the *reference* tag with their location coordinates, the *Location Server* estimates the location for all users by employing a RFID-based positioning (see subsection 4.3.3) algorithm and finally returns the estimated locations back to the corresponding users in LOCATION ESTIMATE messages.

The communication between the reader and the tags is done through the RF interface of the reader, whereas the communication between the reader and the server is possible through the communication interface of the reader, such as IEEE 802.11. Alternatively, assuming multi-mode devices, the TAG LIST and location estimation messages can be exchanged by the wireless interface of the user device.

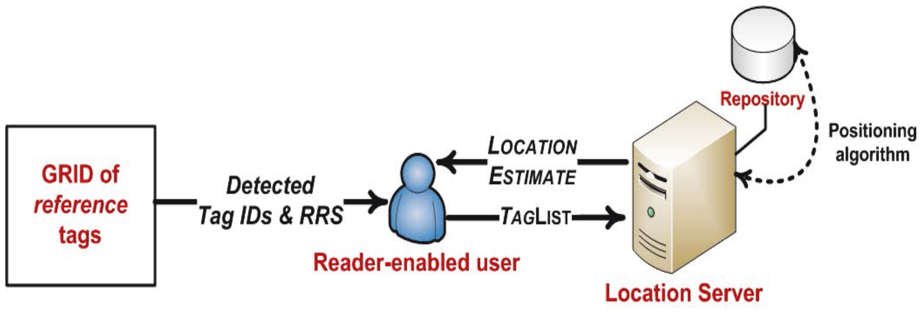


Figure 4.2: RFID-based Positioning System Architecture.

It is worthy mentioning that the proposed architecture may not always be the optimal choice. For example, if the wireless medium between users and the *Location Server* (LS) is not robust enough for exchanging messages successfully, a user-based approach would be more efficient. In this case, when a new user enters the indoor area it can receive information regarding the tag deployment automatically or after having subscribed to a relevant service. Then, by following a positioning algorithm, it can estimate its own location. However, in such approach, greater attention should be given regarding the complexity of the positioning algorithm since mobile terminals have limited resources compared to servers.

4.3.3 Positioning Algorithms

A positioning algorithm defines the method of processing the available information in order to estimate the target's location. The main metrics for evaluating its performance are its accuracy, memory requirements and complexity. In this chapter, we study three positioning algorithms which can be easily implemented in the sense that they do not require any special hardware, but differ in their complexity and memory requirements.

Let $\mathcal{G}_u$ denote the set of *reference* tags successfully detected from a user's reader r_u and $\mathbf{SS}_u$ a vector of the corresponding RSS measurements such that the entry RSS_t is the RSS from the tag t / $\mathcal{G}_u$ to r_u.

4.3.3.1 Simple Average (S-AVG)

This algorithm is based on the assumption that the reader radiation pattern forms a perfect circle. Thus, the user's location is estimated as the simple average of the coordinates

(x_t, y_t) of all tags $t \; / \; \mathcal{G}_u$, i.e.

$$(\widetilde{x}_u, \widetilde{y}_u) = \Big) \frac{\bigcup_{t \in \mathcal{D}_u} x_t}{\mathcal{G}_u}, \frac{\bigcup_{t \in \mathcal{D}_u} y_t}{\mathcal{G}_u} \Big\lfloor \tag{4.9}$$

This scheme has the minimum memory requirements since only the ID information from the detected *reference* tags is used for estimating the unknown location. Regarding its processing requirements, it involves $2 \pm \; \mathcal{G}_u$ additions of the coordinates of the detected tags and two divisions. Therefore, it has linear complexity $O(\; \mathcal{G}_u \;)$.

4.3.3.2 Weighted Average (W-AVG)

Since some of the detected tags may be closer than others, biasing the simple averaging method is proposed as an alternative approach. This can be achieved by assigning a weight w_t to the coordinates of each tag $t \; / \; \mathcal{G}_u$. These weights are based on their RRS from the reader. Thus, (4.9) becomes

$$(\widetilde{x}_u, \widetilde{y}_u) = \Big) \frac{\bigcup_{t \in \mathcal{D}_u} w_t \times x_t}{\bigcup_{t \in \mathcal{D}_u} w_t}, \frac{\bigcup_{t \in \mathcal{D}_u} w_t \times y_t}{\bigcup_{t \in \mathcal{D}_u} w_t} \Big\lfloor \tag{4.10}$$

where $w_t = 1/ \; RSS_t$ and RSS_t the measured RSS value from tag t.

This scheme requires more memory than the S-AVG, since RSS information is used in addition to tags' IDs for estimating the unknown location. Regarding its processing requirements, it involves $4 \pm \; \mathcal{G}_u$ addition, $2 \pm \; \mathcal{G}_u$ multiplication and 2 division operations. Thus, its complexity remains linear, i.e. $O(\; \mathcal{G}_u \;)$.

4.3.3.3 Multi-Lateration (ML)

Finally, we investigate a multi-lateration based approach which tries to take into account the imperfection of the readers' radiation pattern. The distances from all detected tags $\mathcal{G}_u$ are first estimated and then (x_u, y_u) can be obtained by solving the following system of $\mathcal{G}_u$ equations

$$\begin{gathered}
(x_1 \quad x_u)^2 + (y_1 \quad y_u)^2 = \widetilde{d}_1^2 \\
\cdot \\
\cdot \\
\cdot \\
(x_{|\mathcal{D}_u|} \quad x_u)^2 + (y_{|\mathcal{D}_u|} \quad y_u)^2 = \widetilde{d}_{|\mathcal{D}_u|}^2
\end{gathered} \tag{4.11}$$

The above system of equations is not linear. According to [84] it can be linearized by subtracting the last equation from the first $|\mathcal{G}_u| - 1$ equations. The resulting system of linear equations is then given by the following matrix form

$$\mathbf{A}[x_u, y_u]^T = \mathbf{b}, \tag{4.12}$$

where

$$\begin{aligned}
\mathbf{A} &:= \begin{pmatrix} 2(x_t - x_1) & 2(y_t - y_1) \\ \vdots & \vdots \\ 2(x_t - x_{|\mathcal{D}_u|}) & 2(y_t - y_{|\mathcal{D}_u|}) \end{pmatrix}, \\
\mathbf{b} &:= \begin{pmatrix} x_1^2 - x_{|\mathcal{D}_u|}^2 + y_1^2 - y_{|\mathcal{D}_u|}^2 + \widetilde{d}_1^2 - \widetilde{d}_{|\mathcal{D}_u|}^2 \\ \vdots \\ x_{|\mathcal{D}_u|-1}^2 - x_{|\mathcal{D}_u|}^2 + y_{|\mathcal{D}_u|-1}^2 - y_{|\mathcal{D}_u|}^2 + \widetilde{d}_{|\mathcal{D}_u|-1}^2 - \widetilde{d}_{|\mathcal{D}_u|}^2 \end{pmatrix}.
\end{aligned} \tag{4.13}$$

Since $\widetilde{d}_t$ are not accurate, the above system of equations can be solved by a standard Least Squares (LS) approach [84] as:

$$[\widetilde{x}_u, \widetilde{y}_u]^T = (\mathbf{A}^T\mathbf{A})^{-1}\mathbf{A}^T\mathbf{b} \tag{4.14}$$

with the assumption that $\mathbf{A}^T\mathbf{A}$ is nonsingular and $|\mathcal{G}_u| \approx 3$, i.e. at least three tags are detected. This scheme has similar memory requirements with the W-AVG. However, it has polynomial complexity $O(|\mathcal{G}_u|^3)$ and it involves complex matrix operations such as creating an inverse matrix.

4.4 Simulation-based Performance Analysis

In this section we analyze and evaluate the performance of the studied localization schemes through simulations, using Matlab [85] as the simulation tool. Firstly, the simulation settings are specified, then the performance objectives are defined and finally, numerical results demonstrate the behavior of RFID in localization for different system design and environment characteristics.

4.4.1 Simulation Specifications

Table 4.2 summarizes the simulation parameters with their default and varied values during the performed simulations.

Table 4.2: Simulation Parameters

Parameter	Symbol	Default	Varied Range
Area size $[m^2]$	$L \pm W$	50 ± 50	-
Inter-tag spacing $[m]$	δ	1, 2	$[1, 5]$
# of users	$\lceil$	1, 20, 40	$[1, 50]$
RFID frequency $[MHz]$	f	915	-
PL shadowing variance $[dB]$	σ	3.3	$[2, 6]$
Path loss exponent	N	3.6	-
Read range $[m]$	R_{max}	3, 5	$[3, 5]$
Degree of Irregularity	doi	0.3	-
Tag response rate	λ	30	-
# slots/transmission time	K	5	-
Slot duration $[ms]$	s	0.90	-
Reader scan prob.	p^{scan}	1	$U(\beta, 1) : \beta \ / \ [0, 1]$
Tag t non-detection prob.	p_t	0.1	$U(0, \alpha) : \alpha \ / \ [0, 1]$
WLAN link rate (Mbps)	R	2	
Propagation delay (μs)	T_{prop}	1	

The simulation environment is a rectangular area $50 \pm 50m^2$ where *reference* tags are placed in a grid fashion with inter-tag spacing δ. Within this area a set of users $\lceil$ with reader-enabled terminals are randomly located. For the UHF RFID path loss model in eq. (4.6) operating frequency is 915 MHz, $N = 3.6$ and $\sigma_2 \ / \ [2, 6]$.

Regarding the parameters of the Aloha anti-collision protocols we have set the rate of each tag's initial response $\lambda = 30$, the retransmission time is divided in $K = 5$ slots and each slot duration is $s = \frac{96}{106} = 0.90ms$ which corresponds to the time needed for transmitting an ID of length 96 bits over a link with data rate 106 kbps.

We assume that the probability p_u^{scan} a user u's reader r_u queries for tag IDs follows uniform distribution $U(\beta, 1)$, where $\beta \ / \ [0, 1]$ reflects the degree of *multiple-readers-to-tag* and *reader-to-reader* interference types. Indeed, when $\beta = 1$ all readers communicate simultaneously resulting in high level of interference, whereas when $\beta = 0$ the problems are less intense.

R_{max} denotes the maximum read range of each reader which depends on the transmit power, the decoding threshold TH, antenna gains, propagation losses, interference and shadowing, as shown in eq. (4.4).

The probability p_t a tag t is not detected follows uniform distribution $U(0, \alpha)$, where a / $[0, 1]$ characterizes the interference degree from the material of the objects the reference tags are mounted on.

Finally, for the communication between a reader (or wireless interface) and the *Location Server*, the IEEE 802.11b WLAN Standard [65] has been assumed with supported data rate R=2 Mbps and slot time $t_s = 20\mu s$. We have assumed an ideal transmission channel in terms of noise and interference and that the only cause of packet loss is due to their collisions. Collision happens when multiple nodes try to access a shared link at the same time. For wireless links, the multiple access procedure follows the IEEE 802.11 CSMA (Carrier Sense Multiple Access) mechanism. Each node senses the carrier before its transmission. If the link is busy, the node waits for a random back-off period before trying to transmit again. This back-off time follows the equation: back-off time $= CW \pm t_s$, where CW represents the size of contention window in each node whose value is between CW_{min} and CW_{max}. CW_{min} and CW_{max} represent the minimum and maximum size of the contention window. After each collision, the contention window size is doubled and the back-off time is doubled accordingly. For the 802.11b: $CW_{max} = 1023$ and $CW_{min} = 31$. Finally, the propagation delay T_{prop} during message transmission is less than or equal to $1\mu s$ for the IEEE 802.11.

4.4.2 Performance Objectives

In general, the main performance objectives a positioning scheme should satisfy are high accuracy and fast time response. Thus, we define the Mean Location Error (MLE) and Mean Localization Time (MLT) metrics for evaluating both objectives.

MLE is measured as the Euclidean distance between the actual and the estimated positions for all $\lceil$ users, i.e.

$$\text{MLE} = \frac{1}{\lceil} \prod_{u=1}^{|\mathcal{U}|} \overline{(x_u \quad \widetilde{x}_u)^2 + (y_u \quad \widetilde{y}_u)^2}. \tag{4.15}$$

For measuring the MLT the following time factors should be added:

1. the time T_{TR} needed for retrieving successfully all $\mathcal{G}_u$ tags' IDs within range, given

by eq. (4.1),

2. the time T_{R-S} needed for sending successfully the Tag List message from the reader (or user terminal) to the server,

3. the processing time T_{pr} of the positioning algorithm, which depends on its complexity,

4. the time T_{S-R} needed for sending successfully the location estimation from the server to the reader (or user terminal).

The times T_{R-S} and T_{S-R} include the transmission delay T_{tr}, the collision delay T_{col} for accessing the wireless medium and the propagation delay T_{prop}. The transmission delay T_{tr} depends on the message size in bits and the link rate R. For instance, the Tag List message includes mainly $\mathcal{G}_u \pm 96$ bits. The timestamp and some additional control bits are ignored. Thus,

$$T_{tr}^{R-S} \rightarrow \frac{96 \pm \mathcal{G}_u}{2 \times 10^6} = 48 \pm \mathcal{G}_u \ \mu s. \tag{4.16}$$

The collision delay depends on the anti-collision protocol. For instance, for the IEEE 802.11b Carrier Sense Multiple Access (CSMA) mechanism, the mean collision delay is given by

$$T_{col} = \frac{CW_{max} \quad CW_{min}}{2} \pm t_s = 10 \ ms. \tag{4.17}$$

4.4.3 Numerical Results

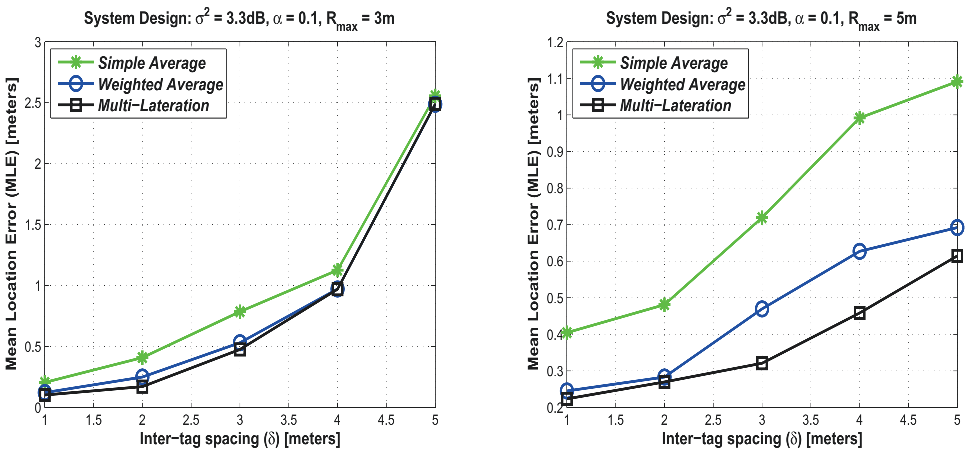
Numerical results based on the average of 1000 independent simulation executions are presented in the following. We first focus on the single-user case and study the impact of several system design and environmental parameters on the positioning performance. In the sequence, we consider the case of multiple co-located users in order to manifest the accuracy degradation due to the several interference types. Finally, we show that this performance degradation can be compensated if the interference problem is alleviated or solved.

4.4.3.1 Single-User Case

The principal parameters related to the design of the proposed RFID-based positioning system are the inter-tag spacing δ of the *reference* tags, the maximum read range R_{max} of the readers, the positioning algorithm (S-AVG, W-AVG or ML) and the anti-collision algorithm (PA or SA).

The environmental parameters characterize the severity of the indoor space. For our model, the main such tuning parameters are the shadowing variance σ in eq. (4.6) and the parameter α of the Uniform probability distribution function $U(a,1)$ followed by $p_t, \mathcal{C}t\ /\ \mathcal{U}$.

Figure 4.3 illustrates the dependency of the positioning accuracy on the inter-tag spacing δ and the three positioning algorithms when $R_{max} = 3m$ in Figure 4.3(a) and $R_{max} = 5m$ in Figure 4.3(b). The main observation is that for all cases, increasing the inter-tag spacing δ reduces the positioning accuracy, which is quite rational since less tags are detected by each reader. Comparing the three positioning algorithms, we remark that considering the RSS information and increasing the processing complexity results in better accuracy, especially when $R_{max} = 5m$. Regarding the two cases of the maximum read range, we observe that for $\delta \geq 2m$ both of them achieve low MLE less than $0.5m$. However, for $\delta \approx 3m$ when $R_{max} = 3m$ the accuracy reduction is much higher. This is because fewer tags are detected when the read range is reduced. On the other hand, when $R_{max} = 5m$ achieving high accuracy does not require a dense tag deployment ($\delta \approx 4m$), especially when the W-AVG or ML techniques are followed.

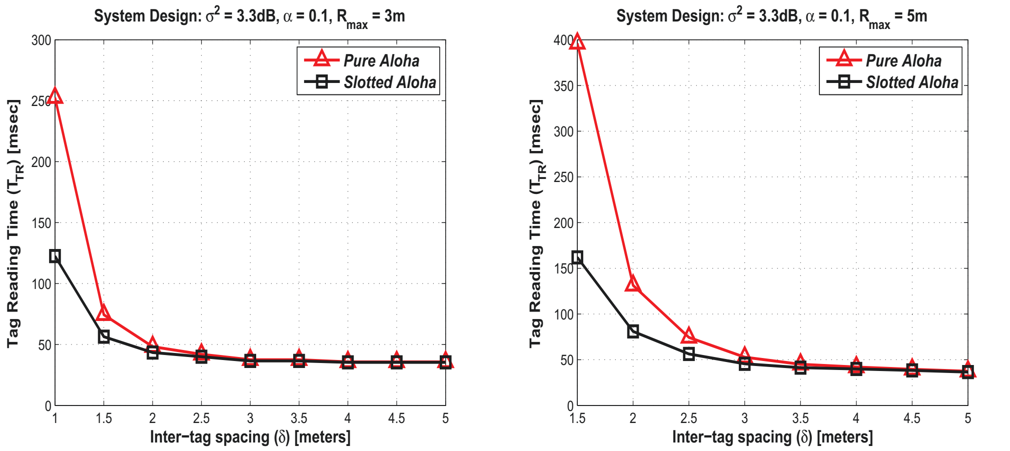


(a) MLE vs δ when $R_{max} = 3m$.

(b) MLE vs δ when $R_{max} = 5m$.

Figure 4.3: Impact of system design parameters on *Accuracy* for a single user.

In Figure 4.4 we study the time-response performance of the positioning system, focusing on the time needed for retrieving the ID information from detected tags, i.e. T_{TR}. From equation (4.1) we see that T_{TR} depends on the total number of detected tags $\mathcal{G}_u$ and the PA or SA anti-collision algorithm which affects parameter x. $\mathcal{G}_u$ depends on the reference tag density δ and the read range R_{max}. Obviously, as δ increases $\mathcal{G}_u$ decreases, whereas when R_{max} is higher more tags are detected. The MLT versus the inter-tag spacing δ for both anti-collision algorithms when $R_{max} = 3m$ and $R_{max} = 5m$ is depicted in Figure 4.4(a) and Figure 4.4(b), respectively. First of all, we observe that Slotted Aloha has better performance than Pure Aloha, due to the reduction of the vulnerability period $2s$ [86]. In both figures, when the grid deployment is dense, the tag reading time is very high due to the big number of responding tags. Comparing the two cases of R_{max} values, when $R_{max} = 3m$ less tags are within a reader's interrogation zone and thus, less reading time is required. Finally, recalling Figure 4.3, we conclude that there is a trade-off between the accuracy and time response objectives, regarding the optimal value of δ. More tags provide more information for the location determination process but on the other hand more time is required for detecting them.



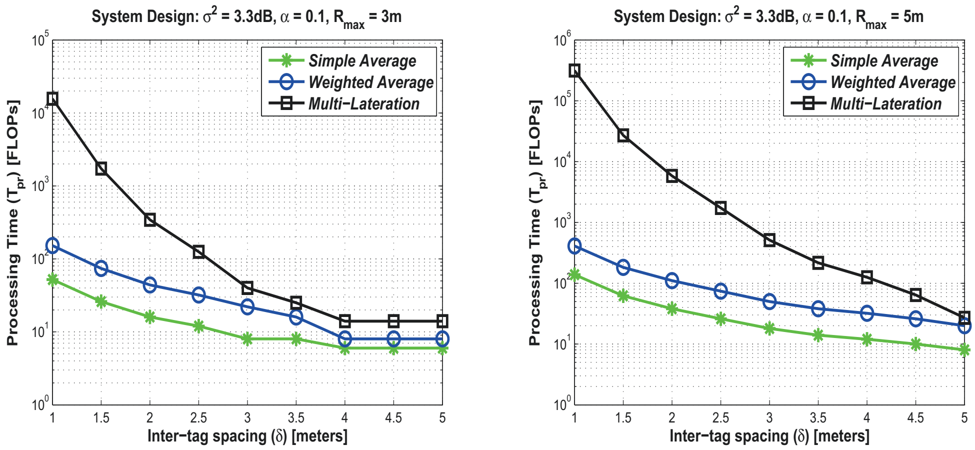
(a) Tag reading time vs δ when $R_{max} = 3m$.
(b) Tag reading time vs δ when $R_{max} = 5m$.

Figure 4.4: Impact of system design parameters on *Time Response*.

Figure 4.5 depicts the processing time T_{pr} (specified in flops[1]) of each positioning algorithm as the inter-tag spacing increases, for $R_{max} = 3m$ and $R_{max} = 5m$ in figures 4.5(a) and 4.5(b), respectively. The main observation is the high processing time of the Multi-Lateration approach for dense tag deployments. The most interesting remarks, however, can be made if Figure 4.3(b) is taken into account. The W-AVG approach has the best

[1] The execution time of a program depends on the number of floating-point operations (FLOPs) involved. Every computer has a processor speed which can be defined in flops/sec. Knowing the processor speed and how many flops are needed to run a program gives us the computational time required: Time required (sec) = Number of FLOPs/Processor Speed (FLOP/sec) [87].

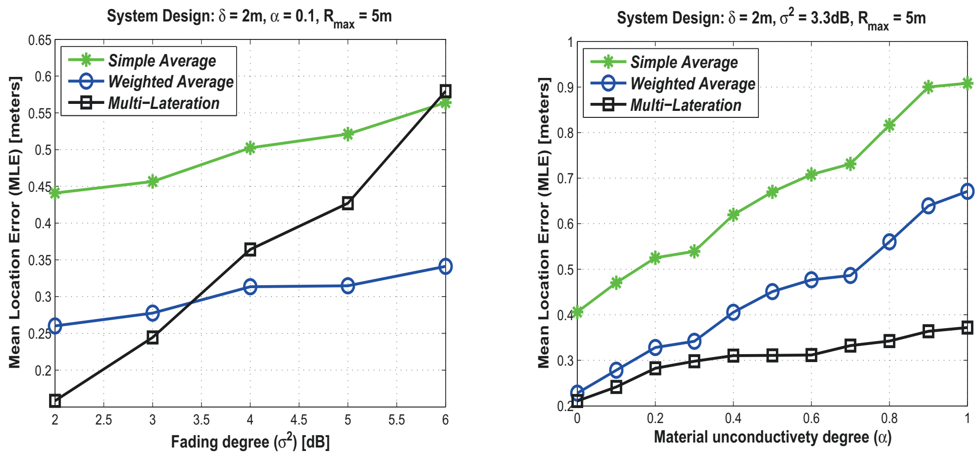
performance if both objectives are considered. Moreover, for $R_{max} = 5m$ and $\delta = 5m$, the accuracy of the ML technique is high without considerable processing cost. Therefore, more sophisticated techniques can alleviate the need for carefully designed systems.



(a) Processing time vs δ when $R_{max} = 3m$. (b) Processing time vs δ when $R_{max} = 5m$.

Figure 4.5: Impact of positioning algorithm on *Time Response*.

In general, the accuracy of indoor wireless positioning depends also on the characteristics of the environment. In Figure 4.6 we examine the impact of the shadowing variance σ and the interference level α from materials on the MLE for the three positioning algorithms. Regarding the shadowing level in Figure 4.6(a), we observe that the S-AVG and W-AVG positioning algorithms exhibit tolerance regardless the increase of σ, whereas the performance of the ML technique is greatly degraded. This is because ML's accuracy depends highly on the accuracy of the path loss model which is used for estimating the distance from each detected tag. On the other hand, the location coordinates of the detected tags are the principal factors for the S-AVG and W-AVG algorithms. Figure 4.6(b) depicts the MLE increase due to the interference rise from nonconductive materials as α increases. This factor is especially detrimental for the S-AVG and W-AVG algorithms, while the ML exhibits great tolerance. This is because in ML, detecting three tags is enough for accurate location estimation.



(a) MLE vs shadowing variance σ. (b) MLE vs interference level from materials α.

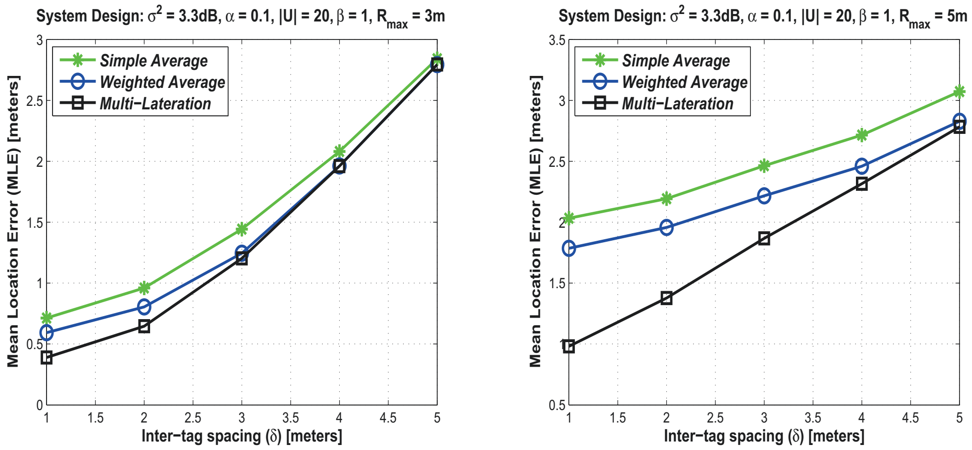
Figure 4.6: Impact of environmental parameters on *Accuracy* for a single user.

4.4.3.2 Multi-User Case

So far, we were considering only one user being randomly located in the indoor space and we were exploring the performance of RFID positioning. In the following, we consider the case of multiple co-located users and we repeat similar performance tests in order to manifest the accuracy reduction caused due to their interference.

Figure 4.7 is the corresponding of Figure 4.3 but for $\lceil \; = 20$ users whose positions need to be determined simultaneously, i.e. $\beta = 1$. Our remarks regarding the impact of the tag density δ and the positioning algorithms are validated for this case as well. However, compared to the single-user case, now there is a noticeable accuracy decay which demonstrates the impairing impact of the interference problem in RFID. Furthermore, while in the single-user case $R_{max} = 5m$ was providing higher accuracy, in this case setting $R_{max} = 3m$ is more beneficent. This is obviously due to the higher probability of overlap among several read zones. Besides these observations, an interesting conclusion that can be made is that by adjusting the reader's range through a power control or another mechanism can alleviate the problem.

Figure 4.8 is the corresponding of Figure 4.6 but for $\lceil \; = 20$ users, $\delta = 1m$ instead of $\delta = 2m$ and $R_{max} = 3m$ instead of $R_{max} = 5m$. The main observation is that the interference problem makes the deteriorating impact of both environmental factors on the accuracy even more harmful. The most interesting remark, however, concerns the behavior

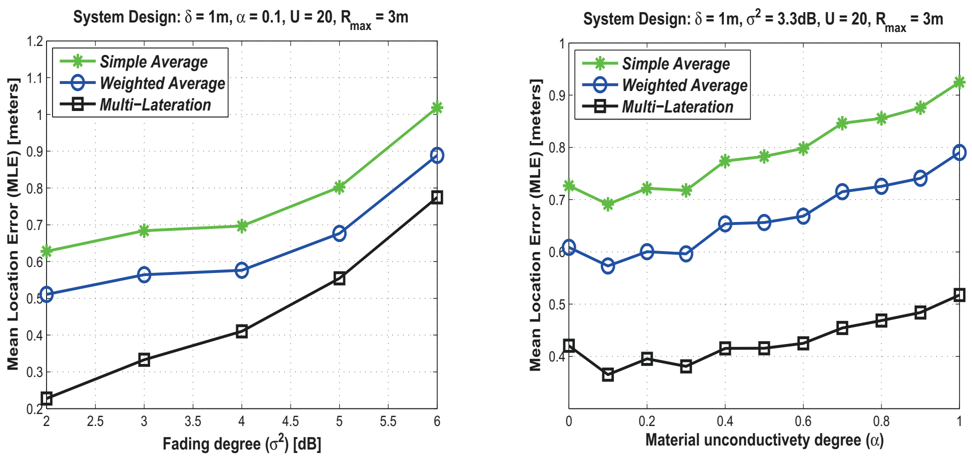


(a) MLE vs δ when $R_{max} = 3m$.

(b) MLE vs δ when $R_{max} = 5m$

Figure 4.7: Impact of system design parameters on *Accuracy* for multiple users.

of the ML technique in the presence of severe shadowing. We notice that while in the single-user case (Figure 4.6(a)) it has worse performance than the W-AVG and almost the same with the S-AVG, in the multi-user case (Figure 4.8(a)) it is superior. This indicates that ML can combat the interference problem more efficiently than the other schemes. However, this comes with higher complexity cost.



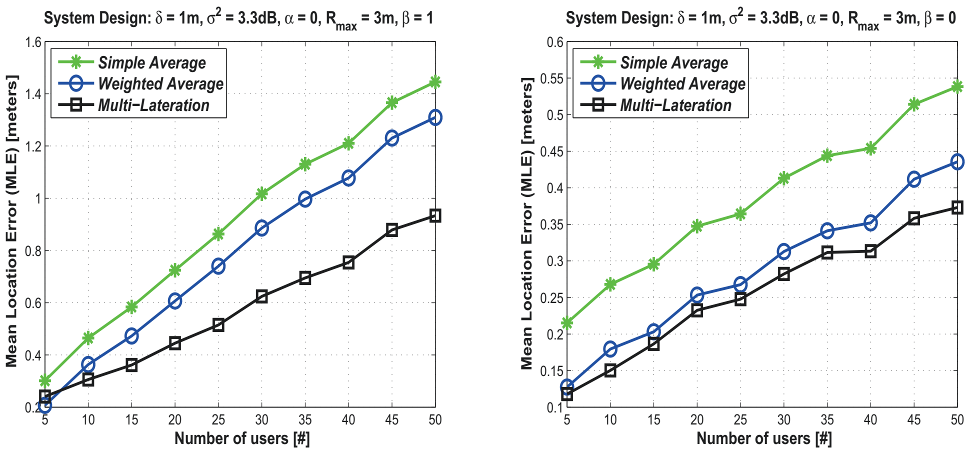
(a) MLE vs shadowing variance σ.

(b) MLE vs interference level from materials α.

Figure 4.8: Impact of environmental parameters on Accuracy for multiple users.

In the following we focus on the main parameters which affect the level of interference, i.e. the number of users $\lceil$, the read range R_{max} and the scanning probability of their reader which is modelled by the parameter β.

In figures 4.9(a) and 4.9(b) we show the impact of increasing the number of users $\lceil$ when $\beta = 1$ and $\beta = 0$, respectively. Obviously, the MLE increases with the users' population expansion. The remarkable notice, however, is that for $\beta = 0$ the accuracy reduction is less. Therefore, if a mechanism for coordinating reader transmissions is designed, the accuracy degradation due to the RFID interference problem can be compensated.



(a) MLE vs Number of users $|\mathcal{U}|$ when $\beta = 1$. (b) MLE vs Number of users $|\mathcal{U}|$ when $\beta = 0$.

Figure 4.9: Accuracy reduction due to users' increase and its potential alleviation.

In figures 4.10(a) and 4.10(b) we show the impact of the reader range R_{max} when $\beta = 1$ and $\beta = 0$, respectively for $\lceil \ = 40$ users. As expected, as R_{max} grows the MLE increases due to the higher probability of overlap among readers' interrogation zones. However, the interference intensity can be greatly alleviated if readers' transmissions are coordinated.

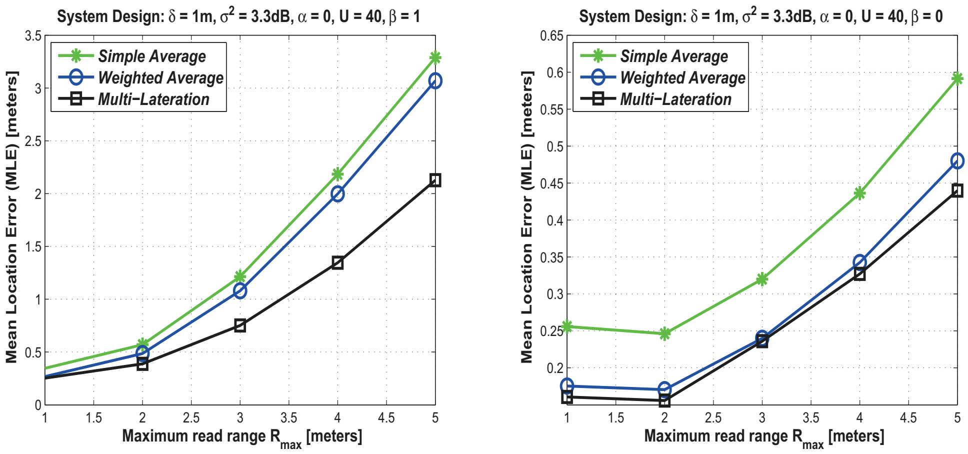
Finally in Table 4.3 we summarize the main advantages and disadvantages of the system design parameters regarding their accuracy, time response, complexity and behavior under different environmental situations.

4.5 Chapter Summary

The growing popularity of the RFID technology and the increasing demand for intelligent location-aware services in indoor spaces motivated exploring its potential for providing

Table 4.3: System Design Guide.

Design Parameter		**Pros**	**Cons**
Reference Tag Deployment	$\delta : [5 \uparrow \; 1]m$	≤ MLE ⇐ ≤ Robustness as interference or environmental harshness increases .	≤ MLT ↓
Maximum Read Range	$R_{max} : [5 \uparrow \; \delta]m$	≤ MLE ⇐for multi-user case ≤ MLT ⇐	≤ MLE ↓ for single-user case
Positioning algorithm	S-AVG	≤ Lowest complexity ≤ Good MLE resilience as shadowing increases	≤ Highest MLE ≤ Suffers the most from all interference types
	W-AVG	≤ Moderate complexity ≤ Best performance when shadowing is high	≤ When interference is high, its increased complexity over SA doesn't provide accuracy advantage
	ML	≤ Best accuracy ≤ Best MLE resilience against all interference types	≤ Highest complexity ≤ Bad performance when shadowing is high
Tag Reading activity	$\beta : [1 \uparrow \; 0]$	≤ MLE ⇐	≤ Less users are simultaneously localized



(a) MLE vs read range R_{max} when $\beta = 1$. (b) MLE vs read range R_{max} when $\beta = 0$.

Figure 4.10: Accuracy reduction due to read range increase and its potential alleviation.

accurate and time efficient localization with low deployment cost. However, despite the great benefits RFID can offer, the interference among its components and some materials are its main limiting factors. Therefore the impact of the RFID interference problem on the positioning performance should be extensively studied before the deployment of RFID-assisted location systems.

In this chapter, this issue was mainly addressed. After modeling the interference problem in RFID by considering its technology and communication specifications, we conducted extensive simulations for analyzing the performance of RFID in tracking single or multiple users, under different system configurations and environmental conditions. Numerical results encourage adopting RFID for localization but also indicate the essentiality of a careful system design in order to exploit its full potential, especially for highly populated environments.

Chapter 5

Integrating WLAN and RFID for Localization Enhancement

In the previous two chapters, we explored the applicability of WLAN and RFID technologies separately for indoor location sensing and identified their main strengths but also shortcomings. In summary, WLAN-based localizers are easily deployed but suffer from limited accuracy, whereas RFID-based solutions are very accurate for tracking a single user but are not efficient in populated environments due to the interference among users.

In this chapter, we consider a heterogeneous WiFi and RFID wireless network and propose utilizing both technologies for determining the location of multiple users with multi-modal terminals but with diverse capabilities. Multi-modality is related to the double interface of user devices, whereas diversity is related to the RFID component type, either reader or tag, each device supports. This scenario is entirely plausible in future heterogeneous wireless networks, whereby users will demand ubiquitous access to different applications from any available network [88]. Under this realistic scenario, we first propose taking advantage of the WLAN infrastructure for providing coordination among readers communication, in order to compensate the reader collision problem. Moreover, we propose exploiting the capability of reader-enabled users to sense neighbor tag-enabled users. Initially, reader-enabled users can use both the WLAN infrastructure and the RFID tag deployment for their localization, whereas the location of tag-enabled users can rely only on the WLAN system. Since RFID reader positioning schemes are more accurate than WLAN-based schemes, the proposed synergetic mechanism among users targets at increasing the WLAN positioning accuracy.

The remaining of this chapter is organized as follows. Section 5.1 explains our motivation for investigating the potential of a hybrid positioning system, which is described in section 5.2 and evaluated in section 5.3. Finally, section 5.4 summarizes this chapter.

5.1 Our Motivation: Need for Technology Integration for Localization Improvement

Our motivation for proposing a hybrid localization scheme stems from the need for synergy between the two technologies in order to take advantage of the benefits and overcome the limitations of the stand-alone solutions. In the following, we review the strengths and shortcomings of both WLAN and RFID positioning systems and explain the synergetic concepts we propose.

5.1.1 Review of Stand-alone Solutions

WLAN-based indoor location systems are attractive, mainly for their popularity in most indoor environments, the availability of RSS measurements during the scanning process of the handoff mechanism, their low cost and ease of deployment. However, there is a lower bound in their optimum achieved accuracy [46]. Since the main target of a WLAN is the communication between its components, the placement of the APs is such that minimum overlapping is achieved. Moreover, the inherent characteristics of the wireless medium, the so called propagation losses, the complicated in-building layout, the dependency on the receiver orientation, the Line Of Sight (LOS) requirement, and uncontrollable environmental changes cause undesirable signal variations, hence deteriorating the positioning process.

On the other hand, RFID is considered as a promising technology for indoor location sensing due to the low cost of *passive* tags, the non-LOS requirement, the fast reading of multiple tags and the reduced sensitivity regarding user orientation. However, when more than one reader need to be tracked, RFID technology suffers from the so-called reader collision problem [89]. The interference problem is more intense in RFID compared to other wireless technologies due to the inability of readers to communicate with each other, the lack of an infrastructure and the limited capabilities of the passive tags. Therefore, applying any of the general multiple access mechanisms, based on time, frequency, code division or carrier sensing, directly in RFID is not trivial [14].

5.1.2 Synergetic Concepts

Since WiFi-enabled devices are very widespread nowadays and passive tags are cheaper than readers, we consider a realistic scenario whereby all user devices are WiFi-enabled, many of them have a passive tag and less an RFID reader. In the following, we explain our proposed synergetic concepts, termed as *mutli-modality* and *diversity*.

5.1.2.1 Multi-modality

Multi-modality is related to the double interface of user devices, so that communication with both the WLAN and RFID interfaces is enabled. Since readers and tags are attached to terminals which also support WiFi communication, we suggest taking advantage of the redundancy of communication channels offered by the multi-modality of user devices in order to compensate the RFID reader collision problem. More precisely, we study the potential benefits if the WLAN infrastructure is exploited for providing coordination among readers' communication. We first model a conceptual coordinating mechanism and then design a realistic scheduling mechanism in order to validate the performance advantages of this synergetic concept.

5.1.2.2 Diversity

Diversity is related to the RFID component type, either reader or tag, that is additionally available at each WiFi-enabled user device. We suggest benefitting from the diversity among the two types of terminals, by taking advantage of the capability a reader-enabled user to detect a nearby tag-enabled user, due to the build-in feature of its reader to detect tags. Since RFID reader localization schemes are more accurate than WLAN-based schemes, the position of the latter can be updated based on the proximity technique with reference point the former. In the following, we term reader-enabled users as active because they participate actively in the positioning process, whereas the tag-enabled users as *passive*.

5.2 Positioning Framework

In this section the overall framework of the positioning system is described.

5.2.1 System Architecture

Figure 5.1 illustrates the architecture of the proposed hybrid positioning system. It includes the WLAN infrastructure, the RFID reference tag deployment, the two user types, namely *active* and *passive*, and a central *Location Server* (LS) within the network which maintains a database correlating tag IDs with location coordinates of reference tags or with *passive* users' IDs.

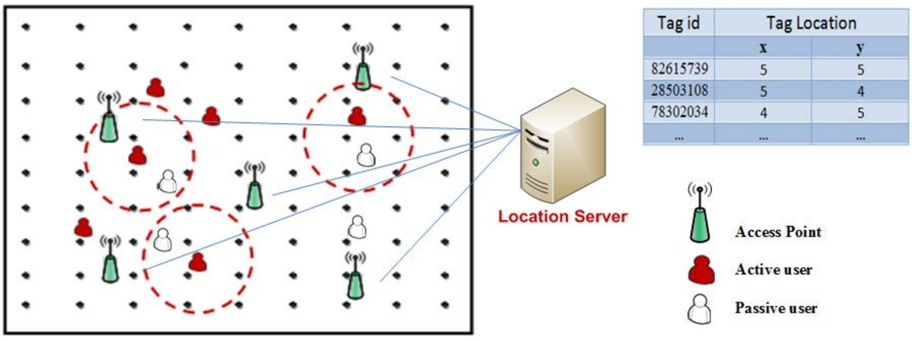


Figure 5.1: Hybrid Positioning Architecture

5.2.2 Conceptual Positioning Process

Figure 5.2 depicts the general concept of our proposed positioning process.

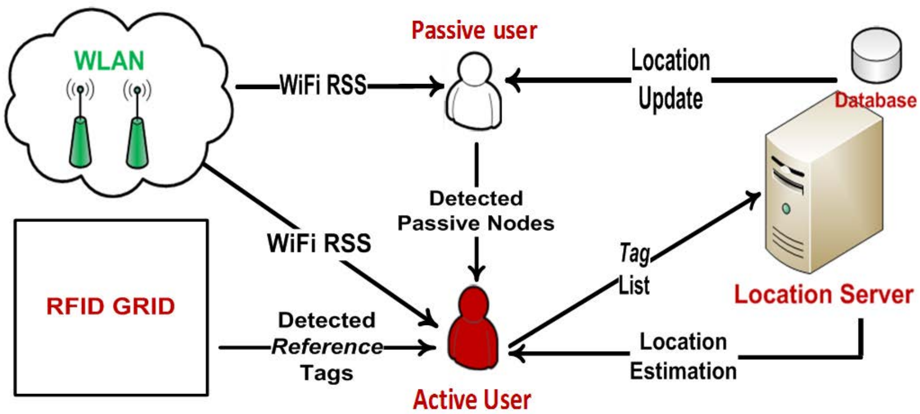


Figure 5.2: Conceptual Positioning Process.

Initially, the localization of both *active* and *passive* users can rely on the WLAN system by utilizing the RRS measurements. However, *active* users can also take advantage of the reference tag deployment.

The reader of each *active* user scans for tags within its coverage in order to retrieve their IDs. We assume that each reader's interrogations follow a transmission schedule provided from the WLAN infrastructure. In order to model this, we assume that an *active* user u's reader queries for tag IDs with some probability p_u^{scan} which follows uniform distribution $U(\beta, 1)$, where β / $[0, 1]$ reflects the synchronization degree. Indeed, $\beta = 1$ corresponds to the case when all readers communicate simultaneously, whereas when $\beta = 0$ a conceptual access control mechanism is assumed.

The list of these retrieved IDs, called Tag List, is then forwarded to the location server. Based on this received Tag List and the database which correlates the IDs of the *reference* tag with their location coordinates, the LS estimates the location of that user by employing an RFID-based positioning algorithm and finally returns this location estimate back to the corresponding user. The positioning algorithm can be any of the Simple Average (S-AVG), Weighted Average (W-AVG) or Multi-Lateration (ML) algorithms that were described in section 4.3.3.

The retrieved IDs in the Tag List of an *active* user, may correspond not only to *reference* tag IDs, but also to *passive* users' IDs which are possibly located within the reader's range of that *active* user. Therefore, if the ID of a *passive* user is included in the Tag List from at least one *active* user, its initial estimated location can be improved. We selected as estimated position of the *passive* user to be the estimated location of the *active* user who has most recently detected him. More advanced positioning techniques can also be applied. However, we preferred to keep the complexity of this scheme low in order to focus on the advantages offered by the proposed synergetic concept even by employing a simple proximity algorithm. Finally, this location update is sent to the *passive* user.

5.2.3 Realistic Positioning Process

In the previous section, a readers' coordinated transmission mechanism was theoretically modeled. In the following, we design a scheduling mechanism for readers' transmissions that can be implemented with the aid of the WLAN infrastructure and we describe again the entire positioning process by employing it instead of assuming a theoretical one.

Figure 5.3 illustrates the process of the proposed positioning approach. It includes two main phases, namely the Initial Phase (IP) and the Collision Compensation Phase (CCP), and five main tasks: (i) initial location estimation, (ii) collision diagnosis, (iii) clustering,

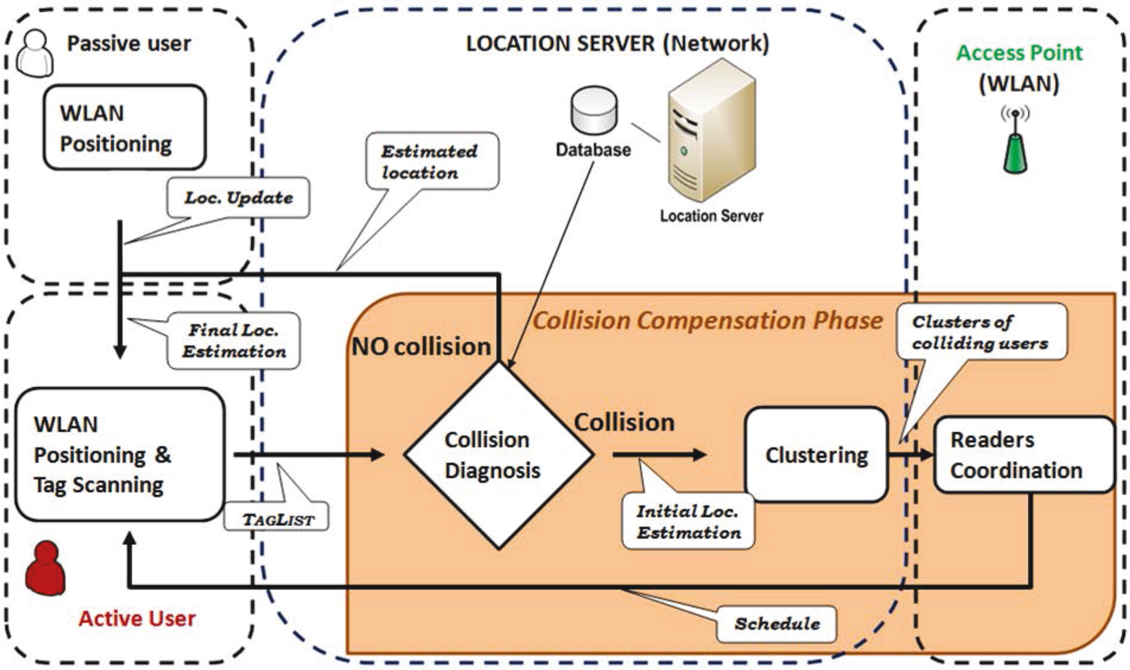


Figure 5.3: Realistic Positioning Process

(iv) readers' transmission coordination (scheduling) and (v) location refinement. During the initial phase, an initial location estimation for all users is performed based on the WLAN infrastructure. During the collision compensation phase, the initial location estimations for some users are improved with the aid of the steps (ii)-(v). In the following, we provide more details of our proposed scheme.

5.2.3.1 Initial location estimation

Initially, each user, *passive* or *active* utilizes its RSSI measurements from all visible APs to estimate its location based on the RSS-based triangulation technique, if there is coverage from at least three APs. Otherwise, proximity and non-proximity constraints are applied for roughly estimating its location. At the same time, the reader of each *active* user u interrogates tags within its coverage, whose retrieved IDs may correspond to both area *reference* tags and *passive* user tags. A list of these retrieved tag IDs, denoted as $\mathcal{G}_u$, is forwarded to the LS within a Tag List message through a WiFi communication channel.

After the completion of the above initial location estimation task during the *Initial Phase*, a *Collision Compensation Phase* (CCP) is arranged to start in order to deal with the positioning performance degradation due to readers' collisions but also to improve the WLAN-based positioning accuracy.

5.2.3.2 Collision diagnosis

Firstly, the LS performs a *Collision Diagnosis* (CD) test for each active user u based on the received $\mathcal{G}_u$ and a threshold TH_{CD}. Algorithm 2 describes the pseudo-code of this test. $\mathcal{N}$ contains all sets $\mathcal{G}_u$ from each user u and TH_{CD} is a threshold whose value is discussed in Section 5.3. Initially, the tag IDs which correspond to *reference* tags ($\mathcal{TU}_u$) are distinguished from these belonging to detected *passive* users ($\mathcal{R}\lceil_u$). According to the collision test, an *active* user u is considered as suffering from collision if the number of its detected *reference* tags $\mathcal{TU}_u$ is less than TH_{CD} and classified into the group of colliding users $\mathcal{L}_1$. Otherwise, it is allocated in group $\mathcal{L}_2$. The idea behind this classification is to diagnose the severity degree of each collision and take action only if necessary with respect to localization performance (not enough number of detected *reference* tags for accurate location estimation). In the sequence, the LS estimates the location of all users within both $\mathcal{L}_1$ and $\mathcal{L}_2$ based on S-AVG, W-AVG or ML positioning algorithm. The locations of *passive* users are updated by the locations of the $\mathcal{L}_2$ *active* users who have detected them. For $\mathcal{L}_2$ and their detected *passive* users, their calculated locations are considered as *final location estimations* and are forwarded to them. However, for $\mathcal{L}_1$ *active* users, they are considered as coarse *initial location estimations* to be used by the next *clustering* step.

Algorithm 2 $[\mathcal{L}_1, \mathcal{L}_2, \widetilde{\mathbf{X}}, \widetilde{\mathbf{Y}}] = \mathit{CollisionDiagnoses}(\mathcal{N}, \mathrm{TH}_{CD})$

for all $\mathcal{G}_u$ / $\mathcal{N}$ **do**
  $[\mathcal{TU}_u, \mathcal{R}\lceil_u] \in \mathit{assort}(\mathcal{G}_u)$
  if $\mathcal{TU}_u < \mathrm{TH}_{CD}$ **then**
    $\mathcal{L}_1 \in \mathcal{L}_1 + u$
  else
    $\mathcal{L}_2 \in \mathcal{L}_2 + u$
  end if
  $(\widetilde{x}_u, \widetilde{y}_u) \in$ based on SA, WA or ML.
  $(\widetilde{x}_p, \widetilde{y}_p) \in (\widetilde{x}_u, \widetilde{y}_u)$, $\mathcal{C}p$ / $\mathcal{R}\lceil_u : u$ / $\mathcal{L}_2$
end for

5.2.3.3 Clustering

We propose clustering active users within group $\mathcal{L}_1$ (whose readers suffer from collisions) into disjoint sets of inter-colliding nodes based on their proximity. The idea behind this is to group together neighbor nodes, since their readers are most probably colliding with each other. Subsequently, only readers' transmissions belonging to nodes within the same cluster need to be coordinated. For performing this *clustering* task, the LS uses the initial coarse location estimations of all users in $\mathcal{L}_1$ to compute the Euclidean distance between all pairs of these nodes. The readers of two users u_i and u_j are expected to collide if their estimated distance $\widetilde{d}_{ij}$ is smaller than a distance threshold TH_{dist}. Therefore, the clusters should be created such that the distance between any pair of nodes which belong to disjoint clusters is certainly greater than the TH_{dist} threshold. Thus, for two disjoint clusters $\mathbb{C}_x$ and $\mathbb{C}_y$ with $x \not\forall y$, it holds

$$\widetilde{d}_{ij} > TH_{dist}, \mathcal{C}i, j : i \ / \ \mathbb{C}_x, \ j \ / \ \mathbb{C}_y. \tag{5.1}$$

The value of the threshold TH_{dist} is also design parameter. Increasing its value creates less but more populated clusters.

5.2.3.4 Readers' transmission coordination

In the sequence, the WLAN is responsible for providing a coordination among readers' transmissions which belong to users within the same cluster such that their collisions are compensated. To that end, information regarding all produced clusters and the $\mathcal{L}_1$ users is forwarded from the LS to their corresponding AP. The *transmission schedule* for each cluster is arranged in a Round Robin (RR) fashion, such that readers within the same cluster are scheduled to transmit one after the other[1]. The process is as follows:

A BEACON message is first broadcasted to notify and prepare all users for the start up of this phase. Users within G_2 cease their readers interrogating tags, whereas a POLL message is sent to each user within each cluster in order to be notified for its allocated time slot, during which its reader is allowed to scan for tags. Note that, users within different clusters may be polled simultaneously since their readers are considered as non-colliding according to the *clustering* step. This actually explains better the idea behind *clustering* nodes, that is reducing the time duration of the scheduled transmissions.

[1] In IEEE 802.11 only one AP is in charge of a MN. We have assumed that MNs within the same cluster are served by the same AP and that time synchronization among WiFi-enabled devices is possible when they operate in infrastructure mode through normal beacon messages broadcasted periodically by the APs.

5.2.3.5 Location refinement

Upon reception of the transmission schedule from its associated AP, the reader of each corresponding active user scans for tags according to its allocated time slot. The list of the detected tags is then send to the LS which then estimates the location of that user and of its detected *passive* users (if any) and transmits it back to them.

5.3 Performance Analysis

In this section we analyze and evaluate the performance of the proposed schemes through simulations, using Matlab [85] as simulation tool. Firstly, the simulation settings are specified, then the performance objectives are defined and finally, numerical results demonstrate the efficiency of both systems in providing accurate and time-efficient localization.

5.3.1 Simulation Setup

Figure 5.4 illustrates our simulation environment, a rectangular area 50 ± 50 square meters where 9 WiFi APs provide data communication with maximum range 15 meters. The indoor log-distance path loss model, described in [33], has been selected to model the communication at the 802.11b (WiFi) channel, i.e.

$$PL(d) = PL(d_o) + 10n \log \Big) \frac{d}{d_o} \Big\lfloor + X_\sigma, \tag{5.2}$$

where d the distance between transmitter (AP) and receiver (MN), $PL(d_o)$ the free space path loss at reference distance d_o, n the path loss exponent whose value depends on the frequency used, the surroundings and building type, and X_σ is a zero-mean Gaussian random variable in dB having a standard deviation of σ_{dB}. The variable X_σ is called the shadow fading and is used to model the random nature of indoor signal propagation due to the effect of various environmental factors such as multipath, obstruction, orientation, etc. This path loss model is used for calculating the RSS from each AP, based on its transmit power P_t, i.e. $RSS(d) = P_t \quad PL(d)$. For our case, the operating frequency is 2.4 GHz, $n = 3.5$ and $\sigma_1^2 = 3.5$.

In addition to the WLAN system, *reference* tags are placed in a grid fashion with inter-tag spacing δ. For the UHF RFID path loss model (see eq. (4.6)) operating frequency is 915 MHz, $N = 3.6$ and σ_2^2 / $[2, 6]$. To consider the factor of interference from the objects we assume that a tag is not detected with some probability which follows uniform distribution $U(0,1)$. Within this area N_A *active* users and N_P *passive* users are randomly located. R_{max} denotes the maximum read range of each active user's reader which depends on the transmit power, antenna gains, propagation losses, interference and shadowing. To incorporate these factors, we assume that during simulations, the actual range is $\tilde{R}_{max} = R_{max} \bullet \sqrt{r}$, where $r \ / \ [0, r_{max}]$.

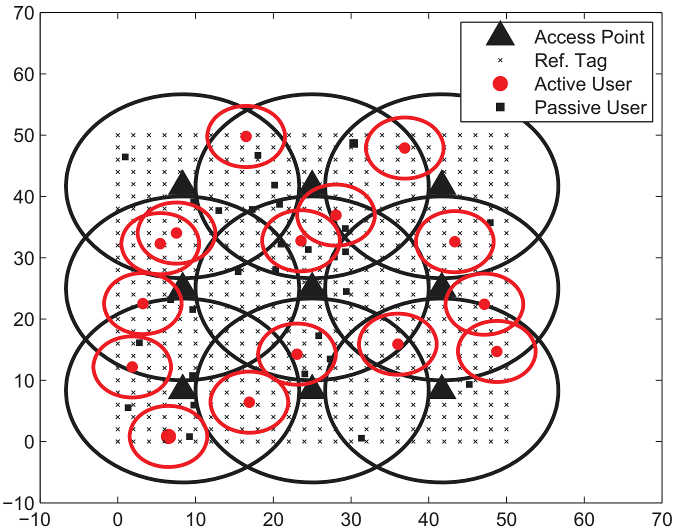


Figure 5.4: Simulation environment.

5.3.2 Performance Objectives

For system evaluation we focus on the achieved accuracy and response time since these are the main performance objectives for a positioning scheme.

5.3.2.1 Localization Accuracy

As accuracy metric we use the Mean Location Error (MLE), measured as the Euclidean distance between the actual and the estimated positions for all N_A active or N_P passive users, i.e.

$$\mathrm{MLE} = \frac{1}{N}\prod_{u=1}^{N} \sqrt{(x_u \quad \tilde{x}_u)^2 + (y_u \quad \tilde{y}_u)^2}, \tag{5.3}$$

where $N = N_A$ or N_P.

5.3.2.2 Response Time

As metric for the response time we define the Mean Localization Time (MLT) given by

$$\mathrm{MLT} = \mathrm{T}_{IP} + \mathrm{T}_{CCP}, \tag{5.4}$$

where T_{IP} and T_{CCP} the duration of the initial and collision compensation phases, respectively.

During the initial phase, both *passive* and *active* users estimate their location based on the WLAN and in parallel, the reader of each *active* user scans for tags. Therefore, the T_{IP} is given by

$$\mathrm{T}_{IP} = \max\left\{\frac{1}{\mathrm{N}_A + \mathrm{N}_P}\prod_{u=1}^{\mathrm{N}_A+\mathrm{N}_P}\mathrm{T}_{WLAN,u}, \frac{1}{\mathrm{N}_A}\prod_{u=1}^{\mathrm{N}_A}\mathrm{T}_{TR,u}\right\}, \tag{5.5}$$

where $\mathrm{T}_{WLAN,u}$ is the duration of the WLAN-based positioning process of user u and $\mathrm{T}_{TR,u}$ is the tag reading time by *active* user u's reader, given by eq. (4.1).

The duration of the collision compensation phase T_{CCP} should be actually evaluated, since this contributes to additional delay overhead over the normal positioning process. It is given by

$$\mathrm{T}_{CCP} = \mathrm{T}_{CD} + \mathrm{T}_{Cl} + \mathrm{T}_{Sch} + \mathrm{T}_{LR} \tag{5.6}$$

where T_{CD}, T_{Cl}, T_{Sch} and T_{LR} the duration of the *collision diagnosis* test, *clustering*, *scheduling* and *location refinement* steps, respectively. From these factors, the prevailing one is T_{LR}, which depends on the cardinality of the bigger collision cluster $\mathcal{D}_{max}$, and the tag reading time $\mathrm{T}_{TR,u}$ of all nodes within $\mathcal{D}_{max}$, i.e.

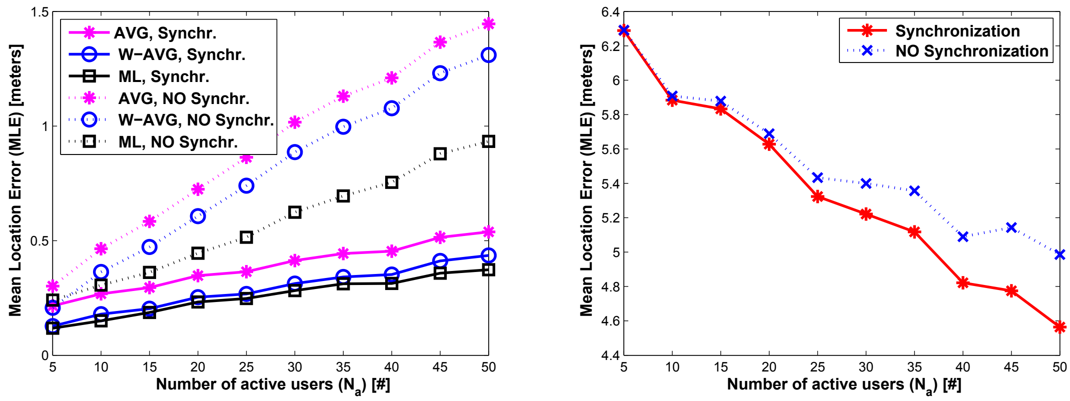
$$\mathrm{T}_{LR} = \prod_{u\in\mathcal{C}_{max}}\mathrm{T}_{TR,u}. \tag{5.7}$$

Therefore, MLT is given by

$$\mathrm{MLT} = \underbrace{\max\left\{\frac{1}{N_A + N_P}\prod_{u=1}^{\mathrm{N}_A+\mathrm{N}_P}\mathrm{T}_{WLAN,u}, \frac{1}{\mathrm{N}_A}\prod_{u=1}^{\mathrm{N}_A}\mathrm{T}_{TR,u}\right\}}_{\mathrm{T}_{IP}} + \underbrace{\prod_{u\in\mathcal{C}_{max}}\mathrm{T}_{TR,u}}_{\approx\mathrm{T}_{CCP}}. \tag{5.8}$$

5.3.3 Numerical Investigations

Numerical results based on the average of 1000 independent simulation executions are presented in the following. We first validate the accuracy improvement offered by the proposed hybrid scheme when a conceptual mechanism for synchronizing readers transmissions



a ctive users

b assive users

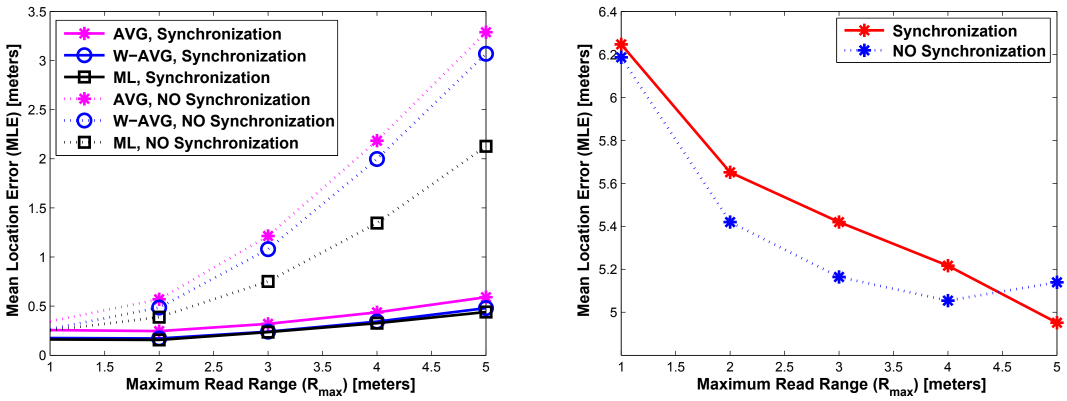
Figure 5.5: Impact of reader population (N_A) increase on localization accuracy with and without synchronization.

is assumed and later we evaluate the performance of the proposed scheduling mechanism, in terms of localization accuracy and response time.

5.3.3.1 Conceptual Positioning System

Figures 5.5(a) and 5.5(b) show the impact of increasing the readers' population on the MLE for *active* and *passive* users, respectively. We have assumed $\delta = 1$ meter, $R_{max} = 3$ meters for all readers and $N_P = 50$. We observe that when all readers query for tags simultaneously (*No Synchronization*), increasing their population results in performance degradation for *active* users, whereas the accuracy improves for *passive* users. This is reasonable since in highly populated environments the collision problem becomes more intense, but concurrently, more *passive* users are detected by *active* users for refining their initial location estimations. However, when the collision problem is mediated by coordinating readers' transmissions (*Synchronization*), both user types benefit. Indeed, the MLE for *active* users remains almost stable even for highly populated environments and the MLE reduction rate for *passive* users is higher when synchronization is employed.

Figures 5.6(a) and 5.6(b) depict the impact of increasing the maximum read range on the accuracy for both user types. We have assumed $\delta = 1$, $N_A = 40$ and $N_P = 50$. When all readers scan simultaneously for tag IDs, their coverage range is a compelling design parameter between the two user types, since for *active* users large values of R_{max} increase the frequency of overlapped interrogation zones, whereas *passive* users have more chances



a ctive users b assive users

Figure 5.6: Impact of read range (R_{max}) on localization accuracy with and without synchronization.

to be detected. However, when synchronization comes into place, increasing the read range does not affect considerably the MLE of *active* users since collisions are avoided. For *passive* users we observe that for almost all values of R_{max} when synchronization among readers' queries is realized, the MLE is slightly worse. This happens because *passive* users may not be detected even if they are located close to a reader, if that reader is not in a scanning mode. However, for $R_{max} \approx 4.5$ meters the MLE is less when synchronization is on. This is due to the corresponding detrimental performance of *active* users. An interesting remark is that for $R_{max} = 5$ meters and controlled reader transmissions, the MLE is less than 0.5 for *active* users and the optimum possible for *passive* users.

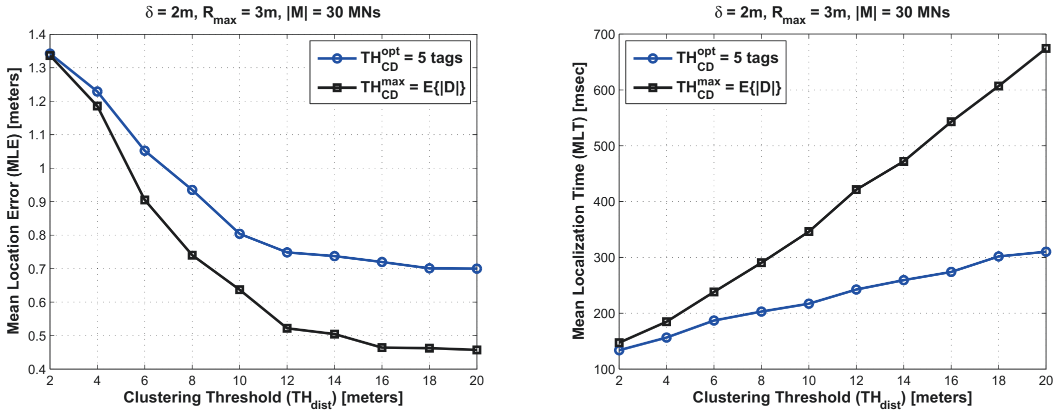
The above results validate the accuracy improvement if the RFID reading process is coordinated and users benefit from their diversity by cooperating. In the following, we evaluate the performance of our proposed positioning system when the realistic CCP scheduling mechanism is employed, regarding both accuracy and accompanied time delays.

5.3.3.2 Realistic Positioning System

Without loss of generality, in the rest we assume the Simple Average as the principle positioning method, mainly for its simplicity and independence on the RFID path loss model. We first explore the impact of the TH_{CD} and TH_{dist} design parameters on the MLE (Figure 5.7(a)) and MLT[2] (Figure 5.7(a)). TH_{CD} is the threshold used by the *collision*

[2] e focus only on the $_{CCP}$ hich is the additional time overhead.

diagnosis test (Algorithm 2) to decide whether an *active* user should participate in the scheduled transmission phase or not. TH_{dist} is the threshold used during the *clustering* step: if the estimated distance between two users is less than TH_{dist}, then they are clustered into the same cluster of most probably inter-colliding nodes.



(a) Mean Location Error.　　(b) Mean Localization Time.

Figure 5.7: Impact of thresholds TH_{CD} and TH_{dist} on positioning performance.

We have set $\delta = 2m$ and assumed $\mathrm{N}_A = 30$ *active* users are within the area with their reader range $R_{max} = 3m$. The two curves correspond to two different values of the TH_{CD}. TH_{CD}^{max} is its maximum value and TH_{CD}^{opt} is the one we selected as optimal for achieving a good trade off between accuracy and time objectives. The expected number of responding tags depends on the geometry of the tag deployment and the reader's range. Considering a grid tag deployment and that the reader's radiation pattern forms a circle, as depicted in Figure 5.8, the expected number of detected tags $\overline{\mathcal{G}}$ is given by

$$\overline{\mathcal{G}} = 4\left\lfloor \frac{R_{max}}{\delta} \right\rfloor^2. \tag{5.9}$$

Setting $\mathrm{TH}_{CD}^{max} = \overline{\mathcal{G}}$ tags, a single tag miss is interpreted as indication of severe collision and thus, almost all active users are included in the scheduled transmission stage. Apparently, the achieved accuracy is optimum but with the cost of high increase in MLT. For satisfying both objectives, a smaller value should be selected. Considering the grid geometry of the *reference* tags setting $\mathrm{TH}_{CD}^{opt} = 4$ 5 tags seems a rational choice.

As TH_{dist} increases, less but more populated clusters are generated. Apparently, overestimated TH_{dist} results in time resource waste since *active* users whose readers are

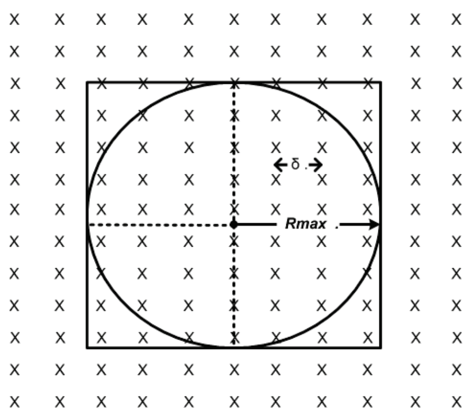


Figure 5.8: Grid tag deployment and Reader radiation pattern.

not really inter-colliding are grouped into the same cluster. Recalling Figure 4.1(a), $\text{TH}_{dist} = 2 \pm (R_{max} + r_{max}) = 2 \pm (R_{max} + 1)$ would be the optimal value. However, the error ε of the initial estimated locations should be taken into account. Thus, we propose

$$\text{TH}_{dist} = 2 \pm (R_{max} + r_{max} + \varepsilon). \tag{5.10}$$

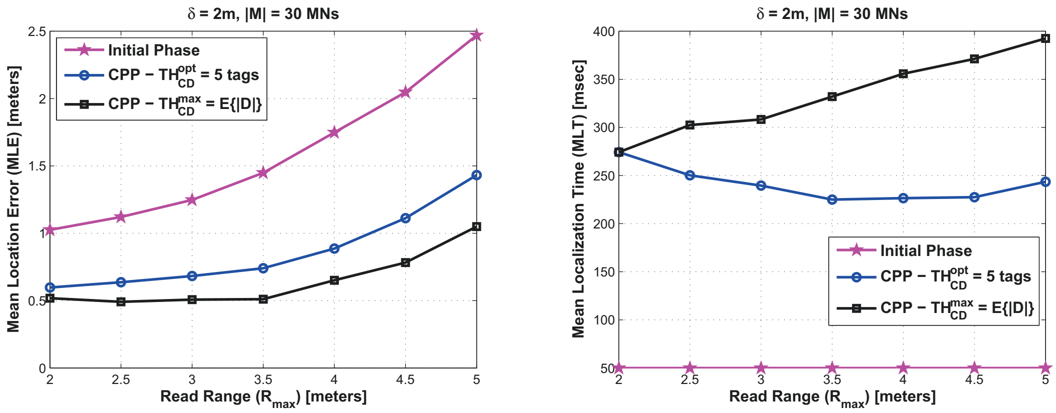
The location estimation error ε is function of several parameters, such as δ, R_{max} and N_A but difficult to model. For $\delta = 2$, $R_{max} = 3$, and $N_A = 30$ (Figure 4.7(a)) setting $\varepsilon = 1.5$ gives $\text{TH}_{dist} = 11m$. This is validated in Figure 5.7: for $\text{TH}_{dist} > 11\ m$ the MLT increases rapidly in Figure 5.7(b) without a considerable accuracy advantage in Figure 5.7(a).

In Figure 5.9 we study the optimal value of the reader range R_{max} with respect to both accuracy and time performance objectives. The three curves correspond to three positioning system cases:

1. CCP is not included, i.e. Initial Phase only.
2. CCP is included with $\text{TH}_{CD} = \text{TH}_{CD}^{max} = \overline{\mathcal{G}}$ tags.
3. CCP is included with $\text{TH}_{CD} = \text{TH}_{CD}^{opt} = 5$ tags.

Note than now the clustering threshold is given by: $\text{TH}_{dist} = 2 \pm (R_{max} + 2.5)$, based on our analysis in eq. (5.10). In Figure 5.9(a) the MLE increase as R_{max} increases is due to the higher probability of overlap among interrogation zones since the reader ranges expand. However, employing the CCP mechanism, the accuracy reduction is compensated. Comparing the two cases of TH_{CD}, we observe that the accompanied time overhead in

Figure 5.9(b) is not high. The increased MLT for $R_{max} < 3m$ is because less users pass the collision diagnosis test since few tags are detected. Overall, $R_{max} = 3m$ or $R_{max} = 3.5m$ appear the optimal choices when all objectives are concerned.



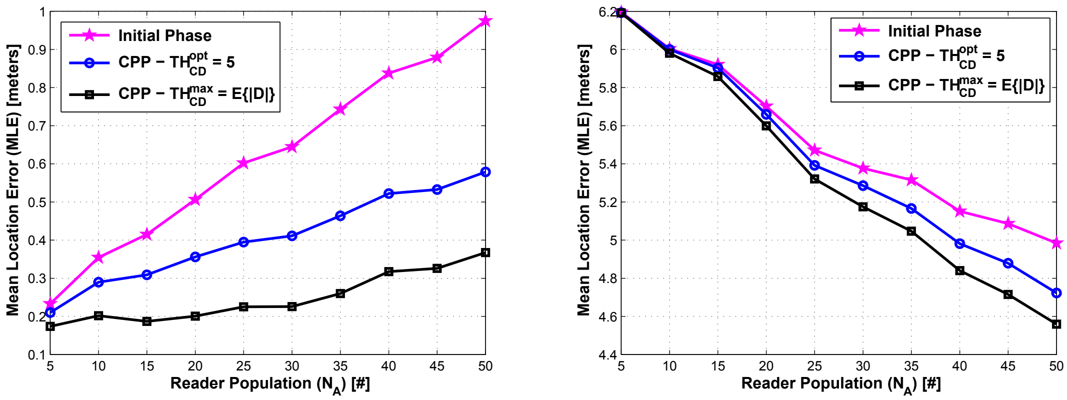
(a) Mean Location Error. (b) Mean Localization Time.

Figure 5.9: Impact of reader range (R_{max}) on positioning performance.

In the following, the advantage of exploiting users' diversity is validated. Figure 5.10 shows the impact of increasing the population of *active* users on the MLE for both user types. For all schemes, increasing readers' population results in accuracy degradation for *active* users (Figure 5.10(a)), but in accuracy improvement for *passive* users (Figure 5.10(b)), similarly with our observations in Figure 5.5. Moreover, the benefits by employing the CCP mechanism (for both $\text{TH}_{\mathcal{CD}}$ cases) for both user types are in accordance with these when the coordination mechanism was conceptually modeled.

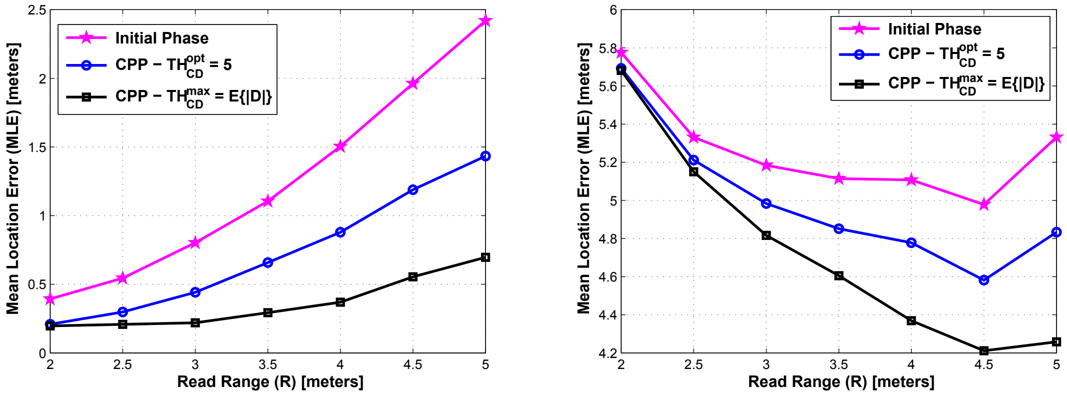
Figures 5.11(a) and 5.11(b) demonstrate the impact of increasing the maximum read range on the MLE for *active* and *passive* users, respectively. The observations here are in accordance with our remarks in Figure 5.6. The reason of the bad MLE performance for *passive* users when $R_{max} = 5\ m$ is because the high MLE for *active* users is propagated to their detected *passive* users. However, when CCP is employed with $\text{TH}_{dist} = 2 \pm (R_{max} + 2)$ and $\text{TH}_{\mathcal{CD}} = 5$ or $\text{TH}_{\mathcal{CD}} = \overline{\ \mathcal{G}\ }$, the MLE decreases for both user types.

Finally, we illustrate the time overhead due to the round robbin (RR) readers' readings during the CCP. The MLT in terms of RR cycles ($\mathcal{D}_{max}$) is depicted as reader population (Figure 5.12(a)) or read range (Figure 5.12(b)) increases. Comparing them in conjunction with Figure 5.10 and Figure 5.11, respectively, we conclude that employing the *collision*



a ctive users b assive users

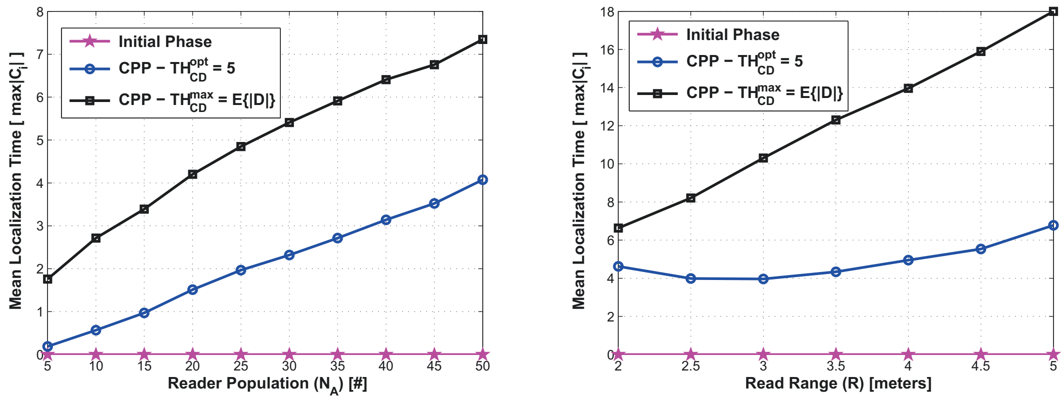
Figure 5.10: Impact of increasing readers population (N_A) on accuracy (MLE).



a ctive users b assive users

Figure 5.11: Impact of read range (R_{max}) on accuracy (MLE)

diagnosis test with and $\text{TH}_{CD} = 5$ and CCP, both accuracy and time-efficiency objectives are well satisfied for both user types. Even in highly populated environments, the MLE increase for *active* users is less than 0.4 m whereas the MLE reduction for *passive* users is greater than 1.4 m. The accompanied time delay is only 4 RR cycles. Regarding the read range, $R_{max} = 4$ m appears the optimal choice when all objectives are concerned, resulting in 0.6 m MLE increase for *active* users, 1.4 m MLE reduction for *passive* users and less than 4 RR cycles. For $R < 3$, the higher MLT is because less tags are detected and thus



(a) Reader popularity (N_A)

(b) Read range (R)

Figure 5.12: Time response performance of CCP mechanism.

more users are allocated to $\mathcal{L}_1$ group after the CD test.

5.4 Chapter Summary

In this chapter we proposed a localization scheme based on the integration of the WLAN and RFID technologies in order to overcome the limitations of the stand-alone positioning solutions. The main advantage of multi-modal devices is the offered redundancy of communication channels. Thus, we suggested utilizing the WiFi channel for coordinating the communication in the RFID channel in order to subdue the restricting factor of reader collisions. Additionally, we considered a realistic scenario where users have devices with diverse capabilities. We proposed exploiting this diversity by benefitting from the inherent property of reader-enabled users to sense tag-enabled users in their vicinity, and hence refining their location estimation. The performance advantages of a conceptual coordination mechanism were first validated and later an easily implemented scheduling scheme was proposed for realizing these benefits. Based on extensive simulations, we tested the impact of various design parameters and we validated the achieved performance advantages of our proposals regarding both accuracy and time-efficiency objectives.

Part II

IP Mobility Management

Chapter 6

Mobility Management

With the rapid growth of wireless access networks, the great advances in mobile computing and the overwhelming success of the Internet, a new communication paradigm has emerged, whereby mobile users require ubiquitous access to their services while roaming, preferably without interruption or degradation of their communication quality. One of the research challenges for next generation (NG) all-IP-based wireless and mobile systems is the design of intelligent mobility management techniques that take advantage of IP-based technologies to achieve global roaming among heterogeneity access technologies [90]. Mobility management issues concern both the link and network layers.

At the link layer, access to the Internet via wireless networking entails the need for frequent changes of the serving Access Points (APs), either due to the small cell size of wireless networks or due to the desire of users for being always best-connected via any of the available wireless networks. However, frequent handoffs not only introduce time delays and packet loss which may be prohibitive for real-time applications but also lead to extensive power consumption which limits the lifetime of the energy-constrained mobile terminals.

At the network layer, mobility support is a requirement not appropriately addressed by the Internet Protocol (IP) of the TCP/IP protocol suite which was originally designed for static, wired networks. The most well known mechanism for mobility support in IP networks is Mobile IP (MIP) [13], an Internet Engineering Task Force (IETF) standard communication protocol that is designed to let MNs move from one network to another while maintaining a permanent IP address. This is done through the interaction of a Home Agent (HA) and a Foreign Agent (FA) and the utilization of two IP addresses by the Mobile Node (MN): one for identification and the other for routing. However, the handoff process for updating the MN's routing address, leads to additional time delays and packet losses degrading the communication quality.

This chapter aims at providing essential background relevant to mobility management issues, standard protocols and literature review of research efforts for enabling seamless mobility over the Internet. The rest of the chapter is organized as follows: In section 6.1 we first describe the challenges for mobility management in next generation all-IP-based wireless systems. In section 6.2 the standard mechanisms currently proposed for dealing with this problem are presented. Finally, in section 6.3 we highlight the substantial shortcomings of the standard solutions and provide a literature review of works which target at amending them or proposing new ones. Finally, section 6.4 provides the chapter summary and our research directions for mobility management.

6.1 IP Mobility Problem

Mobility management (MM) as a general term is defined as the set of mechanisms aiming at providing seamless mobility [91]. *Seamless mobility* is commonly used to describe the requirement for continuation of an ongoing communication of a mobile node, regardless its mobility within the same network (link layer mobility) or among different subnetworks (network layer mobility). MM contains two components: *location management* and *handoff management*. The purpose of *location management* is to keep updated the system of the current location [1] of the mobile node and it is achieved by two types of tasks, *location updates* sent by the mobile node to the system or *location deliveries* (*paging*) whereby the system identifies the mobile node's location based on records of its latest communication. *Handoff management* is the process of transferring an ongoing communication from the old Point of Attachment (PoA) to a new PoA, due to the change of the MN's location. If the new PoA belongs to the same subnetwork with the old PoA (link layer mobility), a link layer handoff is only required. However, if the new PoA belongs to a new subnetwork (network layer mobility), a handoff at the network layer is also necessary. Figure 6.1 illustrates the main processes included in the mobility management mechanism and provides a taxonomy of approaches for the execution of particular tasks on which we are focusing on in the rest of this thesis.

Enabling mobile and ubiquitous wireless access to the Internet has been widely recog-

[1] In this case, location refers to the I address of the that corresponds to its current subnet ork, and not its physical coordinates.

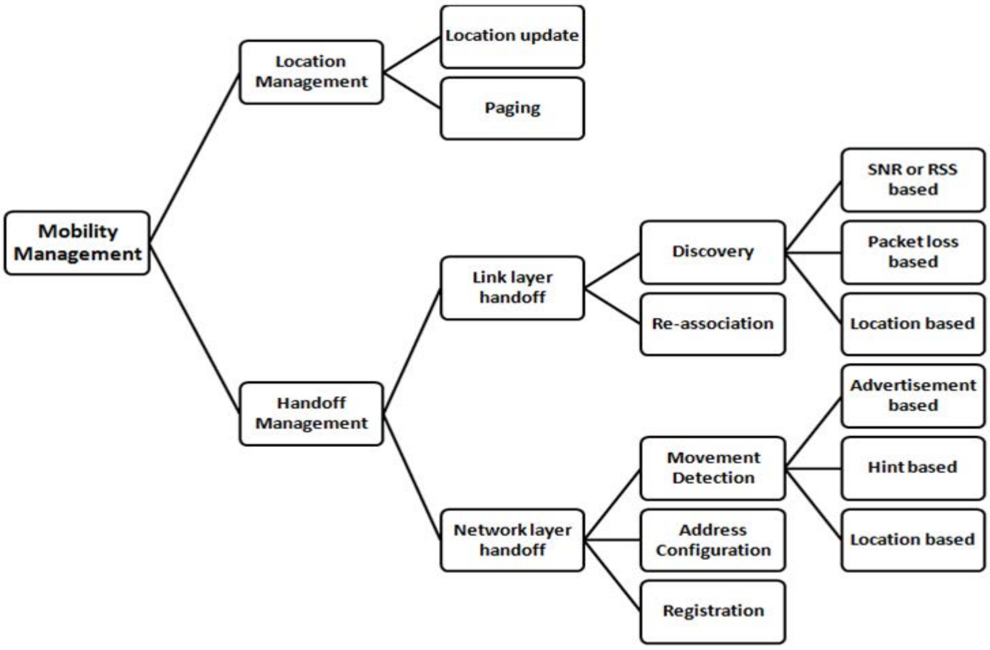


Figure 6.1: Mobility Management Mechanism.

nized as one of the most challenging problems. This is mainly attributed to two factors: (i) the wireless link layer characteristics and (ii) the operation of the TCP/IP protocol.

6.1.1 Limitations of the Wireless Link Layer

At the link layer, access to the Internet via wireless networking entails the need for frequent changes of the serving access points, either due to the small cell size of wireless networks or due to the desire of users for being always best-connected via any of the available wireless networks. However, frequent handoffs not only introduce time delays and packet loss which may be prohibitive for real-time applications but also lead to extensive power consumption which limits the lifetime of the energy-constrained mobile terminals. In addition, the heterogeneity that will characterize future wireless systems instigates the development of an intelligent and global handoff mechanism that can provide seamless roaming capability regardless the actual underlying wireless access technology.

6.1.2 Limitations of the TCP/IP protocol

The TCP/IP protocol suite is a five-layer protocol architecture which defines the specifications for communication over the Internet. The Transmission Control Protocol (TCP) at the transport layer and the Internet Protocol (IP) at the network layer are its main elements which were originally designed for static computer networks, making it difficult for accommodating mobility support.

According to the IP, an IP address has two major functionalities: to uniquely identify a particular node in the entire network and for routing the traffic between two endpoints. The IP address is indicative of the IP subnetwork the terminal resides. Apparently, the problem arises when the node changes subnetwork due to its mobility; its IP address has to be changed to represent its new point of attachment to the network such that packets are routed successfully to it. However, IP address changes cause interruption of any ongoing IP session.

The TCP provides a connection-oriented service that allows for reliability, fragmentation, flow control, and congestion control. Even if the device is able to obtain a new IP address dynamically, the transport connections established in the previous network will be broken after the change of the IP address. In addition, the congestion control of TCP [92] is based on the assumption that the end-to-end path of a connection is relatively stable after connection establishment and therefore it is not able to distinguish whether the packet loss is due to congestion or due to mobility and wireless link properties. Thus, the congestion window is reduced even if there is no congestion, resulting in an unreasonable throughput degradation [93].

6.2 Standard Handoff Protocols

The Standard solutions for handoff management at both the link and network layers are described in the following.

6.2.0.1 Link Layer Handoff

A Link Layer (LL) or layer 2 (L2) handoff (HO) occurs because the MN must establish a new physical connection to a new Access Point (AP). This is because, due to mobility, the received signal strength (RSS) or Signal to Noise Ratio (SNR) from the MN's current AP may decrease, causing degradation of their communication. Even though several protocols have been proposed and for different wireless access technologies, we focus on the IEEE 802.11 standard [64], for its popularity, its inefficiency for mobility support due to small AP coverage, and the availability of numerical results regarding its latency analysis [94].

According to its specifications, the handoff process includes three main steps: *Discovery*, *Authentication* and *Association*, as illustrated in Figure 6.2. During the *Discovery* phase, the MN searches for a AP with stronger RSS to associate with. This is accomplished through a medium access control (MAC) layer function, called *scan*. There are two modes of scanning: *active* and *passive*. In *passive* mode the MN listens for beacon messages (sent periodically by the APs), on assigned channels. In *active* mode, the MN sends in addition PROBE REQUEST broadcast packets on each channel and receives PROBE RESPONSES from APs. The standard defines two parameters to be set while scanning, namely *MinChannelTime* and *MaxChannelTime*. The *MinChannelTime* is the minimum time the MN needs to spend on a channel. If the MN finds the channel to be busy before the *MinChannelTime* elapses, it concludes that there exists at least one AP operating on that channel. Therefore, the MN waits till the *MaxChannelTime* transpires to give to AP(s) operating on that channel enough time to send back their PROBE RESPONSEs. After scanning all channels, the MN selects a target AP and enters the *Authentication* step, which includes the transmission of the MN's identity to the AP and the AP's AUTHENTICATION RESPONSE. The L2 handoff terminates upon the reception of an ASSOCIATION RESPONSE message.

Handoffs are a major challenge in wireless networks since they occur frequently due to the small coverage area of the APs and the wireless link quality. This is because, during handoff the MN is unable to send or receive data, therefore its duration is critical for meeting the needs of real-time applications such as VoIP, 802.11 phones, mobile video conferencing and chat. For instance, Voice over IP (VoIP) requires a maximum end-to-end delay of 50 ms [95]. Furthermore, the scanning process is power consuming and should be avoided by the energy-constrained mobile terminals. Finally, the transmission of PROBE REQUESTS and PROBE RESPONSES leads to considerable bandwidth waste. According to the experimental results in [94] the discovery phase delay is the dominating factor in L2 handoff latency, accounting for more than 90% of the overall cost. This is mainly because the MN has to wait for *Probe Response* messages even if no APs are operating on specific channels.

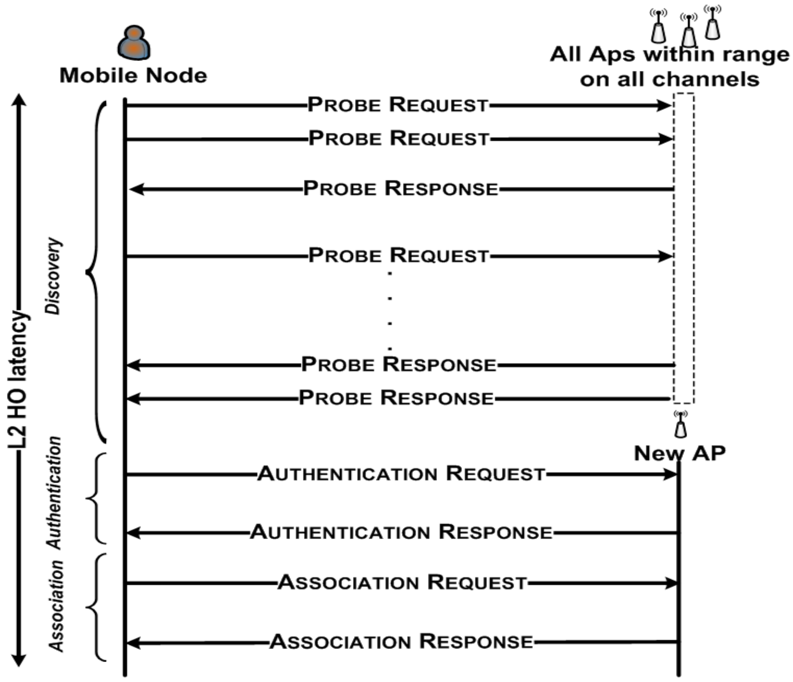


Figure 6.2: IEEE 802.11 handoff mechanism.

6.2.0.2 Network Layer Handoff

If the MN roams between two APs of the same subnetwork, no routing (IP-based) issues occur and its session is not interrupted. However, if the APs belong to different IP subnetworks, the routing subnetwork prefix changes and thus a Network Layer (NL) or layer 3 (L3) handoff follows the L2 handoff. Figure 6.3 illustrates the handoff process as described in MIP [13]. It includes three stages: *Movement Detection* (MD), *Address Configuration* (AC) and *Binding Update* (BU). The *movement detection* stage is entered after a MN has attached itself to the new network (i.e. after the L2 handoff). In this stage a MN detects that it has moved to a new network, based on messages broadcasted by the ARs in either a *passive* or *active* mode. In *passive* mode, the ARs regularly send broadcast ROUTER ADVERTISEMENTS messages that contain their identity and their IP addresses. In *active* mode, the MN is sending in addition ROUTER SOLICITATION requests to ARs in order to discover new points of attachment to the network. The MN receives relevant information from the network that will allow it to configure its CoA and other network settings. Finally, it sends a BINDING UPDATE to its Home Agent.

The movement detection mechanism in MIP is designed to be suitable for mobility

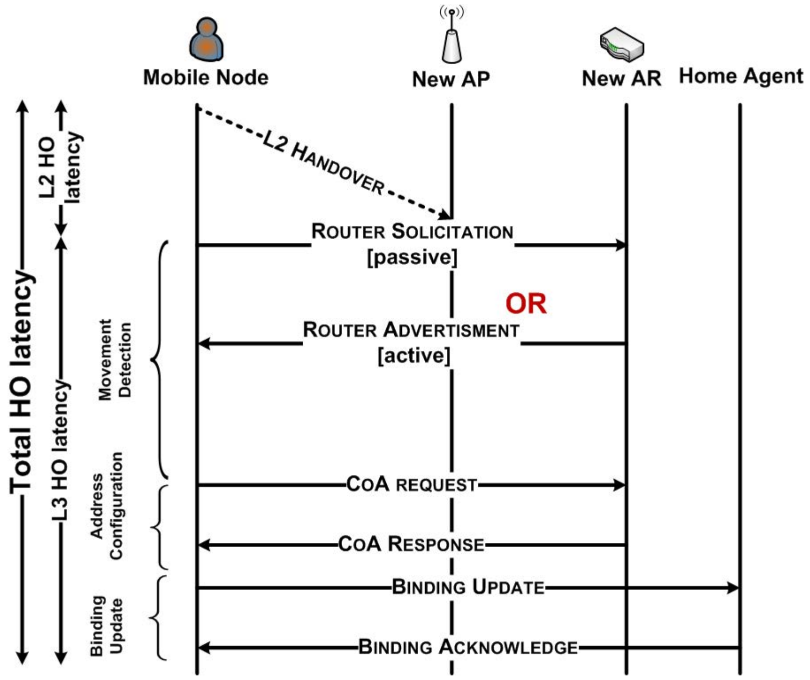


Figure 6.3: Mobile IP handoff mechanism.

over heterogeneous networks and therefore it lacks information of the layer 2 handoffs. When a MN moves to a new sub network, packets are not delivered to the MN at the new location until the Care-of-Address (CoA) registration to the HA is completed, due to the time difference between the completion of the link layer handoff and the registration of the new PoA to the Home Agent. In fact, during MD, the MN is physically connected to the new PoA, whereas at network layer it is still connected to the old PoA. Therefore, synchronizing the link and network layer handoffs is necessary, which can be achieved by minimizing the movement detection delay. MD duration is the main delay factor which depends on the frequency of the Router Advertisement or Router Solicitation messages. Statistically, the longer the time between two consecutive messages, the more it takes the movement detection to be completed. According to results found in [96], MD latency is on average $36ms$ to $558ms$ when Router Advertisements are broadcasted every $0.05s$ to $1.5s$.

6.3 State of the Art Handoff Schemes

The increasing demand for the support of real-time multimedia applications over the Internet via wireless and mobile networking, but also the failure of the standard solutions to fulfil this requirement drove the research towards the improvement of the handoff mechanism, resulting in a vast variety of proposals.

At the link layer most of proposals aim at improving the *discovery* phase, which is the dominating delay and energy consuming factor. The authors in [97] claim that a slight increase (about 4%) of AP's capacity used for beacon transmission can shorten the beacon interval from 100 ms to 60 ms and adjusting *MinChannelTime* and *MaxChannelTime* in the active scanning can reduce the search phase by 20%. The authors in [95] target at decreasing the probe delay by reducing both the total number of channels to be probed and the waiting time on each channel. For doing this, they propose two novel L2 handoff schemes, called Neighbor Graph (NG) algorithms and NG-pruning algorithms, which make use of two data structures, namely the neighbor graph (NG) and the non-overlap graph (NOG), respectively. These structures abstract the handoff relationships between access points. In the SyncScan approach [98], the MN monitors the proximity of APs in its neighborhood by scanning channels intermittently and recording the corresponding signal strengths. By synchronizing the APs and forcing the APs to transmit the beacon signals based on the channel they operate on, the MN knows when the beacon signals are transmitted on each channel. Therefore, the MN does not need to wait for the full beacon interval. Since SyncScan is based on the regular monitoring of APs, time synchronization is a critical issue. Moreover, the accompanied channel switching delay incurred for each channel scan is not considered.

Rather than relying on RSS measurements, there are several schemes which follow alternative approaches. The authors of [99] propose a cross layer handoff ordering scheme, which adopts the frame success rate (FSR) at MAC layer rather than the RSS at the PHY layer, as the link quality metric. They claim that FSR is more suitable to represent the link quality, because it can be easily mapped to the application layer QoS requirements of various applications, e.g. throughput, delay, and packet success rate. Another important class of handoff schemes make use of location information, based on the assumption that the closest AP provides better quality of communication. The authors of [100] propose using the mobile node's position for increasing the stability of the network, preventing call-drops, traffic congestion and increasing the resource utilization. Furthermore, geolocation information can also be used in heterogeneous networks. In [101] the authors present a location assisted algorithm to manage handoffs between WLAN and GPRS networks. A new network entity monitors the movement of MNs and detects when a MN moves inside the coverage area of a WLAN. According to various parameters, such as velocity, direction and ongoing traffic of MNs, it can estimate if a handoff is appropriate. [102] presents an architecture for the seamless location-aware integration of WLAN hotspots into cellular networks. Location-awareness, obtained by GPS receivers, can assist whether to join or leave WiFi hotspots. A location-based vertical handoff scheme in WLAN and UMTS networks is introduced in [103] for reducing the ping-pong effect, while in [104] two location tracking algorithms are described for achieving reduced number of handoffs without additional connections between the mobile stations and the non-serving Base Station in a IEEE 802.16e network. Finally, the authors in [105] demonstrate via experimental results the advantages of location-assisted handoffs over traditional RSS-based schemes regarding handoff latency and packet loss.

At the network layer, minimizing the duration of movement detection is mainly proposed. The authors in [106] discriminate two broad classes of movement detection approaches, advertisement-based and hint-based schemes.

The first rely on the periodic broadcasting of AR advertisements which include mobility related information. CARD (Candidate Access Router Discovery) [107] is an IETF proposal where an AR announces its capabilities in broadcast messages. In such schemes, there is an inherent trade-off between the bandwidth wasted by advertisements and the MD performance. The higher the rate that periodic advertisements are broadcast, the more bandwidth is wasted by these messages.

Hint-based mechanisms try to compromise the layer independence between Mobile IP and the link-layer by utilizing triggers or events from the link layer in order to detect the movement of the mobile node to a new network. The most popular of hint-based MD scheme is Fast Mobile IP (FMIPv6) [108]. It defines two modes of operation depending on the predictability of MN's mobility: the *predictive* mode and the *reactive* mode. In the predictive mode, the MN can predict its movement and the identifier of a prospective point of attachment, e.g. IEEE 802.11 Access Point (AP), and most of the handoff operations can be finished before the link layer handoff. On the contrary, in the reactive mode, the MN starts handoff operations after the link layer handoff. The performance of FMIPv6 suffers from problems such as predictive latency and reactive loss [109]. Predictive latency is the time difference between the moment that packets for the MN are forwarded from the old AR to the new AR and the moment that the link between the MN and the old AR is really down. On the other hand, reactive loss is due to the fact that the old AR starts forwarding packets after the MN is attached to the new AR.

In the past few years, it has been proposed that geolocation information can be used for improving handoff management at the network layer as well. In [110] GPS coordinators are used to configure care-of-address, which provides faster IP address discovery. However, this strategy consumes too much address space and lacks flexibility, since it is mostly efficient for fast moving vehicles. Finally, few schemes rely on sensing techniques. [111] proposes a sensor-augmented architecture for limiting the number of scanned channels and taking informed decision about the most appropriate AP to be associated with. In [112] sensor networks are deployed at the network fringes in order to detect the L3 movement of a MN between two APs and prepare proactively its registration to the new network.

6.4 Chapter Summary

Mobility support is the main requirement for the accomplishment of the envisioned wireless and mobile Internet. This chapter provided essential background regarding the main mobility management problems and solutions focusing on the handoff process at both the link and network layers.

Solutions of the Standard protocols were firstly presented highlighting their main limitations. In the sequence, literature proposals trying to tackle them were explored and their advantages and disadvantages were discussed, in order to aid the comprehension of our motivation behind our proposed handoff schemes in the following chapters.

Undoubtedly, in future communication networks mobility management techniques should be designed in a way such that global roaming among heterogeneity access technologies will be possible. Moreover, considering the significance of location information in future context-aware communication makes location-aware mobility management schemes more attractive and viable solutions. These observations conducted our research efforts for designing efficient handoff schemes which are described in the following chapter.

Chapter 7

Location-aware Mobility Management

Handoff management is one of the main research challenges for the realization of the envisioned mobile and wireless Internet. This is mainly due to the latency delay and energy consumption introduced during handoff, which are of major concern for real-time applications and battery-constrained mobile terminals. Moreover, the co-existence of heterogeneous networks which will be available to satisfy different needs of users impels for global handoff solutions, i.e. independent of any specific wireless access technology triggers.

In this chapter, we explore whether handoff management can benefit from the pervasiveness of future communication networks. The key idea is to follow the ambient intelligence paradigm for the purpose of context-aware handoff. Focusing again on the Radio Frequency Identification (RFID) but also on the Wireless Sensor and Actuator Networks (WSANs) pervasive technologies, we propose two schemes for handoff prediction at the network layer or at both link and network layers. Analytical models for their time response and energy consumption are firstly derived and finally simulation-based results validate their performance superiority over the Standard solutions.

The rest of this chapter is organized as follows: section 7.1 explains our motivation for conducting this study. Sections 7.2 and 7.3 describe our two proposed handoff management schemes. Section 7.4 analyzes their performance theoretically while section 7.5 provides numerical results based on simulations. Finally, section 7.6 summarizes the main points of this chapter.

7.1 Motivation: Need for Seamless, Energy-aware and Global Handoff

Our motivation stems from the necessity for the design of seamless but also energy-efficient handoff mechanisms that will meet the requirements of real-time and QoS-demanding applications and can be easily adopted by the battery-constrained mobile terminals. Moreover, we target at schemes that do not rely on special triggers or characteristics of the underlying wireless access technology in order to be easily integrated in heterogeneous networks.

In the context of the upcoming pervasive communication era, several heterogeneous technologies will be available enabling ubiquitous access to different applications from a plethora of available interfaces at future multi-mode mobile terminals. Investigating potential synergies among these heterogeneous technologies appears indispensable in order to tackle more efficiently different functionalities in this network. We focus our attention on the possible interactions between wireless access technologies such as IEEE 802.11 with RFID (Radio Frequency Identification) technology and/or WSAN (Wireless Sensor/ Actuator Network) technology, in order to improve the handoff process from the latency and energy consumption points of view, both of which are of major interest in the generalized Internet mobility.

The main strengths of RFID include the low cost of passive tags, the fast and accurate reading of tags, the better resilience to harsh environmental factors, the ease and flexibility in associating tag IDs with handoff decision related information in a database, its independence from the principal wireless access technology and its anticipated widespread deployment and integration in future communication networks. Based on these observations, we first propose utilizing a RFID tag deployment for performing the movement detection step of the L3 handoff process, illustrated in Figure 6.3. In our proposed scheme, by associating area location with network topology information with the aid of the RFID technology, a MN can predict its next PoA and consequently pro-actively proceed with its registration to this PoA (if different from the current PoA). Thus, the IP handoff latency can be reduced to match the L2 handoff latency.

In the sequence, we try to take also into the factor of energy consumption and propose a second handoff scheme for both link and network layers which relies on the the deployment of a hybrid RFID and WSAN system. Even though RFID and WSAN are under parallel development, few integration schemes have been proposed [113]. The main strength of WSANs is their wireless communication for performing distributed sensing and actuation tasks. However, sensors are power-limited and require strict time-synchronization for performing real-time computations. In contrast, RFID tags do not need battery and correlating their IDs with network information [114] enables real-time information retrieval by reader-enabled terminals. However, direct communication among readers is not supported. Thus, we argue that their integration is essential for enabling a complete pervasive solution. In our system architecture, the WSAN is responsible for initiating/ceasing the handoff process, predicting the next point of attachment (PoA) and communicating through multi-hop all handoff related information. For predicting the next PoA, RFID passive tags are deployed at the outer part of APs' range in order to track the movement pattern of a MN with a reader-enabled terminal.

In the following sections, both schemes are described in detail.

7.2 Scheme A: RFID-assisted Network Movement Detection

Scheme A aims at reducing the movement detection latency for matching the handoffs at the link and network layers. *Passive tags* are deployed throughout the studied area in order to detect the movement of a MN with a *reader*-enabled terminal. The tags can be deployed in the area such that their IDs are associated with network topology information, i.e. each tag ID is matched to its best PoA. Then, during MN's mobility, information retrieved from the detected tags is used for detecting the user's movement and thus anticipating its next best PoA. Moreover, the selection of the best PoA is based on a *decision function* which can incorporate several parameters. The flexibility on its definition offers the opportunity for the provision of QoS support, by taking into account preferences of users or network providers.

7.2.1 System Architecture Design

We consider a wireless network divided into a set $\mathcal{P}$ of smaller subnetworks each one served by a single AP, acting as the Access Router (AR) of that subnetwork as well. Within the entire network, a MN m is roaming among these subnetworks while communicating. When located within a subnetwork served by AP_i, MN m has this AP as its Point of Attachment (PoA) for gaining access to the Internet, i.e. $PoA_m = AP_i$.

Apart from a wireless interface, the terminal of MN m is also equipped with an RFID reader r_m, which retrieves information from a set $\mathcal{U}$ of passive RFID tags deployed in a grid fashion on the floor of the area. Each tag $t \,/\, \mathcal{U}$ has certain ID ID_t and location (x_t, y_t) and is called *reference* tag.

Finally, a dedicated server within the network domain, called RFID-Server (RFID-S), maintains a database to be utilized for the purpose of the *movement detection* procedure during the roaming of the MN.

7.2.2 Mechanism

The mechanism details are described in the following.

7.2.2.1 Message Exchange

Figure 7.1 illustrates the process and message exchange diagram of the proposed mechanism, during the real-time movement of a MN. Initially, the RFID reader r_m of each MN m's device queries periodically (or on demand) for tags within its coverage in order to retrieve their IDs. The list of the retrieved IDs, denoted as $\mathcal{G}_m$, is then forwarded to the RFID-S in a Tag List message. The reading period, i.e. time interval between consecutive tag readings or equivalently the frequency of the Tag List updates, are system design parameters.

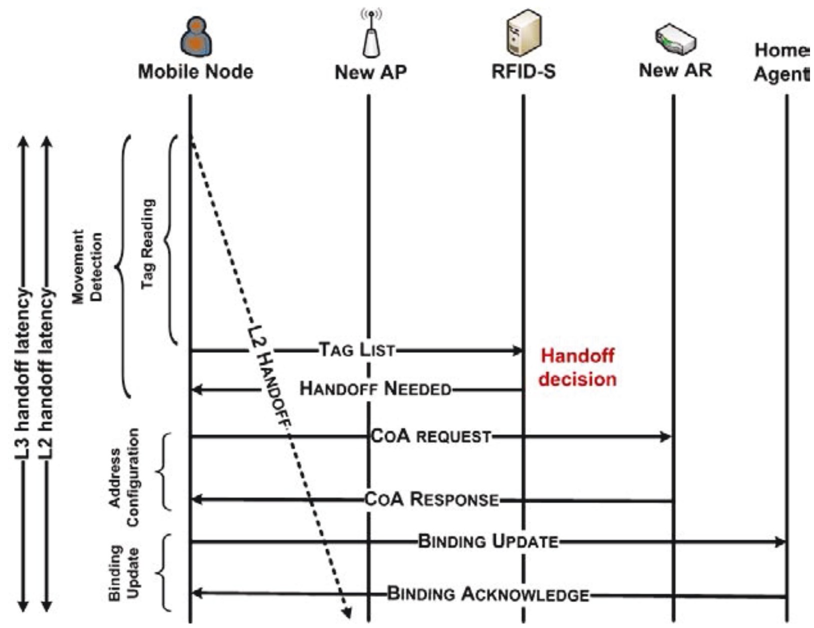


Figure 7.1: Scheme A handoff mechanism.

Based on the received Tag List messages, a database called PAM (see section 7.2.2.2) and a well defined *decision function* (see section 7.2.2.3), the RFID-S predicts the most suitable PoA with which the MN m most probably will associate, i.e. PoA_m, after the L2 handoff. If the selected next PoA is different from the current PoA of the MN, the RFID-S sends a Handoff Needed message to that MN, which contains information required for the new CoA acquisition. Hence, the *Movement Detection* step in our proposal does not rely on Router Advertisements or Router Solicitations messages which add to the handoff delay and consume valuable bandwidth. Upon successful association to the target PoA (if different from the current PoA), the MN can configure a new CoA using the IP prefix included in the Handoff Needed message and immediately send a Binding Update message to its Home Agent (HA).

Note that the L2 handoff process is not explicitly modified and can be assumed the one described in IEEE 802.11 standard [64]. However the MD stage in the above proposal can be initiated in parallel with it or even trigger its initiation. In this case, our proposal helps L3 handoff to better synchronize with L2 handoff. After the reception of a successful Binding Acknowledgement message, the handoff is completed and the MN can continue its ongoing communication. In the case of movement between APs within the same subnetwork (same Access Router), no L3 registration is needed since the CoA has not changed. In this case, our proposal would trigger the L2 handoff to start pro-actively the scanning phase for discovering the best AP's RSS before loosing the signal from the current AP.

7.2.2.2 Database Construction

The Point of Attachment Map (PAM) is built during an offline pre-phase and associates each reference tag ID with *topology* or *connectivity* information. As *connectivity* information, several characteristics can be considered as most appropriate to be stored depending on the requirements of the network and preferences of users or the network provider. We consider a simple scenario according to which each tag ID is associated with its best PoA. Best PoA_t for tag t is considered the AP_j from which the RSS at that tag's position (x_t, y_t) is stronger, similar to the RSS-based L2 handoff, i.e.

$$PoA_t = AP_{\arg\max_{j \in \mathcal{N}} RSS_{WiFi}(d_{tj})}, \tag{7.1}$$

where d_{tj} the distance between tag t and AP_j. Table 7.1 shows the format of the PAM.

Table 7.1: PAM Database format.

#	**Tag ID**	**Location**	**Best PoA**
1	0000...	(x_1, y_1)	AP_1
...	...	...	...
t	0101...	(x_t, y_t)	AP_j
...	...	...	...
$\mathcal{U}$	1111...	$(x_{\|\mathcal{T}\|}, y_{\|\mathcal{T}\|})$	$AP_{\|\mathcal{N}\|}$

Building the above PAM database requires manual effort for collecting RSS measurements from all APs at all reference tags' positions, which may be undesirable in some cases. However, our proposed PoA prediction scheme is actually independent of this choice. For instance, the distance between APs and reference tags could have alternatively been used, such that best PoA_t for tag t is the AP_j which is closer to this tag, i.e.

$$PoA_t = AP_{\arg\min_{j \in \mathcal{N}} d_{tj}}. \tag{7.2}$$

7.2.2.3 Handoff Decision function

Similar to the information selected for constructing the PAM during the system training phase, defining the *decision function* for selecting the next PoA of MNs during the real-time phase can also be flexible and based on special preferences of the network designer. We design a simple *decision function* in order to focus our attention on the precision achieved by the RFID technology in predicting the next PoA. Thus, given the set $\mathcal{G}_m$ of detected tag IDs of a MN m (information contained in the TAG LIST message) and the set of their best PoAs $\}ID_t, PoA_t|$, $\mathcal{C}t$ / $\mathcal{G}_m$ (information obtained by looking up the database), each unique AP_j is assigned a frequency f_j equal to the number of tags in $\mathcal{G}_m$ which have assigned this AP as their best PoA. Then, the AP_j which appears most frequently (f_j is maximum) is selected as the next PoA_m of the MN m, i.e.

$$PoA_m = AP_{\arg\max_{j \in \mathcal{N}} f_j}. \tag{7.3}$$

7.3 Scheme B: RFID and WSAN for Handoff at Link and Network layer

According to Scheme A, the reader is querying for tag IDs even when there is no need for handoff, leading to considerable power waste. To deal with this limitation we propose employing WSAN in addition to the RFID deployment in order to control the MN's reader activity and minimize the energy consumption.

In the proposed system architecture, a deployment of RFID passive tags is used for capturing the mobility pattern of a MN with a reader-enabled terminal in order to predict its next PoA. In this way, there is no need for performing the power and time consuming RSS scanning process as defined in the 802.11 MAC protocol. In addition, if the predicted AP belongs to a different subnetwork, there is no need for waiting for the reception of Router Advertisement messages, hence minimizing the movement detection delay.

The main role of the WSAN is to serve as an overlay control plane on the top of the WLAN data plane, for monitoring and controlling the handoff process. In this way, the handoff-related overhead is shifted from the main data communication channel. *Sensor* nodes monitor the absence or presence of the MN within a *specified* region and *route* this information to *actuator* nodes which are then responsible for triggering the initiation or termination of the handoff prediction process, respectively. Thus, by selectively performing handoff prediction, further power consumption savings are achieved.

7.3.1 System Architecture Design

Figure 7.2 illustrates the system architecture, which consists of the WLAN infrastructure and the deployment of the RFID and WSANs at strategic points. Mobile nodes are multi-mode terminals equipped with RF transceiver, RFID reader and sensor.

The WLAN infrastructure consists of APs, deployed at known positions similar to the cellular concept and is responsible for providing data communication and wireless access to the Internet to MNs. R_{max} denotes the maximum range of each AP and R_{safe} a *safe region* within which there is no need for handoff preparation. Defining these ranges can be done during the network configuration and may depend on parameters such as RSS level, obstruction, etc. In this study, we consider the distance from the AP. A database, called WLAN-*Knowledge Table*, is used to store all this information such that an entry associates an AP identifier with the position and the ranges R_{max} and R_{safe} of that AP.

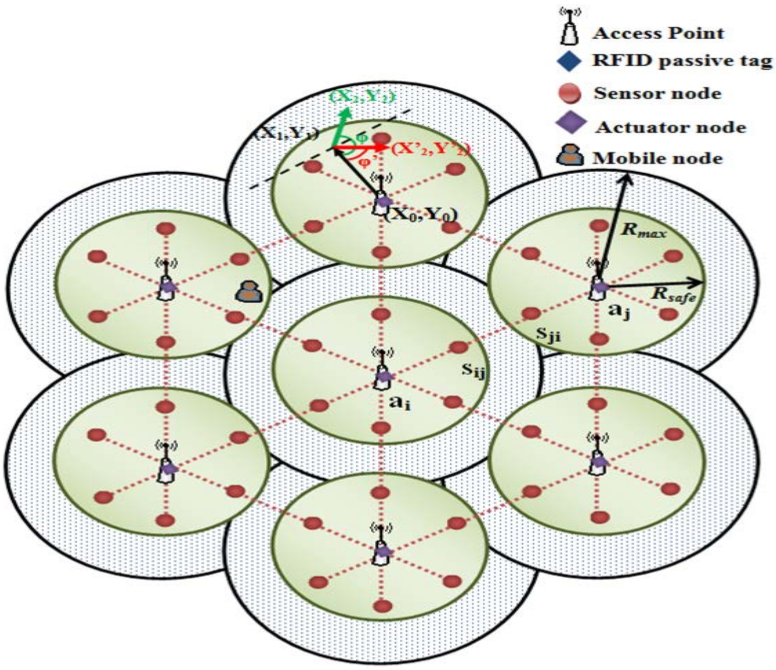


Figure 7.2: Scheme B system architecture.

Regarding the RFID deployment, cheap *passive tags* are uniformly distributed throughout the outer range of each AP. Their IDs are associated with their location coordinates in a database called RFID-*Knowledge Table*. The MN's reader can retrieve IDs of tags within its range.

The WSAN is composed of two types of nodes, namely *sensors* and *actuators*. *Actuators* are attached to APs and maintain the RFID- and WLAN- *Knowledge Table*s. *Sensors* are deployed at strategic positions such that each pair of sensor nodes is responsible for routing information between a particular pair of neighboring *actuators*. In Figure 7.2, the pair s_{ij} s_{ji} is responsible for the communication between actuators a_i and a_j. Sensors are also pre-configured with *safe region* information (R_{safe}) in order to monitor the MN within or without this region and inform the *actuator* only in the case of change of the MN's state.

7.3.2 Mechanism

In the following, a detailed mechanism description is provided.

7.3.2.1 Message Exchange

Figure 7.3 depicts the message exchange time-diagram. It includes three phases: *sensing*, *handoff prediction* and *handoff execution*.

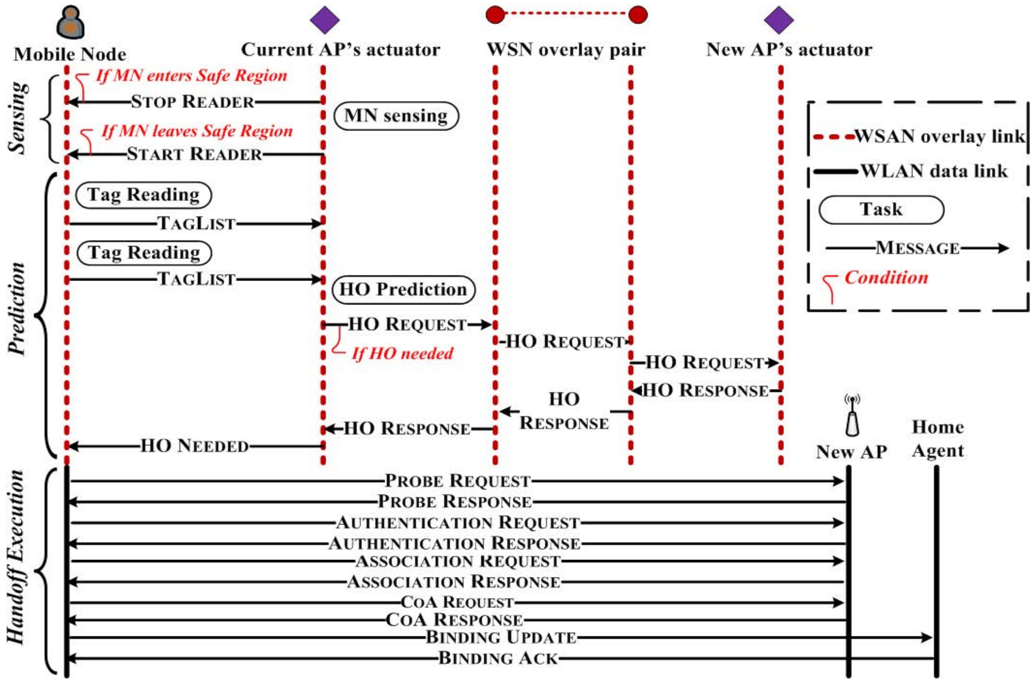


Figure 7.3: Scheme B handoff mechanism.

During the *sensing* phase, sensor nodes monitor the presence or absence of the MN within the *safe region* and forward this information (absence or presence) to the actuator node attached to the MN's serving AP. If the MN moves out of this region, the actuator activates the MN's reader to start the tag scanning process, by sending a START READER command. In the reverse case, a STOP READER command is sent for ceasing the reading process.

The *handoff prediction* phase is entered after a START READER command. During this phase, the MN's reader scans *periodically* for surrounding area tags for two consecutive times (needed for *mobility modeling* as explained in section 7.3.2.2). The retrieved tags' IDs are then sent in two time-stamped TAG LIST messages to its serving AP's actuator. Based on these messages and the WLAN- and RFID- *Knowledge Tables*, the actuator estimates the mobility pattern of the MN in order to predict its next handoff point. If the predicted handoff point is different from its current PoA, it sends a HO REQUEST message to the new

AP's actuator through the corresponding pair of sensor nodes. The new actuator replies with a HO Response message, reversing the same path. Upon its reception, the serving AP's actuator sends to the MN a HO Needed message which contains information relevant to the new AP. If no such message is received, the MN continues periodically sending Tag List reports to the actuator, until it receives either a HO Needed message or Stop Reader command. We propose exchanging these messages on the WSAN for reducing the handover control overhead from the main data channel. However, this is not a strict protocol requirement.

Finally, during the *handoff execution* phase, the Standard steps are followed without the need for the L2 *discovery* and L3 *movement detection* steps.

7.3.2.2 Mobility Modeling

The movement pattern of the MN is modeled by three main mobility characteristics: current position $(\widetilde{X}, \widetilde{Y})$, velocity $\mathbf{v}$ and direction of movement ϕ. The estimation of these parameters relies on the RFID deployment and the reading capability of the MN's terminal.

Let $\mathcal{U}_i$ the list of detected tag IDs at time t_i. By looking-up at the RFID *Knowledge Table*, the MN's position can be estimated as the weighted average of the location coordinates $(x_t, y_t)\mathcal{C}t \ / \ \mathcal{U}_i$, with weighting factor w_t depending on the signal strength of tag t's response, i.e.

$$\Big) \widetilde{X}_i, \widetilde{Y}_i \Big(= \Bigg) \frac{\bigcup_{t\in\mathcal{T}_i} w_t \times x_t}{\bigcup_{t\in\mathcal{T}_i} w_t}, \frac{\bigcup_{t\in\mathcal{T}_i} w_t \times y_t}{\bigcup_{t\in\mathcal{T}_i} w_t} \Bigg\{ . \tag{7.4}$$

For estimating the velocity, location estimations at two different time instances t_i and t_{i+1} are required, such that

$$\mathbf{v}_{i+1} = (v_{i+1,x}, v_{i+1,y}) = \Bigg) \frac{\widetilde{X}_{i+1} \quad \widetilde{X}_i}{t_{i+1} \quad t_i}, \frac{\widetilde{Y}_{i+1} \quad \widetilde{Y}_i}{t_{i+1} \quad t_i} \Bigg\{ \tag{7.5}$$

Finally, the direction of movement is estimated with reference to the serving AP's position (X_0, Y_0) by using vector analysis. Let $\mathbf{V}_i = (X_i \quad X_0, Y_i \quad Y_0)$ and $\mathbf{V}_{i+1} = (X_{i+1} \quad X_i, Y_{i+1} \quad Y_i)$ the movement vectors at times t_i and t_{i+1}, respectively. The angle $\phi \ / \ [0, 2\pi]$ between them is given by

$$\phi = \cos^{-1} \Bigg) \frac{\mathbf{V}_i \times \mathbf{V}_{i+1}}{\mathbf{V}_i \quad \mathbf{V}_{i+1}} \Bigg\lfloor , \tag{7.6}$$

where $< \times>$ denotes the dot product between two vectors and $\mathbf{V}$ the norm operator for vector $\mathbf{V}$.

7.3.2.3 Handoff Prediction Algorithm

The handoff prediction algorithm uses the MN's current mobility parameters and the APs position information (from the WLAN-knowledge table) for predicting whether the MN is moving towards a new AP and if so, for determining the most probable next PoA. For identifying whether the MN is moving away from its serving AP, its movement direction is used. As shown in Figure 7.2, if $\phi < \pi/2$ the MN is moving towards its current PoA and therefore there is no need for handoff. However, if $\phi \approx \pi/2$ the MN will most probably need handoff and therefore its next PoA should be predicted in advance. Assuming constant velocity $\mathbf{v} = \mathbf{v}_{i+1}$ and direction of movement, the position of the MN a time t_{i+2} can be predicted as

$$\left(\widetilde{X}_{i+2}, \widetilde{Y}_{i+2}\right) = \left(\widetilde{X}_{i+1} + v_x\delta t, \widetilde{Y}_{i+1} + v_y\delta t\right), \tag{7.7}$$

where $\delta t = t_{i+2} - t_{i+1} = t_{i+1} - t_i$ the reading rate.

The next handoff decision is then based on the distance from the surrounding APs, such that the closest one is selected as the best AP^{i+2} at time t_{i+2}. However, for avoiding the ping pong phenomenon when the MN moves along the borders of two neighbor APs, a distance threshold TH condition is incorporated in the decision algorithm, such that

$$\mathrm{AP}^{i+2} = \mathrm{AP}_{\arg\min\left\{\min\limits_j d^{i+2}(\mathrm{AP}_j),\, d^{i+2}\left(\mathrm{AP}^{i+1}\right) - \mathrm{TH}\right\}} \tag{7.8}$$

where $d^i(\mathrm{AP}_j)$ the predicted distance from AP_j at time t_i and $AP_j \forall\neq AP^{i+1}$.

Recalling the handoff decision function of Schemes A, described in subsection 7.2.2.3, the selection of the next PoA was based on a simple maximum likelihood concept, instead of relying on accurate location and distance estimations. However, it is worthy mentioning that this is not the main difference between the two schemes. Either or even another decision function could be employed by any of them. We selected that decision function for Scheme A in order to emphasize the potential benefits of an available RFID deployment for the purpose of handoff prediction. Whereas the main focus of Scheme B is the accurate location estimation and energy savings that can be achieved if the key properties of many technologies are combined in a common architecture.

7.4 Theoretical Analysis

In this section, we analyze theoretically the performance of the Standard protocols and our proposed schemes with respect their time response and energy consumption.

7.4.1 Time Response

In general, the total handoff duration T_{HO} includes the time needed for the link and possibly network layer handoffs, denoted as T_{L2} and T_{L3}, respectively.

7.4.1.1 Standard Protocols

According to the specifications of the Standard solutions, the L3 handoff starts after the completion of the L2 handoff. Therefore, the total handoff duration T_{HO}^{S} is given by adding these two factors, i.e.

$$\mathrm{T}_{HO}^{S} = \mathrm{T}_{L2}^{S} + \mathrm{T}_{L3}^{S} = (\mathrm{T}_{D} + \mathrm{T}_{AU} + \mathrm{T}_{AS}) + (\mathrm{T}_{MD} + \mathrm{T}_{AC} + \mathrm{T}_{BU}),$$

where T_D, T_{AU} and T_{AS} are the delays during the *discovery*, *authentication* and *association* steps of the IEEE 802.11 handoff process, while T_{MD}, T_{AC} and T_{BU} count for the *movement detection*, *address configuration* and *binding update* steps of the MIP handoff process.

The duration of the discovery phase includes the channel switching and transmission (CS&T) delay and the probe delay T_{prob} [95]. The CS&T delay is the time needed to switch and transmit on a channel and is about 40-150 usec [115]. The probe delay depends on the scanning mode, passive or active. In passive mode, the average probe delay is function of the number of scanned channels and the transmission rate of the beacon frames from the APs. For instance, in the IEEE 802.11b/g (11 channels) and with beacon interval 100 ms, the average probe delay is 1100 ms. On the other hand, in active mode the probe delay can be determined by the *MinChannelTime* and *MaxChannelTime* values, which are device-dependent. The current active scanning procedure requires for a MN to scan all available channels. Therefore, the probe delay is given by

$$\mathrm{T}_{prob} = C \pm \frac{MaxChannelTime \quad MinChannelTime}{2}, \tag{7.9}$$

where C the number of channels (i.e., 11 channels for IEEE 802.11b and 32 channels for IEEE 802.11a).

7.4.1.2 Scheme A

In our proposed Scheme A, the L3 *movement detection* step is performed by the RFID system, independently of the WiFi channel. Thus, in contrast with MIP, the MD can start before the completion of the L2 handoff and even complete before it. Therefore, its latency T_{HO}^{A} is given by

$$\mathrm{T}_{HO}^{A} = \max\}\mathrm{T}_{L_2}, \mathrm{T}_{MD}^{A} + \mathrm{T}_{AC} + \mathrm{T}_{BU}| \tag{7.10}$$

In our case, T_{MD}^{A} is given by

$$\mathrm{T}_{MD}^{A} = \mathrm{T}_{TR} + \mathrm{T}_{MN-S} + T_{dec} + \mathrm{T}_{S-MN} \tag{7.11}$$

which includes the time needed for the MN's reader to scan all *reference tags* within its vicinity (T_{TR}), the time needed for transmitting the TAG LIST message from the MN to the RFID-S (T_{MN-S}), the processing time needed for choosing the next best PoA (T_{dec}) and the time needed for sending the HANDOFF NEEDED message from the RFID-S back to the MN (T_{S-MN}).

From the above components, the time factors T_{MN-S} and T_{S-MN} depend on the messages' size, supported data rate, the propagation delay and the time spent due to collisions before accessing the medium. Considering the high data rates (1 up to 54-Mbps) of the current IEEE 802.11 protocols, these time parameters are negligible. In fact, the prevailing one is the time needed for reading the tags by the MN's reader, i.e. T_{TR}, which is analyzed in the following.

T_{TR} depends on two factors: (i) the number of tags within a reader's range whose IDs need to be acquired with a single reading and (ii) the anti-collision protocol followed by the reader for resolving the collisions among multiple tags' responses. The number of responding tags depends on the geometry of the tags deployment and the reader's range. Considering a grid tag deployment and that the reader's radiation pattern forms a circle, as depicted in Figure 7.4, the maximum number of detected tags N is given by

$$\mathrm{N} = 4]r/\delta\{^2, \tag{7.12}$$

where δ the inter-tag spacing and r the range radius.

For retrieving information from multiple tags, resolving the collisions among their transmissions is necessary. Reviewing the literature, several anti-collision protocols have been proposed, which mainly differ in the number of tags that can be read per second, their power and processing requirements [82]. In this work, we have selected as base of our analysis the Pure and Slotted Aloha, which are time-division multiple schemes.

For retrieving information from N tags, resolving the collisions among their transmissions is necessary. [82] provides a detailed analysis for several anti-collision protocols. In this

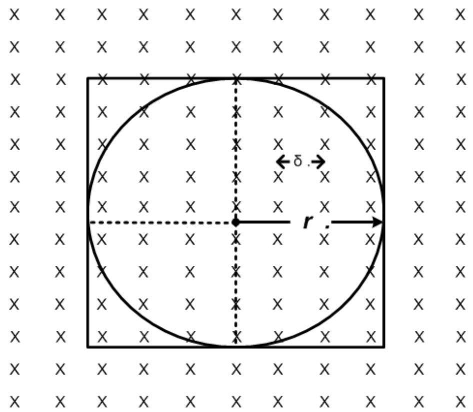


Figure 7.4: Grid tag deployment and reader radiation pattern.

work, we have selected the Pure and Slotted Aloha time-division multiple access schemes. When reading starts, each tag transmits its ID randomly irrespectively of the rest N 1 tags. The communications from a tag to the reader is modeled as a Poisson process [83]. Each tag responds on average λ times per second. The model requires independence among tag transmissions, which is supported by the lack of tag-to-tag communication capabilities. Since each tag's transmission is Poisson distributed, there is a mean delay of $1/\lambda$ between consecutive transmissions. This is referred to as the arrival delay [83]. Thus, on average each tag takes $1/(\mathrm{N}\lambda)$ time to transmit its ID for the first time. During collisions, colliding tags retransmit after a random time. In Aloha-based schemes, the retransmission time is divided into K time slots of equal duration t_s and each tag transmits its ID at random during one of the next time slots with probability $1/K$. This means tags will retransmit within a period of $K \pm t_s$ after experiencing a collision. On average, a tag will retransmit after a duration of $((K+1)/2) \pm t_s = a$ slots. The number of collisions before a tag successfully responds is $e^{xG_A} \quad 1$, where e^{xG_A} denotes the average number of retransmission attempts made before a successful identification, where $G_A = N\lambda t_s$ is the offered load and $x = 1$ for Pure Aloha and $x = 2$ for Slotted Aloha. Since each collision is followed by a retransmission, the average delay before a successful response is $(e^{xG_A} \quad 1)a$, followed by a single successful transmission of duration t_s. In total, the average delay a tag takes to transmit its ID successfully is $\mathrm{t}_{TR} = (e^{xG_A} \quad 1)at_s + t_s + \frac{1}{\mathrm{N}\lambda}$. For non-saturated case, i.e. tags to be detected are less than the maximum number of tags that can be read per inventory round, the total time needed for reading successfully N tags follows the linear model

$$\mathrm{T}_{TR} = \mathrm{N} \pm t_{TR} = \mathrm{N} \pm \Big\} t_s \,\big]1 + (e^{xG_A} \quad 1)a\Big(+ \frac{1}{\mathrm{N}\lambda}\Big(. \tag{7.13}$$

7.4.1.3 Scheme B

In our second proposal, the L2 *discovery* and L3 *movement detection* phases are replaced by the *handoff prediction* phase performed by the RFID and WSAN deployment. Therefore, the actual handoff latency T_{HO}^{B} is given by

$$\mathrm{T}_{HO}^{B} = \mathrm{T}_{PRED} + \max\} \mathrm{T}_{AU} + \mathrm{T}_{AS}, \mathrm{T}_{AC} + \mathrm{T}_{BU} | , \tag{7.14}$$

where T_{PRED} is the time taken from the latest MN's Tag List report until the handoff initiation. With the aid of Figure 7.3, T_{PRED} can be calculated by adding the following factors

$$\mathrm{T}_{PRED} = \mathrm{T}_{TR} + \mathrm{T}_{MN-AP} + \mathrm{T}_{C} + \mathrm{T}_{AP-AP} + \mathrm{T}_{AP-MN}, \tag{7.15}$$

where T_{TR} is the time needed to read all tags within range, T_{MN-AP} the time needed to transmit the Tag List message from MN's sensor to its serving AP's actuator, T_{C} the computational time for handoff prediction, T_{AP-AP} the time for exchanging the HO Request and HO Reply messages between the current AP's and the new AP's actuators through their dedicated sensor pair and T_{AP-MN} the time required for sending the HO Needed message from the serving AP's actuator to the MN.

T_{TR} is given in eq. (7.13), but in this case the number of detected tags N is different, since tags are deployed in a uniform distribution instead of grid. Assuming their density is $\delta = \mathrm{N}_T/\pi R^2$, where N_T the total number of tags in a surface πR^2, and that the reader's radiation pattern forms a circle with radius r, the maximum number of detected tags N is given by

$$\mathrm{N} = \rceil \mathrm{N}_T(\pi r/\pi R)^2 \{ = \rceil \mathrm{N}_T(r/R)^2 \{ . \tag{7.16}$$

Finally, the time factors T_{MN-AP}, T_{AP-AP} and T_{HO-ND} depend on the messages' size, supported data rate, the propagation delay and the time spent due to collisions before accessing the medium. The parameters T_{MSG} and T_{AP-MN} have been neglected due to their order of magnitude (μs) compared to the rest.

7.4.2 Energy Consumption

Energy consumption is another critical performance aspect since mobile terminals are energy constrained.

7.4.2.1 IEEE 802.11 Scanning

According to IEEE 802.11 specifications, when the RSS or SNR from the serving AP drops below a certain threshold value TH_{HO}, the handoff process is initiated. The main power-demanding process of standard handoff is the RSS scanning, during which the MN's wireless NIC needs to periodically probe all legitimate channels in order to obtain RSS measurements from all visible APs. For a given trajectory of a MN, the energy consumed for this MAC operation depends on the frequency of RSS scans. Let D_T the total duration of a MN's trajectory and D_S the average WiFi scanning period[1], i.e. the time between two consecutive scan operations. The total energy consumed is given by

$$\mathrm{E}^S = \frac{\mathrm{D}_T}{\mathrm{D}_S} \mathrm{T}_{prob} \mathrm{P}_S^{WiFi}, \tag{7.17}$$

where T_{prob} given in eq. (7.9) and P_S^{WiFi} the power consumption during WiFi scanning.

7.4.2.2 Scheme A

At Scheme A the main energy consuming processes are the scanning operations at both the WiFi and RFID channels. During a MN's trajectory, its reader emits periodically RF signals to energize reference tags within its vicinity in order to retrieve their IDs. Assuming the ALOHA variants as the anti-collision algorithms, the energy consumed during a single inventory round is given by $\mathrm{T}_{TR} \pm P_S$, where T_{TR} is the duration of the inventory round given in eq. (7.13) and P_S^{RFID} the power consumption during scanning. Let D_T the total duration of a MN trajectory and $D_R > \mathrm{T}_{TR}$ the reading period, i.e. time between two consecutive inventory rounds. The energy consumed is given by

$$\mathrm{E}^A_{RFID} = \frac{\mathrm{D}_T}{\mathrm{D}_R} \Big] \mathrm{T}_{TR} \mathrm{P}_S^{RFID} + (\mathrm{D}_R \quad \mathrm{T}_{TR}) \mathrm{P}_I^{RFID} \Big(, \tag{7.18}$$

where P_I^{RFID} the power consumed during idle listening.

Therefore, the total energy consumption for Scheme A is

$$\mathrm{E}^A = \mathrm{E}^S + \mathrm{E}^A_{RFID}. \tag{7.19}$$

7.4.2.3 Scheme B

At Scheme B the *prediction* phase involves the main energy consuming tasks by the MN, which are (i) RFID scanning and (ii) sensor communication.

[1]The average scanning period depends on the threshold TH_{HO}; the higher its value the smaller the scanning period.

While the MN is monitored within the *safe region*, there is no need for tag scanning, i.e. its reader is in idle listening mode. However, as soon as it exceeds this region, a *handoff prediction* phase is entered during which its reader *periodically* retrieves ID information from the RFID tag deployment. The frequency and duration of the prediction and sensing sessions depend on the system configuration regarding the selection of the R_{safe} parameter. Apparently, larger values of R_{safe} lead to power savings (no scanning operation) but with the risk of wrong or missed handoff predictions. Let f_{pred} and D_{pred} the frequency and average duration of the prediction phase, respectively, for a given MN's trajectory. If D_R is the *reading period* within each prediction phase, the energy consumed during a *single handoff prediction* phase by the reader is given by

$$\mathrm{E}_{pred,R} = \frac{\mathrm{D}_{pred}}{\mathrm{D}_R} \big] \mathrm{T}_{TR}\mathrm{P}_S^{RFID} + (\mathrm{D}_R \quad \mathrm{T}_{TR})\mathrm{P}_I^{RFID} \big(. \tag{7.20}$$

The sensor communication includes the transmission of two Tag List messages and the reception of the Start Reader and HO Needed or Stop Reader messages at the beginning and end of the *HO prediction* phase, respectively. Assuming P_{Tx}^{WSAN} and P_{Rx}^{WSAN} the power consumed during data transmission and reception over the WSAN, respectively, the energy consumed during a *single handoff prediction* phase due to sensor communication is given by

$$\mathrm{E}_{pred,S} = \frac{\mathrm{D}_{pred}}{\mathrm{D}_R} \; 2\mathrm{T}_{MN-AP}\mathrm{P}_{Tx}^{WSAN} \big[+ \mathrm{P}_{Rx}^{WSAN} \left(T_{Start} + \mathrm{T}_{AP-MN}\right), \tag{7.21}$$

where T_{Start} the time spent to receive the Start Reader.

For the entire trajectory duration D_T, the total energy consumed is computed as

$$\mathrm{E}^B = (\mathrm{D}_T \quad f_{pred}\mathrm{D}_{pred})\mathrm{P}_I^{RFID} + f_{pred}(\mathrm{E}_{pred,R} + \mathrm{E}_{pred,S}) \tag{7.22}$$

7.5 Performance Analysis

In this section, we evaluate the performance of our scheme based on simulations, using MATLAB [85] as simulation tool.

7.5.1 Simulation Setup

Our simulation environment which corresponds to a rectangular indoor area $200 \pm 200m^2$. The WLAN consists of 11 APs deployed according to the cellular concept with $R_{max} = 30m$, $R_{safe} = 20m$ (for Scheme B) and distance between two adjacent APs $50m$.

All APs are identical and follow the 802.11b (WiFi) standard with operating frequency at 2.4GHz. Heterogeneous and alternative radio technologies could have been assumed since the proposed mechanisms do not rely on triggers from lower layers. The indoor log-distance path loss model, described in [33], has been selected to model the communication at the 802.11b channel

$$PL(d) = PL(d_o) + 10n \log \left(\frac{d}{d_o} \right) + X_\sigma, \tag{7.23}$$

where d the distance between transmitter (AP) and receiver (MN), $PL(d_o)$ the free space path loss at reference distance d_o, n the path loss exponent whose value depends on the frequency used, the surroundings and building type, and X_σ is a zero-mean Gaussian random variable in dB having a standard deviation of σ_{dB}. The variable X_σ is called the shadow fading and is used to model the random nature of indoor signal propagation due to the effect of various environmental factors such as multipath, obstruction, orientation, etc. This path loss model is used for calculating the RSS from each AP, based on its transmit power P_t, i.e. $RSS(d) = P_t - PL(d)$.

Within this region, a MN whose terminal supports an interface to the WLAN and an RFID reader roams among the 11 available subnetworks. Regarding its mobility, we have assumed the Random WayPoint (RWP) mobility model [116]. Briefly, in the RWP model (i) a MN moves along a zigzag line from one waypoint to the next, (ii) the waypoints are uniformly distributed over the given area and (iii) at the start of each leg a random velocity is randomly selected from the velocity distribution $[O, V_{max}]$. During Standard L2 handoff, we have assumed that its WLAN NIC consumes about 1600 mW for scanning the neighboring APs [117] and the values of *MinChannelTime* and *MaxChannelTime* waiting times for the active scan operation are set to 20 ms and 40 ms, respectively [94].

Regarding the RFID system, we have assumed the UHF case at 890-960 MHz, with reader range $r = 5m$, $\text{P}_R^{RFID} = 500$ mW and $\text{P}_I^{RFID} = 10$ mW. Each tag's initial response follows Poisson distribution with rate $\lambda = 30$. The retransmission time is divided in $K = 5$ slots of duration $t_s = 92/102$ ms which corresponds to the time needed for transmitting an ID of length 92 bits over a link with data rate 102 Kbps.

Finally, Mica2 [118] has been assumed for the MN's sensor with data rate 38.4 Kbps, $\text{P}_{Tx}^{WSAN} = 52$ mW and $\text{P}_{Rx}^{WSAN} = 27$ mW.

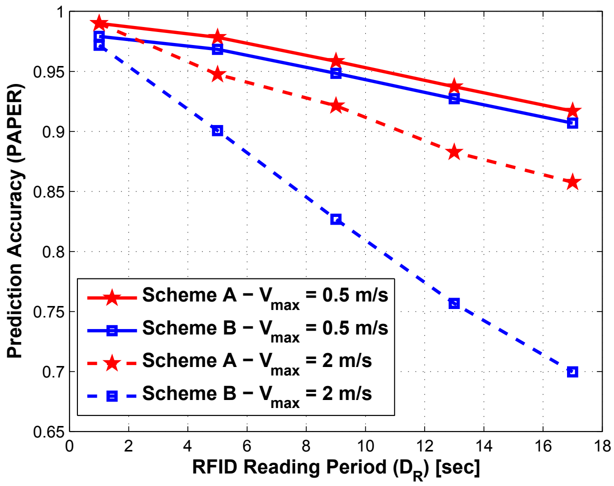


Figure 7.5: Handoff prediction accuracy versus reading period increase for both schemes A and B.

7.5.2 Accuracy Analysis

For evaluating the performance of our handoff approaches their accuracy in predicting the next PoA is of major concern. In order to quantify this, we define a new performance metric named *Point of Attachment Prediction Error Ratio* (PAPER) and given by

$$\text{PAPER} = \frac{\#\ correct\ PoA\ decisions}{\#\ all\ PoA\ decisions} \tag{7.24}$$

Correct PoA decision is considered the case when the predicted PoA is identical with the AP from with the strongest RSS. *PoA decision* is taken by the RFID-S every time it receives a Tag List update by the MN which depends on the *reading period*.

In Figure 7.5 the prediction accuracy of schemes A and B is evaluated as the *reading period* D_R increases, for two different V_{max} values. For all cases, decreasing the frequency of Tag List updates (by increasing the reading period) degrades the accuracy performance. For slow-moving cases however, the performance degradation is less intense. Comparing the two schemes, Scheme A performs better even for higher speed. This is because at this scheme the MN's movement is detected over the entire AP range, whereas at Scheme B it is tracked only outside the safe region. Adjusting the frequency of the reader reports or the design parameter R_{safe} depending on the MN speed of movement could be possible techniques for alleviating this accuracy degradation.

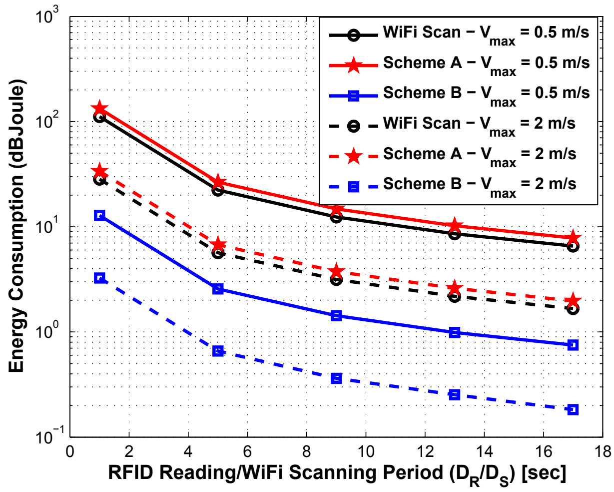


Figure 7.6: Energy consumption versus reading period increase for IEEE 802.11 handoff and schemes A and B.

7.5.3 Energy Consumption

Figure 7.6 depicts the accompanied energy consumption (in a base 10 logarithmic scale) for both of our schemes and the IEEE 802.11 Standard. First of all, we observe that there is a trade off between accuracy and energy performance objectives regarding the value of the scanning frequency. Comparing the three systems, we observe that the WiFi scanning is much more power demanding than RFID tag scanning. Therefore, at Scheme A the overall consumed energy is slightly increased due to the additional tag reading by the MN's reader. Scheme B gives the best performance, leading to considerable power savings, even in the case of very frequent TAG LIST reports. This is apparently due to the elimination of the WiFi scanning process and the controlled RFID reading.

7.5.4 Time Latency

In Figure 7.7 the main prediction delay factors are depicted for both mechanisms as the tag density increases. As analyzed in Section 7.4, the time required for retrieving *reference* tag IDs contributes the most in the overall handoff latency for both schemes. Both Pure and Slotted Aloha variants are considered. Another time factor that should be also considered is the sensor communication in Scheme B, since the supported data rates are much lower compared to the WiFi channel. We observe that for a dense tag deployment

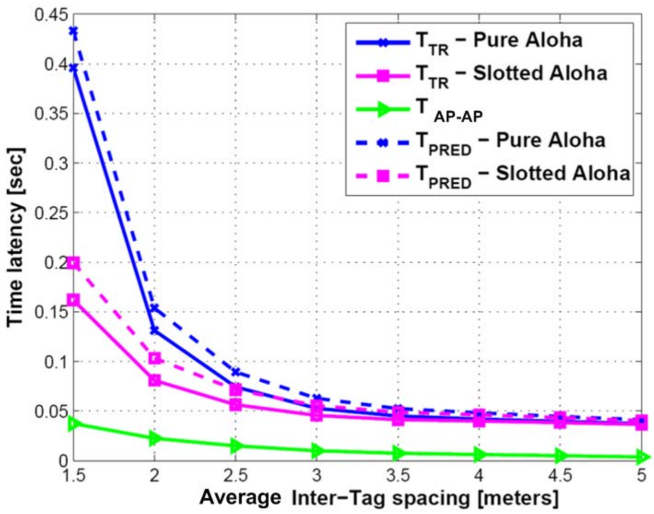


Figure 7.7: Time response of tag reading and sensor communication versus average inter-tag spacing.

(small inter-tag spacing), the reading time T_{TR} and the time needed to send the TAG LIST messages T_{MN-AP} are very high due to the big number of responding tags. As density decreases, however, they both improve due to the smaller number of detected tags and the size reduction of the TAG LIST messages (fewer bits), respectively. Comparing the Pure and Slotted Aloha we observe that Slotted Aloha has better performance, due to the reduction of the vulnerability period $2t$ [86].

Finally, we compare the time response of the prediction processes of both of our schemes with their equivalents of the Standard protocols. According to experimental results in [94] the L2 discovery latency is between $58.74ms$ and $396.76ms$ and the movement detection delay is on average $36ms$ to $558ms$ when router Advertisements are broadcasted every $0.05s$ to $1.5s$, according to [96]. In our schemes for $\delta = 3$, the total handoff delay is just around $60ms$, which validates their performance superiority.

7.6 Conclusions and Future Directions

In the emerging pervasive communication era, several smart objects such as sensors and RFID tags will be deployed all around the user enabling coupling the physical environment with the computing applications. In this chapter, we extended the functionality of the sensor and RFID technologies by exploiting their properties for purposes other than simply sensing and item identification or tracking. More precisely, we presented how these technologies can also assist in improving network functionalities such as handoff management.

Two such schemes were proposed. The first one relies on a deployment of RFID passive tags for detecting the IP movement of a MN. The proposed mechanism predicts the MN's target PoA, so that it can pro-actively associate with it, i.e. before its physical disconnection from its current PoA. The main benefit of this solution is that it does not rely on the broadcast of ROUTER ADVERTISEMENT messages, hence achieving considerable waiting time and bandwidth savings. Moreover, being independent of the underlying wireless access technology (such as IEEE 802.11), it can offer mobility support over heterogeneous networks. The second scheme tries to reduce the energy consumption as well by controlling the RFID scanning operation and eliminating the need for sensing the WiFi channel during link layer handoff. For achieving this, a smart space with sensors, actuators and RFID tags is deployed for predicting the mobility of mobile devices with sensor and RFID reader capabilities.

The main consideration for both schemes is their feasibility due to their deployment requirements. However, in the context of the envisioned ambient intelligent environments where large numbers of everyday objects scattered all over will become smart, such solutions are entirely plausible. Moreover, our system design and configuration choices such as grid tag deployment, placement of sensors, etc. are not the core concepts but serve for the purpose of convenience in performance analysis and elaboration of the achieved benefits.

This was a preliminary study for validating the potential of pervasive intelligence in mobility management. Further performance analysis, such as packet loss for different types of traffic, or experimental validation need to be done.

Chapter 8

Conclusions

This thesis was motivated by the ultimate goal of next generation communication systems to enhance the experience users perceive from their network. Common approaches for achieving this goal include the development of context-aware applications and the provision of mobility support. The location of the user is indispensable part of the general term context, while mobility support mainly refers to the handoff process that is required for retaining an ongoing communication of the user during its movement among different networks.

Within this context, we focused on the indoor localization and handoff management problems and we tried to tackle them more efficiently by taking advantage of the most prominent technologies in the current and future communication networks, that is Wireless Local Area Networks (WLANs), Radio Frequency Identification (RFID) and Wireless Sensor and Actuator Networks (WSANs).

Despite the intensive research efforts over the last few decades towards successful indoor location systems, indoor localization still remains a challenging task. This is mainly attributed to the harshness of the indoor environments on signal propagation, caused by obstacles and frequent environmental changes. Moreover, most applications require solutions with minimum hardware and deployment costs or human intervention. Finally, compared with outdoor scenarios, scalability issues occur more frequently inside a building where there is higher tendency for coexistence of many users.

Handoff management has also received considerable attention but still there is no handoff scheme that satisfies all objectives for seamless and global roaming in future communication networks. With the growing popularity of the Internet and the high speed evolution of wireless access networks, novel applications emerge and become even more demanding in their QoS requirements. Some of the most common approaches rely on special characteristics of specific wireless access technologies which apparently limits their applicability and easy integration in heterogeneous networks.

In the following sections, we first summarize our main contributions towards the thesis objectives and later we discuss some possible future directions for extending our research study.

8.1 Contributions

Our approach for solving both problems of indoor localization and handoff management was motivated by the general context of the envisioned pervasive computing systems. It is generally accepted that in the near future an increasingly large numbers of everyday objects scattered throughout the surrounding environment will become smart by having some kind of simple computation and communication technology embedded into them, which will allow them to be connected to each other within local networks and, ultimately, connected to the Internet. Exploring whether and how several popular technologies, such as WLAN, RFID and WSANs, either alone or in combination, can aid tackling efficiently our two problems was actually the main core of this thesis.

The main contributions of this thesis include:

≤ Focusing on the case of WLAN fingerprinting location systems, we studied both deterministic and probabilistic cases and proposed the incorporation of simple additional modules in the positioning mechanism for mitigating the main shortcomings. Our main contributions include: considering orientation information and filtering incompatible RSSI samples during the training or the entire operation and a hierarchical pattern matching algorithm for selecting candidate locations from the training set during the run-time process. Additionally, the impact of two design parameters was discussed. More precisely, we suggested including RSS information from less APs and adapting the number of candidate locations depending on each user RSS characteristics. Numerical results based on real experimental evaluation of our proposals showed accuracy enhancement, especially for the deterministic case, without sacrificing considerably the time-efficiency of the localization process.

≤ The growing popularity of RFID for indoor localization but also the lack in the literature of studies regarding the effect of its interference problem on the localization performance motivated us in addressing this issue. After modeling the interference problem in RFID by considering its technology and communication specifications, we conducted extensive simulations for analyzing the performance of RFID in tracking single or multiple users, under different system configurations and environmental conditions. Numerical results encourage adopting RFID for localization but also indicate the essentiality of a careful system design in order to exploit its full potential, especially in highly populated environments.

≤ Considering the benefits but also the limitations of the standalone positioning solutions, we proposed an integration localization scheme that combines both WLAN and RFID technologies. The main advantage of multi-modal devices is the offered redundancy of communication channels. Thus, we suggested utilizing the WiFi channel for coordinating the communication in the RFID channel in order to subdue the restricting factor of reader collisions. Additionally, we considered a realistic scenario where users have devices with diverse capabilities. We proposed exploiting this diversity by benefitting from the inherent property of reader-enabled users to sense tag-enabled users in their vicinity, and hence refining their location estimation. The performance advantages of a conceptual coordination mechanism were first validated and later a feasible scheduling scheme was proposed for realizing these benefits. Based on extensive simulations, we tested the impact of various design parameters and we validated the achieved performance advantages of our proposals regarding both accuracy and time-efficiency objectives.

≤ For handoff management, we first focused on the movement detection step of the MIP network layer handoff mechanism and proposed a scheme that relies on a deployment of RFID passive tags for detecting the IP movement of a MN. The proposed mechanism predicts the MN's target PoA, so that it can pro-actively associate with it, i.e. before its physical disconnection from its current PoA. The main benefit of this solution is that it does not rely on the broadcast of Router Advertisement messages, hence achieving considerable waiting time and bandwidth savings. Moreover, being independent of the underlying wireless access technology (such as IEEE 802.11), it can offer mobility support over heterogeneous networks.

≤ Finally, considering also the problem of extensive energy consumption during the scanning process of the Standard link layer handoff mechanism, we proposed a second scheme for handoff management at both link and network layers. For achieving this, a smart space with sensors, actuators and RFID tags is deployed for predicting the mobility of mobile devices with sensor and RFID reader capabilities. The proposed scheme proved beneficial in terms of handoff latency, energy consumption, accuracy and bandwidth utilization.

8.2 Future Directions

Even though most of the objectives were well satisfied by our proposed systems, we believe that our research can go beyond for achieving further improvements. Some possible future directions may include:

≤ The design of novel localization algorithms which will take into account the specific characteristics of each technology or exploit their integration.

≤ The development of cooperative schemes which take advantage of possible interactions among users in a more sophisticated way appears promising and should certainly be studied more extensively.

≤ Studying different deployment and configuration schemes for both localization and handoff management is also interesting direction in order to decrease the cost of the systems.

≤ The handoff decision functions of our proposed schemes can easily incorporate more factors, such as user preferences, profile etc. However, we limited our study in simple decision functions in order to focus more on the achieved accuracy and not the potential flexibility. However, exploring more sophisticated decision functions should be studied especially for vertical handoff in heterogenous networks.

≤ Last but not least the experimental testing of our systems is an essential step for cross validating the simulation based performance evaluation results.

Chapter 9

Thesis' French Version

Avec la croissance rapide des communications sans fil et des technologies de réseaux, les grandes avancées de l'informatique mobile et les appareils portables, et l'immense succès de l'Internet, une ère de communication révolutionnaire omniprésente et mobile est en train de devenir le successeur naturel des systèmes actuels de communication mobile. L'objectif de cette vision envahissante ou omniprésente est de créer une intelligence ambiante avec le concept de base de l'interaction entre l'homme avec son environnement et le but ultime amélioration de l'expérience utilisateur du réseau. Dans ce but, un nombre de plus en plus grande des objets du quotidien disséminés dans l'environnement va devenir à intelligentes en faisant une sorte de calcul simple et de la technologie de communication intégré en eux, qui leur permettra d'être reliés les uns aux autres au sein des réseaux locaux et, finalement, connecté à Internet. Les utilisateurs deviennent encore beaucoup plus exigeants par rapport à la connectivité et l'accès universel aux différentes applications n'importe où, n'importe quand, en utilisant la meilleure technologie d'une pléthore d'interfaces disponibles à l'avenir des terminaux mobiles mult-interfaces, et sans la nécessité d'une prise d'une conscience explicite de la communication sous-jacente et de la technologie de l'informatique.

Pour réaliser un tel environnement ubiquitaire, la connaissance de l'emplacement et de la gestion de la mobilité sont deux notions de base, tandis qu'une forte corrélation existe entre eux. Le besoin continu pour déterminer l'emplacement d'une entité inconnue découle de la capacité de la mobilité de cette entité tandis que les questions soulevées en raison de la gestion de la mobilité peuvent en bénéficier si les informations de localisation relative sont disponibles. Cette thèse a pour objectifs à améliorer les procédures de la localisation et de handoff et propose de bénéficie de la disponibilité de plusieurs technologies sans fil pour s'attaquer de façon plus efficace les objectifs des réseaux de communication future.

Dans la suite, les principaux objectifs, défis et nos approches pour atteindre cet objectif sont décrits.

9.1 Les objectifs et Les défis

Les informations intérieur liées à la position sont utiles pour faciliter l'interaction entre un utilisateur et son environnement et par conséquent le développement de services géolocalisés (LBS) ou plus généralement des applications sensibles au contexte, dont l'emplacement est un élément clé du contexte de l'utilisateur. Ces applications adaptent leurs fonctionnalités en fonction du contexte de l'utilisateur et ils coconcernet des applications de vie de tous les jours des utilisateurs, l'environnement de travail, les secteurs commerciaux et industriels à des fonctions qui visent à l'amélioration des performances de la fonctionnalité réseau sans fil. Quelques exemples typiques d'applications de localisation subventionnés sont:

≤ **Ambient Assisted Living**: les informations de positionnement précis est essentiel pour le succès de l'Ambient Assisted Living (AAL) du projet [1] qui vise à renforcer la vie quotidienne des personnes âgées et des personnes souffrant de handicaps, grâce à l'utilisation de l'information et des technologies de la communication (TIC).

≤ **Person et Asset Tracking**: le suivi des personnes à l'intérieur des bâtiments est essentiel dans les situations d'urgence comme les incendies, les tremblements de terre ou autres catastrophes. En outre, les systèmes de localisation en intérieur sont utiles dans les hôpitaux pour dépister des membres du personnel à tout moment, sans leur intervention, dans les musées ou les écoles pour garder la trace de la localisation des enfants [2].

   Le suivi des objets est utile pour trouver la localisation d'équipements hospitaliers dans un hôpital, trouver des livres dans une bibliothèque ou des produits dans un entrepôt. L'emplacement de différentes ressources physiques telles que les imprimantes, les projets et les photocopieurs permet également aux applications de découvrir de ressources [3].

≤ **Navigation**: les informations de localisation à l'intérieur peuvent être utilisés pour construire des outils de navigation dans les bâtiments peu familier [4], comme les aéroports, les gares, les musées, les campus, les grands magasins ou les bâtiments de grands bureaux.

≤ **Location-Based Advertising and Social Networking**: les méthodes de localisation peuvent être utilisées pour les divertissements sélectives et orientés [5] et de fournir des informations sur les produits à l'intérieur de magasins [6].

D'autre part, l'emplacement orienté réseau social peut améliorer encore les services de l'Internet oriené réseau social tels que Facebook, Friendsters, MySpace, etc en permettant aux utilisateurs de former des groupes en fonction de leur préférence sociale et d'intérêt.

≤ **l'amélioration des performances du réseau**: de les informations de localisation des utilisateurs peuvent également être exploitées pour améliorer la fonctionnalité et la QoS dans les réseaux sans fil. Ces méthodes ont été proposées pour le contrôle d'accès basés sur la localisation [7], handoff basés sur la localisation et dans les réseaux ad hoc afin d'optimiser les algorithmes de routage et d' auto-configuration du réseau [8]. Un pas de plus, en combinant des données de positionnement avec les profils des utilisateurs pourrait considérablement faciliter la planification du réseau, l'équilibrage de charge, la mise en cache des informations proches de l'utilisateur, la gestion des ressources radio et de la conception d'autres méthodes d'amélioration des performances [9].

Pour la réussite de ces applications, la conception d'une détermination d'un système de localisation précise et fiable est essentielle. La localisation sans fil, c.-à-d. l'estimation de la position en se basant sur des signaux radio (RS), a attiré une attention considérable dans le domaine des télécommunications et de la navigation. Le système de positionnement le plus connu est le système de positionnement global (GPS) [10], qui se base sur la satellite et qui est une réussite pour le suivi des utilisateurs en environnements plein air. Toutefois, l'incapacité de signaux de satellite pour pénétrer dans les bâtiments de la cause échec complet du GPS dans les environnements intérieurs. Pour la détection de la localisation intérieur, certain nombre d'autres technologies sans fil ont été proposées, telles que l'échographie infrarouge (IR), réseaux sans fil local (WLAN), la bande ultralarge (UWB), l'identification par radiofréquence (RFID), Bluetooth, réseaux de capteurs sans fil (WSN) [11]. Cependant, les canaux intcanauxa de la propagation radio souffrent d'une atténuation sévère et une propagation de vu direct pour la propagation de signale entre l'émetteur et le récepteur [12], ce qui rend le positionnement précis à l'intérieur très difficile.

En outre, par rapport aux systèmes extérieurs, déterminer l'emplacement d'un utilisateur ou un dispositif intérieur d'un bâtiment est beaucoup plus difficile non seulement en raison de sa nature rude, mais aussi en raison de l'exigence de services à l'intérieur pour précision de plus en plus précis. La gestion de handoff est unea procédure pour maintenir connexion de l'utilisateur mobile active tout en changeant son point d'attachement de son réseau en raison de la mobilité. Dans l'avenir des réseaux omniprésents, plusieurs technologies sans fil hétérogènes seront disponibles et les utilisateurs ont un accès universels à la demande de meilleur connectivité parmi un large éventail d'applications lors de leurs déplacements. Pour l'intégration harmonisée de ces différentes technologies dans un cadre commun, la conception de systèmes intelligents de gestion de la mobilité est requise afin de permettre aux utilisateurs mobiles d'avoir une continuité de service sans interruption n'importe où, à tout moment, quelle que soit leur technologie d'accès. En outre, les méthodes de gestion de la mobilité devraient être en mesure de satisfaire les besoins des applications émergentes qui devient de plus en plus exigeants quant à leurs contraintes de QoS. Cependant, le temps de latence au cours de la procédure de handoff conduit à une dégradation des performances.

Pour le cas de réseaux sans fil WLAN basé sur la norme d' IEEE 802.11, la procédure de handoff nécessite que le noeud mobile cherche régulièrement des points d'accès pour mieux associer, en balayant tous les canaux WLAN. Toutefois, ce processus fait perdre l'énergie et introduit la perte de paquets, vu que lors du balayage, le noeud mobile n'est pas en mesure d'être desservi par son actuel AP. Mobile IP [13] est un protocole de couche réseau pour la gestion de mobilité pour les réseaux IP. Il transmet les paquets aux utilisateurs mobiles qui sont loin de leurs réseaux à la maison en utilisant des tunnels IP dans IP. Le handoff en Mobile IP est composé d'une séquence d'étapes, dont l'un porte sur la détection d'un noeud mobile en mouvement vers le nouveau réseau. Toutefois, lorsque le noeud mobile subit le mouvement de détection, il est incapable de recevoir des paquets IP, ce qui entraîne une dégradation des performances supplémentaires.

9.2 Un Aperçu de la thèse

La connaissance de l'emplacement des utilisateurs et des objets dans un environnement intérieur et leur gestion de la mobilité à travers des réseaux hétérogènes sont considérés comme des jalons clés vers la réalisation des futurs réseaux de communication mobile. En outre, la forte corrélation entre ces mandats tâches d'instruction de leurs aspects en parallèle, au lieu de les considérer comme deux processus indépendants.

Cette thèse vise le développement de la localisationt et les systèmes de gestion de la mobilité avec objectifs de conception principaux:

≤ **Précision**. Sachant exactement où quelqu'un ou quelque chose se déplace vers peut améliorer l'expérience utilisateur par la prestation de services personnalisés et d'améliorer le réseau fonctionnalité.

≤ **Temps de réponse rapide**. Les nouvelles applications seront plus exigeantes en termes de exigences de qualité de service, poussant pour la localisation rapide et systèmes de transfert.

≤ **Extensibilité**. La présence de nombreux utilisateurs ne doivent pas dégrader les performances du système.

≤ **Handoff Générique**. La coexistence de réseaux hétérogènes dans lequel les utilisateurs peuvent se déplacer, faire des handoffs intercellulaires indépendamment de la technologie des solutions les plus viables.

≤ **L'orientation énergie**. Comme les appareils mobiles sont contraints de consommation d'énergie de la batterie, cette question devraient être prise en compte.

Les systèmes de communication sont envisagées à l'avenir pour offrir une connectivité hétérogènes et omniprésente , permettant aux utilisateurs mobiles qui seront entourés par des technologies différentes mais complémentaires, de capturer leurs différents besoins et exigences. Motivé par cette observation, explorer les synergies possibles et les interactions entre plusieurs technologies sont notre principale approche afin de faire face plus efficacement nos objectifs.

Pour connaître la détection de la localisation à l'intérieur, nous avons concentré notre attention sur deux technologies sans fil; WLAN et RFID. WLAN, tels que IEEE 802.11, est considéré comme prometteur car il offre un faible coût et une solution fiable en raison de sa disponibilité dans la plupart des environnements intérieurs et la capacité de coordination de la communication en mode infrastructure. Toutefois, la précision est très affectée en présence de trajets multiples et de graves changements environnementaux. Plus récemment, la RFID a émergé comme une technologie intéressante pour une localisation précise de détection en raison du faible coût des étiquettes passives, la lecture rapide des étiquettes multiples, la vue directe (LOS), le rend moins sensible à l'orientation des utilisateurs. Cependant, la principale lacune de la RFID est considérée comme le problème d'interférence entre ses composantes, principalement en raison de les capacités limitées des étiquettes passives et l'incapacité de communication directe entre lecteurs [14]. Afin de surmonter les limites des deux technologies, nous avons proposé une architecture d'intégration pour améliorer la performance de localisation.

En ce qui concerne le problème de gestion de la mobilité, nous nous sommes concentrés sur le volet handoff et nous avons exploré le potentiel de deux technologies populaires omniprésentes: RFID et WSAN, pour fournir une solution rapide de handoff dans le cas de la mobilité à Internet via un accès Internet / WiFi réseau. Toutefois, nos méthodes proposées peuvent être appliqués pour la liaison de différents et niveau du réseau pour les scénarios de mobilité, ce qui les rend des solutions viables dans les réseaux hétérogènes.

9.3 Le cheminement de travail et les contributions

Pour atteindre les buts et objectifs de cette thèse, les étapes successives ont été suivies dans un ordre chronologique:

≤ Au départ, nous nous sommes concentrés sur l'approche de positionnement dans les réseaux WLAN qui se base sur les empreintes digitales. Cette méthode est considéré comme le plus populaire pour la localisation en intérieur à faible coût. Considérant à la fois son variantes déterministe et probabiliste, nous avons proposé quelques techniques simples pour améliorer la précision de localisation sans augmenter considérablement la complexité les besoins en matériel et. Les references suivantes comprennet nos travaux dans cette direction:

- *C1* A. Papapostolou and H. Chaouchi, *WIFE: Wireless Indoor positioning based on Fingerprint Evaluation*, in Proceeding of the 8th IFIP NETWORKING conference, Aachen, Germany, March 2009 [15].
- *C2* A. Papapostolou and H. Chaouchi, *Orientation - Based Radio Map Extensions for Improving Positioning System Accuracy*, in Proceeding of the 6th ACM International Wireless Communications and Mobile Computing Conference (ACM IWCMC), Leipzig, Germany, June 2009 [16].

- *J1* A. Papapostolou and H. Chaouchi, *Scene Analysis Indoor Positioning Enhancements*, Annals of Telecommunications journal, October 2010 [17].

≤ Le positionnement RFID est considéré comme une autre solution intéressante pour la localité de détection avec une plus grande précision que celle d systèmes WLAN. Cependant, peu d'attention a été donnée au problème de collision, dans la mesure où le positionnement est concerné, qui est le talon d'Achille de la technologie RFID. Par conséquent, nous avons étudié longuement la performance de la plupart des algorithmes populaires de positionnement de RFID en présence de plusieurs utilisateurs. Les références suivantes montre nos contributions dans ce domaine:

- *C3* A. Papapostolou and H. Chaouchi, *Considerations for RFID-based Indoor Simultaneous Tracking*, in Proceedings of the 2nd Joint IFIP Wireless and Mobile Networking Conference, Gdansk, Polland, September 2009 [18].
- *J2* A. Papapostolou and H. Chaouchi, *RFID-assisted Indoor Localization and the Impact of Interference on its Performance*, in the SI on RFID Technology, Systems, and Applications of the Journal of Network and Computer Applications (Elsevier), April 2010 [19].

≤ Motivé par les avantages mais aussi les limites des solutions autonomes, comme identifiés dans les étapes précédentes, une architecture d'intégration combinant à la fois WLAN et les technologies RFID a alors été proposée. L'idée principale est de profiter de la précision de localisation offerts par le déploiement de la RFID et la capacité de coordination de l'infrastructure WLAN pour minimiser des problèmes liés à collision sur la canal RFID avec l'objectif ultime d'améliorer la précision de la localisation d'une manière efficace le temps. No travaux dans ce domaines sont représentés par les références suivantes:

- *C4* A. Papapostolou and H. Chaouchi, *Simulation-based Analysis for a Heterogeneous Indoor Localization Scheme*, in Proceedings of the 7th IEEE Consumer Communication and Networking Conference (IEEE CCNC), Las Vegas, Nevada, January 2010 [20].
- *C5* A. Papapostolou and H. Chaouchi,*Exploiting Multi-modality and Diversity for Localization Enhancement: WiFi and RFID usecase*, in Proceedings of the 20th

IEEE International symposium on Personal Indoor and Mobile Radio Communications (IEEE PIMRC), Tokyo, Japan, September 2009 [21].

≤ L'étape suivantes a été motivé par le constat que une architecture qui combine WLAN et RFID pourrait être également utilisé pour la gestion de la mobilité. Ayant comme but l'amélioration de handoff au niveau de couche réseau, nous avons proposé d'utiliser le déploiement de la RFID afin de minimiser le délai dans la procédure de gestion en utilisant IP mobile dans la phase de détection de mouvement dans le canal WiFi. Toutefois, il est digne de mentionner que l'architecture proposée est également valable dans d'autres réseaux de mobilité. Nos références comprennent:

- *C6* A. Papapostolou and H. Chaouchi, *RFID-assisted Movement Detection Improvement in IP Mobility*, in Proceedings of the 3rd IFIP International Conference on New Technologies, Mobility and Security (IFIP NTMS), Cairo, Egypt, December, 2009 [22].

- *C7* A. Papapostolou and H. Chaouchi, *Handoff Management relying on RFID Technology*, in Proceedings of the IEEE Wireless Communication and Networking Conference (IEEE WCNC), Sydney, Australia, April 2010 [23].

≤ Dans la séquence de l'architecture du système unifié pour la localisation et la mobilité la gestion a été conçu et analysé dans:

- *B1* A. Papapostolou and H. Chaouchi, *RFID Deployment for Location and Mobility Management on the Internet*, in H. Chaouchi (ed), The Internet of Things: Connecting Objects, Wiley, John & Sons, May 2010 [24].

- *J3* A. Papapostolou and H. Chaouchi, *Integrating RFID and WLAN for Indoor Positioning and IP Movement Detection* journal of Wireless Networks (Springer), submitted in November 2009.

≤ Enfin, pour compléter la viabilité de nos systèmes proposés, nous avons essayé de prendre en compte leur consommation d'énergie accompagnée. Motivé par cette idée, nous avons proposé une méthode qui combine les avantages de la RFID et les technologies de handoff dans le WSAN pour l'amélioration par rapport à la réduction de latence et de l'énergie. Nos références comprennent:

- *C8* A. Papapostolou and H. Chaouchi, *Deploying Wireless Sensor/Actuator Networks and RFID for Handoff Enhancement* in Proceeding of the International Conference on Ambient Systems, Networks and Technologies (ACM ANT), Paris, France, November 2010 [25].
- *J4* A. Papapostolou and H. Chaouchi, *Handoff Management Schemes in Future Pervasive Environments*, submitted to the journal of Mobile Networks (Springer), *SI on Future Internet for Green and Pervasive Media of the journal of Mobile Networks and Applications (Springer)*, submitted in December 2010.

9.4 L'Organisation de la thèse

Le reste de cette thèse est organisé comme suit. Afin de faciliter sa présentation, nous l'avons divisé en deux parties: la première partie est notée à la localisation, alors que la deuxième partie se concentre sur les aspects gestion de la mobilité. Le premier chapitre de deux parties, (chapitres 2 et 6), comprendra des renseignements généraux et les travaux connexes essentielles à la compréhension et la mise en évidence des nos contributions. Le chapitre 3 décrit nos méthodes proposées pour améliorer la précision de la localisation des empreintes digitales dans le WLAN, le chapitre 4 étudie les performances de la RFID lorsque le problème des collisions entre en lieu et le chapitre 5 termine la première partie en décrivant un système hétérogène qui combine les avantages des deux technologies. Le chapitre 7 décrit et compare les deux méthodes que nous proposons pour la gestion de la mobilité. Enfin le chapitre 8 résume nos conclusions principales, les réalisations et les questions en suspens pour la recherche future.

References

[1] "Ambinet Assisted Living project (AAL), http://www.aal-europe.eu/."

[2] M. Srivastava, R. Muntz, and M. Potkonjak, "Smart kindergarten: sensor-based wireless networks for smart developmental problem-solving environments," in *MobiCom '01: Proceedings of the 7th annual international conference on Mobile computing and networking*, (New York, NY, USA), pp. 132–138, ACM, 2001.

[3] W. Adjie-Winoto, E. Schwartz, H. Balakrishnan, and J. Lilley, "The design and implementation of an intentional naming system," *SIGOPS Oper. Syst. Rev.*, vol. 34, pp. 22–, April 2000.

[4] F. Kargl, S. Geβler, and F. Flerlage, "The inav indoor navigation system," in *Ubiquitous Computing Systems* (H. Ichikawa, W.-D. Cho, I. Satoh, and H. Youn, eds.), vol. 4836 of *Lecture Notes in Computer Science*, pp. 110–117, Springer Berlin / Heidelberg, 2010.

[5] L. Aalto, N. Göthlin, J. Korhonen, and T. Ojala, "Bluetooth and wap push based location-aware mobile advertising system," in *MobiSys '04: Proceedings of the 2nd international conference on Mobile systems, applications, and services*, (New York, NY, USA), pp. 49–58, ACM, 2004.

[6] T. Design, , N. Sukaviriya, M. Podlaseck, R. Kjeldsen, A. Levas, G. Pingali, and C. Pinhanez, "Embedding interactions in a retail store environment:," in *In Proc. of the Ninth IFIP International Conference on Human Computer Interaction*, 2003.

[7] K. Kleisouris and R. Martin, "Parallel algorithms for bayesian indoor positioning systems," pp. 15 –15, sep. 2007.

[8] M. Bocquet, C. Loyez, and A. Benlarbi-Delai, "Using enhanced-tdoa measurement for indoor positioning," *Microwave and Wireless Components Letters, IEEE*, vol. 15, no. 10, pp. 612 – 614, oct. 2005.

[9] P. Prasithsangaree, P. Krishnamurthy, and P. Chrysanthis, "On indoor position location with wireless lans," vol. 2, pp. 720 – 724 vol.2, sep. 2002.

[10] B. H. Wellenhoff, H. Lichtenegger, and J. Collins, *Global Positions System: Theory and Practice*. Springer Verlag, forth ed., 1997.

[11] Y. Gu, A. Lo, and I. Niemegeers, "A survey of indoor positioning systems for wireless personal networks," *Communications Surveys & Tutorials, IEEE*, vol. 11, no. 1, no. 1, pp. 13–32, 2009.

[12] K. Pahlavan and A. H. Levesque, *Wireless Information Networks*. New York: John Wiley & Sons, second ed., 2005.

[13] P. Bhagwat, C. Perkins, and S. Tripathi, "Network layer mobility: an architecture and survey," *Personal Communications, IEEE*, vol. 3, no. 3, pp. 54–64, jun 1996.

[14] J. GP and K. SW, "Survey, Nomenclature and Comparison of Reader Anti-Collision Protocols in RFID," *IETE Tech Rev*, vol. 25, no. 5, no. 5, pp. 285–292, 2008.

[15] A. Papapostolou and H. Chaouchi, "WIFE: Wireless Indoor Positioning Based on Fingerprint Evaluation," in *Networking 2009*, pp. 234–247, 2009.

[16] A. Papapostolou and H. Chaouchi, "Orientation-based radio map extensions for improving positioning system accuracy," in *IWCMC '09: Proceedings of the 2009 International Conference on Wireless Communications and Mobile Computing*, (New York, NY, USA), pp. 947–951, ACM, 2009.

[17] A. Papapostolou and H. Chaouchi, "Scene analysis indoor positioning enhancements," *Annals of Telecommunications*, pp. 1–15, 2010. 10.1007/s12243-010-0220-0.

[18] A. Papapostolou and H. Chaouchi, "Considerations for RFID-Based Indoor Simultaneous Tracking," in *Wireless and Mobile Networking* (J. Wozniak, J. Konorski, R. Katulski, and A. Pach, eds.), vol. 308 of *IFIP Advances in Information and Communication Technology*, pp. 309–320, Springer Boston, 2009.

[19] A. Papapostolou and H. Chaouchi, "Rfid-assisted indoor localization and the impact of interference on its performance," *Journal of Network and Computer Applications*, vol. In Press, Corrected Proof, 2010.

[20] A. Papapostolou and H. Chaouchi, "Simulation-based analysis for a heterogeneous indoor localization scheme," in *CCNC'10: Proceedings of the 7th IEEE conference on Consumer communications and networking conference*, (Piscataway, NJ, USA), pp. 67–71, IEEE Press, 2010.

[21] A. Papapostolou and H. Chaouchi, "Exploiting multi-modality and diversity for localization enhancement: WiFi & RFID usecase," in *IEEE 20th International Symposium on Personal Indoor and Mobile Radio Communications (PIMRC)*, pp. 1903 – 1907, 2009.

[22] A. Papapostolou and H. Chaouchi, "Rfid-assisted movement detection improvement in ip mobility," in *NTMS 2009, 3rd International Conference on New Technologies, Mobility and Security, 20-23 December 2009, Cairo, Egypt*, pp. 1–5, 2009.

[23] A. Papapostolou and H. Chaouchi, "Handoff management relying on rfid technology," in *2010 IEEE Wireless Communications and Networking Conference, WCNC 2010, Proceedings, Sydney, Australia, 18-21 April 2010*, pp. 1–6, 2010.

[24] A. Papapostolou and H. Chaouchi, "Rfid deployment for location and mobility management on the internet," in *The Internet of Things: Connecting Objects* (H. Chaouchi, ed.), pp. 157–190, John Wiley & Sons, first ed., May 2010.

[25] A. Papapostolou and H. Chaouchi, "Deploying wireless sensor/actuator networks and rfid for handoff enhancement," in *ANT 2010, The International Conference on Ambient Systems, Networks and Technologies, 8-10 November 2010, Paris, France*, 2010.

[26] A. Küpper, *Location-Based Services: Fundamentals and Operation.* Wiley, October 2005.

[27] I. Guvenc and C.-C. Chong, "A survey on toa based wireless localization and nlos mitigation techniques," *IEEE Communications Surveys & Tutorials*, vol. 11, no. 3, pp. 107–124, August 2009.

[28] H. Liu, H. Darabi, P. Banerjee, and J. Liu, "Survey of Wireless Indoor Positioning Techniques and Systems.," *IEEE Transactions on Systems, Man, and Cybernetics, Part C*, vol. 37, no. 6, no. 6, pp. 1067–1080, 2007.

[29] S. Gezici, "A survey on wireless position estimation," *Wirel. Pers. Commun.*, vol. 44, no. 3, no. 3, pp. 263–282, 2008.

[30] G. Turin, "An introduction to matched filters," *Information Theory, IEEE Transactions on*, vol. 6, no. 3, no. 3, pp. 311–329, 1960.

[31] B. D. Van Veen and K. M. Buckley, "Beamforming: A versatile approach to spatial filtering," *IEEE Signal Processing Magazine*, vol. 5, no. 2, pp. 4–24, April 1988.

[32] J. J. Caffery, *Wireless Location in CDMA Cellular Radio Systems.* Norwell, MA, USA: Kluwer Academic Publishers, 1999.

[33] T. S. Rappaport, *Wireless Communications: Principles and Practice (2nd Edition).* Prentice Hall PTR, 2 ed., January 2002.

[34] Y. Qi, H. Kobayashi, and H. Suda, "Analysis of wireless geolocation in a non-line-of-sight environment.," *IEEE Transactions on Wireless Communications*, vol. 5, no. 3, no. 3, pp. 672–681, 2006.

[35] T. He, C. Huang, B. M. Blum, J. A. Stankovic, and T. F. Abdelzaher, "Range-free localization schemes for large scale sensor networks.," in *MOBICOM* (D. B. Johnson, A. D. Joseph, and N. H. Vaidya, eds.), pp. 81–95, ACM, 2003.

[36] N. Bulusu, J. Heidemann, and D. Estrin, "GPS-less low-cost outdoor localization for very small devices," *IEEE Personal Communications*, vol. 7, no. 5, pp. 28–34, Oct 2000.

[37] D. Niculescu and B. Nath, "DV Based Positioning in Ad Hoc Networks.," *Telecommunication Systems*, vol. 22, no. 1-4, no. 1-4, pp. 267–280, 2003.

[38] R. Nagpal, H. Shrobe, and J. Bachrach, "Organizing a global coordinate system from local information on an ad hoc sensor network," in *IPSN'03: Proceedings of the 2nd international conference on Information processing in sensor networks*, (Berlin, Heidelberg), pp. 333–348, Springer-Verlag, 2003.

[39] J. Hightower and G. Borriello, "Location Systems for Ubiquitous Computing.," *IEEE Computer*, vol. 34, no. 8, no. 8, pp. 57–66, 2001.

[40] P. Sahi, "Geolocation on cellular networks," in *Geographic Location in the Internet* (B. Sarikaya, ed.), vol. 691 of *The Kluwer International Series in Engineering and Computer Science*, pp. 13–49, Springer Netherlands, 2002.

[41] R. Want, A. Hopper, V. Falcao, and J. Gibbons, "The Active Badge Location System," *ACM Transactions on Information Systems*, vol. 10, no. 1, no. 1, pp. 91–102, 1992.

[42] K. Hinckley and M. Sinclair, "Touch-Sensing Input Devices," in *CHI*, pp. 223–230, 1999.

[43] A. Harter, A. Hopper, P. Steggles, A. Ward, and P. Webster, "The anatomy of a context-aware application," in *MobiCom '99: Proceedings of the 5th annual ACM/IEEE international conference on Mobile computing and networking*, (New York, NY, USA), pp. 59–68, ACM, 1999.

[44] N. B. Priyantha, A. Chakraborty, and H. Balakrishnan, "The Cricket Location-Support system," in *Proceedings of the 6th ACM International Conference on Mobile Computing and Networking*, (Boston, MA, USA), pp. 32–43, ACM, August 2000.

[45] V. Otsason, A. Varshavsky, A. LaMarca, and E. de Lara, "Accurate gsm indoor localization.," in *Ubicomp* (M. Beigl, S. S. Intille, J. Rekimoto, and H. Tokuda, eds.), vol. 3660 of *Lecture Notes in Computer Science*, pp. 141–158, Springer, 2005.

[46] A. M. Ladd, K. E. Bekris, G. Marceau, A. Rudys, L. Lydia, and D. S. Wallach, "Robotics-based location sensing using wireless ethernet," in *Eighth ACM International Conference on Mobile Computing and Networking (MOBICOM 2002)*, (Atlanta, Georgia), ACM, September 2002.

[47] T. D. Hodes, R. H. Katz, E. Servan-Schreiber, and L. A. Rowe, "Composable ad-hoc mobile services for universal interaction.," in *MOBICOM*, pp. 1–12, 1997.

[48] P. Bahl and V. Padmanabhan, "RADAR: An In-Building RF-Based Location and Tracking System," in *IEEE INFOCOM 2000*, 2000.

[49] A. Smailagic, D. P. Siewiorek, J. Anhalt, D. Kogan, and Y. Wang, "Location sensing and privacy in a context aware computing environment," *IEEE Wireless Communications*, vol. 9, pp. 10–17, 2001.

[50] M. Youssef and A. Agrawala, "The Horus WLAN location determination system," in *MobiSys '05: Proceedings of the 3rd international conference on Mobile systems, applications, and services*, (New York, NY, USA), pp. 205–218, ACM Press, 2005.

[51] P. Castro, P. Chiu, T. Kremenek, and R. R. Muntz, "A probabilistic room location service for wireless networked environments," in *UbiComp '01: Proceedings of the 3rd international conference on Ubiquitous Computing*, (London, UK), pp. 18–34, Springer-Verlag, 2001.

[52] Ekahau. http://www.ekahau.com.

[53] F. Forno, G. Malnati, and G. Portelli, "Design and implementation of a Bluetooth ad hoc network for indoor positioning," *IEE Software*, vol. 152, no. 5, pp. 223–228, October 2005.

[54] J. Hightower, R. Want, and G. Borriello, "SpotON: An Indoor 3D Location Sensing Technology Based on RF Signal Strength," UW CSE 00-02-02, University of Washington, Department of Computer Science and Engineering, Seattle, WA, February 2000.

[55] L. M. Ni, Y. Liu, Y. C. Lau, and A. P. Patil, "LANDMARC: Indoor Location Sensing Using Active RFID," *Wireless Networks*, vol. 10, no. 6, no. 6, pp. 701–710, 2004.

[56] WhereNet. http://www.wherenet.com.

[57] Ubisense. http://www.ubisense.net/default.asp.

[58] R. Orr and G. Abowd, "The smart floor: A mechanism for natural user identification and tracking," tech. rep., Georgia Institute of Technology, 2000.

[59] D. Niculescu, "Positioning in ad hoc sensor networks.," *IEEE Network*, vol. 18, no. 4, no. 4, pp. 24–29, 2004.

[60] A. S.-I. Noh, W. J. Lee, and J. Y. Ye, "Comparison of the mechanisms of the zigbee's indoor localization algorithm.," in *SNPD*, pp. 13–18, IEEE Computer Society, 2008.

[61] C. A. Patterson, R. R. Muntz, and C. M. Pancake, "Challenges in location-aware computing," *IEEE Pervasive Computing*, vol. 2, pp. 80–89, 2003.

[62] Y. Gwon, R. Jain, and T. Kawahara, "Robust Indoor Location Estimation of Stationary and Mobile Users.," in *INFOCOM*, 2004.

[63] M. Hossain, H. Nguyen Van, Y. Jin and W.-S. Soh, "Indoor Localization using Multiple Wireless Technologies," in *Proc. IEEE MASS*, (Pisa, Italy), Oct. 2007.

[64] "IEEE Standard for Information technology-Telecommunications and information exchange between systems-Local and metropolitan area networks-Specific requirements - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications," *IEEE Standard 802.11*, June 1999.

[65] "IEEE Standard for Information technology-Telecommunications and information exchange between systems-Local and metropolitan area networks-Specific requirements - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications High Speed Physical Layer Extension in the 2.4 GHz Band," *IEEE Standard 802.11b*, September 1999.

[66] "IEEE Standard for Information technology-Telecommunications and information exchange between systems-Local and metropolitan area networks-Specific requirements - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications High Speed Physical Layer in the 5 GHz Band," *IEEE Standard 802.11a*, June 1999.

[67] "IEEE Standard for Information technology-Telecommunications and information exchange between systems-Local and metropolitan area networks-Specific requirements - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 4: Further Higher Data Rate Extension in the 2.4 GHz Band," *IEEE Standard 802.11g*, June 2003.

[68] V. Honkavirta, "Location fingerprinting methods in wireless local area networks," Master's thesis, Tampere University of Technology, Finland, 2008.

[69] T. King, S. Kopf, T. Haenselmann, C. Lubberger, and W. Effelsberg, "COMPASS: A probabilistic indoor positioning system based on 802.11 and digital compasses," in *WiNTECH '06: Proceedings of the 1st international workshop on Wireless network*

testbeds, experimental evaluation & characterization, (New York, NY, USA), pp. 34–40, ACM, 2006.

[70] Y.-C. Chen, J.-R. Chiang, H.-h. Chu, P. Huang, and A. W. Tsui, "Sensor-assisted wi-fi indoor location system for adapting to environmental dynamics," in *MSWiM '05: Proceedings of the 8th ACM international symposium on Modeling, analysis and simulation of wireless and mobile systems*, (New York, NY, USA), pp. 118–125, ACM, 2005.

[71] P. Bahl, A. Balachandran, and V. Padmanabhan, "Enhancements to the radar user location and tracking system," 2000.

[72] R. Want, "An Introduction to RFID Technology," *IEEE Pervasive Computing*, vol. 5, no. 1, no. 1, pp. 25–33, 2006.

[73] M. Baudin and A. Rao, "RFID applications in manufacturing," 2005.

[74] C. Wang, H. Wu, and N.-F. Tzeng, "RFID-Based 3-D Positioning Schemes.," in *INFOCOM*, pp. 1235–1243, IEEE, 2007.

[75] A. Stelzer, K. Pourvoyeur, and A. Fischer, "Concept and application of lpm - a novel 3-d local position measurement system," *Microwave Theory and Techniques, IEEE Transactions on*, vol. 52, no. 12, pp. 2664 – 2669, dec. 2004.

[76] A. Bekkali, H. Sanson, and M. Matsumoto, "RFID Indoor Positioning Based on Probabilistic RFID Map and Kalman Filtering.," in *WiMob*, p. 21, IEEE Computer Society, 2007.

[77] H.-J. Lee and M. C. Lee, "Localization of mobile robot based on radio frequency identification devices," in *SICE-ICASE, 2006. International Joint Conference*, pp. 5934–5939, 18-21 2006.

[78] S. Han, H. Lim, and J. Lee, "An efficient localization scheme for a differential-driving mobile robot based on rfid system," *Industrial Electronics, IEEE Transactions on*, vol. 54, no. 6, pp. 3362 –3369, dec. 2007.

[79] K. Yamano, K. Tanaka, M. Hirayama, E. Kondo, Y. Kimuro, and M. Matsumoto, "Self-localization of mobile robots with rfid system by using support vector machine,"

in *Intelligent Robots and Systems, 2004. (IROS 2004). Proceedings. 2004 IEEE/RSJ International Conference on*, vol. 4, pp. 3756 – 3761, 28 2004.

[80] B. Xu and W. Gang, "Random sampling algorithm in rfid indoor location system," in *Electronic Design, Test and Applications, 2006. DELTA 2006. Third IEEE International Workshop on*, 17-19 2006.

[81] EPCglobal. http://www.epcglobalinc.org.

[82] D. Klair, K.-W. Chin, and R. Raad, "On the energy consumption of pure and slotted aloha based rfid anti-collision protocols," *Comput. Commun.*, vol. 32, no. 5, no. 5, pp. 961–973, 2009.

[83] M. Schwartz, *Telecommunication networks: protocols, modeling and analysis.* Boston, MA, USA: Addison-Wesley Longman Publishing Co., Inc., 1986.

[84] J. Caffery, J.J., "A new approach to the geometry of toa location," in *52nd IEEE Vehicular Technology Conference (IEEE VTS-Fall VTC'00)*, vol. 4.

[85] Matlab. http://www.mathworks.com.

[86] L. A. Burdet, "Rfid multiple access methods," tech. rep., ETH Zürich, 2004.

[87] C. Canale, *Numerical Methods for Engineers.*

[88] ITU, "Internet of things," 2005.

[89] D. W. Engels, "WHITE PAPER - The Reader Collision Problem," *AUTO-ID Center Massachusetts Institute of Technology*, 2001.

[90] I. F. Akyildiz, J. Xie, and S. Mohanty, "A survey of mobility management in next-generation all-ip-based wireless systems," *Wireless Communications, IEEE [see also IEEE Personal Communications]*, vol. 11, no. 4, no. 4, pp. 16–28, 2004.

[91] E. Cerqueira, L. Veloso, A. Neto, M. Curado, E. Monteiro, and P. Mendes, "Mobility management for multi-user sessions in next generation wireless systems.," *Computer Communications*, vol. 31, no. 5, no. 5, pp. 915–934, 2008.

[92] M. Allman, V. Paxson, and W. Stevens, "TCP Congestion Control." RFC 2581 (Proposed Standard), April 1999. Obsoleted by RFC 5681, updated by RFC 3390.

[93] H. Elaarag, “Improving tcp performance over mobile networks,” *ACM Comput. Surv.*, vol. 34, no. 3, no. 3, pp. 357–374, 2002.

[94] A. Mishra, M. Shin, and W. A. Arbaugh, “An empirical analysis of the ieee 802.11 mac layer handoff process.,” *Computer Communication Review*, vol. 33, no. 2, no. 2, pp. 93–102, 2003.

[95] A. Mishra, M. Shin, and W. A. Arbaugh, “Context Caching using Neighbor Graphs for Fast Handoffs in a Wireless Network.,” in *INFOCOM*, 2004.

[96] J. S. Lee, S. J. Koh, and S. H. Kim, “Analysis of handoff delay for mobile ipv6,” in *Vehicular Technology Conference, 2004. VTC2004-Fall. 2004 IEEE 60th*, vol. 4, pp. 2967 – 2969 Vol. 4, 26-29 2004.

[97] H. Velayos and G. Karlsson, “Techniques to reduce the ieee 802.11b handoff time,” in *Communications, 2004 IEEE International Conference on*, vol. 7, pp. 3844– 3848, 2004.

[98] *SyncScan: practical fast handoff for 802.11 infrastructure networks*, vol. 1, 2005.

[99] P.-C. Lin, T. Lin, and C. Wang, “Performance analysis of a cross-layer handoff ordering scheme in wireless networks,” *IEEE Transactions on Wireless Communications*, vol. 7, no. 12-2, no. 12-2, pp. 5166–5171, 2008.

[100] S. Kyriazakos, D. Drakoulis, and G. Karetsos, “Optimization of the handover algorithm based on the position of the mobile terminals,” in *Communications and Vehicular Technology, 2000. SCVT-200. Symposium on*, pp. 155–159, 2000.

[101] J. Pesola, S. Pönkänen, and A. Markopoulos, “Location-aided handover in heterogeneous wireless networks,” *Wirel. Pers. Commun.*, vol. 30, no. 2-4, no. 2-4, pp. 195–205, 2004.

[102] M. Ylianttila, J. Mäkelä, and K. Pahlavan, “Analysis of handoff in a location-aware vertical multi-access network,” 2004.

[103] T. Inzerilli, A. Vegni, A. Neri, and R. Cusani, “A location-based vertical handover algorithm for limitation of the ping-pong effect,” in *Networking and Communications, 2008. WIMOB ’08. IEEE International Conference on Wireless and Mobile Computing,*, pp. 385–389, 12-14 2008.

[104] P.-H. Tseng and K.-T. Feng, "Location tracking assisted handover algorithms for broadband wireless networks," in *Personal, Indoor and Mobile Radio Communications, 2008. PIMRC 2008. IEEE 19th International Symposium on*, pp. 1–5, 15-18 2008.

[105] A. Dutta, S. Chakravarty, K. Taniuchi, V. Fajardo, Y. Ohba, D. Famolari, and H. Schulzrinne, "An experimental study of location assisted proactive handover," in *GLOBECOM*, pp. 2037–2042, 2007.

[106] N. A. Fikouras and C. Görg, "Performance comparison of hinted- and advertisement-based movement detection methods for mobile ip hand-offs.," *Computer Networks*, vol. 37, no. 1, no. 1, pp. 55–62, 2001.

[107] M. Liebsch, A. Singh, H. Chaskar, and D. Funato, "Fast Router Discovery with RA Caching," March 2003. draft-jinchoi-dna-frd-00.txt.

[108] R. Koodli, "Fast Handovers for Mobile IPv6." RFC 4068 (Experimental), July 2005. Obsoleted by RFC 5268.

[109] H. Lu, X. Zhou, and P. Hong, "Improving the performance of fast handovers in mobile ipv6.," in *GLOBECOM*, pp. 1808–1812, IEEE, 2007.

[110] A. Dutta, S. Madhani, W. Chen, O. Altintas, and H. Schulzrinne, "Gps assisted fast-handoff mechanism for real-time communication," in *Sarnoff Symposium, 2006 IEEE*, pp. 1 –4, 27-28 2006.

[111] S. Waharte, J. Xiao, and R. Boutaba, "Sensor-based architecture for qos provisioning and fast handoff management in wlans," *Annals of Telecommunications*, vol. 63, pp. 137–148, 2008. 10.1007/s12243-008-0017-6.

[112] V. Bahety and R. Pendse, "Scalable qos provisioning for mobile networks using wireless sensors," in *IEEE Wireless Communications and Networking Conference*, pp. 1528–1533, IEEE, 2004.

[113] L. Zhang and Z. Wang, "Integration of rfid into wireless sensor networks: Architectures, opportunities and challenging problems," pp. 463 –469, oct. 2006.

[114] A. Papapostolou and H. Chaouchi, "Handoff management relying on rfid technology," pp. 1 –6, apr. 2010.

[115] P. Bahl and R. Chandra, "SSCH: Slotted Seeded Channel Hopping for Capacity Improvement in IEEE 802.11 Ad-Hoc Wireless Networks," in *in IEEE 802.11 Ad-Hoc Wireless Networks, in ACM Mobicom*, pp. 216–230, 2004.

[116] T. Camp, J. Boleng, and V. Davies, "A survey of mobility models for ad hoc network research.," *Wireless Communications and Mobile Computing*, vol. 2, no. 5, no. 5, pp. 483–502, 2002.

[117] Intel, "Data tranfer over wireless lan power consumption analyis." http://softwarecommunity.intel.com/articles/eng/2806.htm.

[118] Mica2, "http://www.xbow.com/products/product-pdf-files/wireless-pdf/mica2-datasheet.pdf."

List of publications

Book Chapters

-*B1* A. Papapostolou and H. Chaouchi, *RFID Deployment for Location and Mobility Management on the Internet*, in H. Chaouchi (ed), The Internet of Things : Connecting Objects, Wiley, John & Sons, May 2010 [24].

International Conferences

-*C1* A. Papapostolou and H. Chaouchi, *WIFE : Wireless Indoor positioning based on Fingerprint Evaluation*, in Proceeding of the 8th IFIP NETWORKING conference, Aachen, Germany, March 2009 [15].

-*C2* A. Papapostolou and H. Chaouchi, *Orientation - Based Radio Map Extensions for Improving Positioning System Accuracy*, in Proceeding of the 6th ACM International Wireless Communications and Mobile Computing Conference (ACM IWCMC), Leipzig, Germany, June 2009 [16].

-*C3* A. Papapostolou and H. Chaouchi, *Considerations for RFID-based Indoor Simultaneous Tracking*, in Proceedings of the 2nd Joint IFIP Wireless and Mobile Networking Conference, Gdansk, Polland, September 2009 [18].

-*C4* A. Papapostolou and H. Chaouchi, *Simulation-based Analysis for a Heterogeneous Indoor Localization Scheme*, in Proceedings of the 7th IEEE Consumer Communication and Networking Conference (IEEE CCNC), Las Vegas, Nevada, January 2010 [20].

-*C5* A. Papapostolou and H. Chaouchi,*Exploiting Multi-modality and Diversity for Localization Enhancement : WiFi and RFID usecase*, in Proceedings of the 20th IEEE International symposium on Personal Indoor and Mobile Radio Communications (IEEE PIMRC), Tokyo, Japan, September 2009 [21].

-*C6* A. Papapostolou and H. Chaouchi, *RFID-assisted Movement Detection Improvement* *in IP Mobility*, in Proceedings of the 3rd IFIP International Conference on New Technologies, Mobility and Security (IFIP NTMS), Cairo, Egypt, December, 2009 [22].

-*C7* A. Papapostolou and H. Chaouchi, *Handoff Management relying on RFID Technology*, in Proceedings of the IEEE Wireless Communication and Networking Conference (IEEE WCNC), Sydney, Australia, April 2010 [23].

-*C8* A. Papapostolou and H. Chaouchi, *Deploying Wireless Sensor/Actuator Networks and RFID for Handoff Enhancement* in Proceeding of the International Conference on Ambient Systems, Networks and Technologies (ACM ANT), Paris, France, November 2010 [25].

International Journals

-*J1* A. Papapostolou and H. Chaouchi, *Scene Analysis Indoor Positioning Enhancements*, Annals of Telecommunications journal, October 2010 [17].

-*J2* A. Papapostolou and H. Chaouchi, *RFID-assisted Indoor Localization and the Impact of Interference on its Performance*, in the SI on RFID Technology, Systems, and Applications of the Journal of Network and Computer Applications (Elsevier), April 2010 [19].

-*J3* A. Papapostolou and H. Chaouchi, *Integrating RFID and WLAN for Indoor Positioning and IP Movement Detection* journal of Wireless Networks (Springer), submitted in November 2009.

-*J4* A. Papapostolou and H. Chaouchi, *Handoff Management Schemes in Future Pervasive Environments*, submitted to the journal of Mobile Networks (Springer), *SI on Future Internet for Green and Pervasive Media of the journal of Mobile Networks and Applications (Springer)*, submitted in December 2010.

List of acronyms

AAL	*Ambient Assisted Living*
AC	*Address Configuration*
AoA	*Angle of Arrival*
AP	*Access Point*
AR	*Access Router*
BS	*Base Station*
BSS	*Basic Service Set*
BU	*Binding Update*
CCP	*Collision Compensation Phase*
CSMA	*Carrier Sense Multiple Access*
CoA	*Care of Address*
CoG	*Center of Gravity*
CoO	*Cell of Origin*
DoI	*Degree of Irregularity*
DS	*Distribution System*
EPC	*Electronic Product Code*
ESS	*Extended Service Set*
FRP	*Fixed Reference Point*
JLO	*Joint Location and Orientation*
HF	*High Frequency*
GPS	*Global Positioning System*
GSM	*Global System for Mobile Communications*
ID	*IDentification*
IETF	*Internet Enginneering Task Force*
ICT	*Information and Communication Technologies*

IP	*Internet Protocol*
ISO	*International Standards Organization*
LAN	*Local Area Network*
LBS	*Location Based Services*
LF	*Low Frequency*
LL	*Link Layer*
LOS	*Line Of Sight*
LS	*Least Squares*
MAC	*Medium Access Control*
MANET	*Mobile Ad Hoc Networks*
MD	*Movement Detection*
MF	*Matched Filter*
MIP	*Mobile IP*
ML	*Multi-Lateration*
MLE	*Mean Location Error*
MLT	*Mean Localization Time*
MM	*Mobility Management*
MN	*Mobile Node*
NIC	*Network Interface Card*
NL	*Network Layer*
NLOS	*Non Line Of Sight*
NN	*Nearest Neighbor*
NNSS	*Nearest Neighbor in Signal Space*
PA	*Pure Aloha*
PAM	*Point of Attachment Map*
PDA	*Personal Digital Assistan*
PHY	*PHYsical*
PM	*Pattern Matching*
PoA	*Point of Attachment*
QoS	*Quality of Service*
RF	*Radio Frequency*
RFC	*Request For Comments*
RFID	*Radio Frequency IDentification*
RM	*Radio Map*

RR	*Round Robin*
RRS	*Received Radio Signal*
RS	*Radio Signals*
RSS	*Received Signal Strength*
RSSI	*Received Signal Strength Indicator*
RWP	*Random Way Point*
SNR	*Signal to Noise Ratio*
SA	*Slotted Aloha*
S-AVG	*Simple Average*
SELFLOC	*SELective Fusion LOCation*
STA	*mobile STAtion*
SVM	*Support Vector Machine*
TCP	*Transmission Control Protocol*
TDoA	*Time Difference of Arrival*
TMI	*Triangulation, Mapping and Interpolation*
ToA	*Time of Arrival*
UHF	*Ultra High Frequency*
UWB	*UltraWideBand*
WE	*Worst Error*
WiFi	*Wireless Fidelity*
W-AVG	*Weighted Average*
WMN	*Wireless Mesh Network*
WSAN	*Wireless Sensor and Actuator Network*
WSN	*Wireless Sensor Network*
WLAN	*Wireless Local Area Networks*

List of figures

List of tables

Localisation en Intérieur et Gestion de la Mobilité dans les Réseaux Sans Fils Hétérogènes Émergents

Résumé Au cours de ces dernières décennies, nous avons été témoins d'une évolution considérable dans l'informatique mobile, réseaux sans fil et des appareils portatifs. Dans les réseaux de communication à venir, les utilisateurs devraient être encore plus mobiles exigeant une connectivité omniprésente à différentes applications qui seront de préférence au courant de leur contexte. Certes, les informations de localisation dans le cadre de leur contexte est d'une importance primordiale à la fois la demande et les perspectives du réseau. De point de vu de l'application ou l'utilisateur, la provision de services peuvent mettre à jour si l'adaptation au contexte de l'utilisateur est activée. Du point de vue du réseau, des fonctionnalités telles que le routage, la gestion de handoff, l'allocation des ressources et d'autres peuvent également bénéficier si l'emplacement de l'utilisateur peuvent être suivis ou même prédit.

Dans ce contexte, nous nous concentrons notre attention sur la localisation à l'intérieur et de la prévision de handoff qui sont des composants indispensables à la réussite ultime de l'ère de la communication omniprésente envisagé. Alors que les systèmes de positionnement en plein air ont déjà prouvé leur potentiel dans un large éventail d'applications commerciales, le chemin vers un système de localisation réussi à l'intérieur est reconnu pour être beaucoup plus difficile, principalement en raison des caractéristiques difficiles liées à l'intérieur et l'exigence d'une plus grande précision. De même, la gestion de handoff dans des réseaux hétérogènes sans fil de futur est beaucoup plus difficile que dans les réseaux traditionnels homogènes. La procédure de handoff doit être transparente pour satisfaire la qualité de service requise par les applications de futur et leurs fonctionnalités, cela ne doit pas dépendre de la caractéristique de l'opération des technologies différentes. En outre, les décisions de handoff devraient être suffisamment souples pour tenir compte aux préférences des utilisateurs d'un large éventail de critères proposés par toutes les technologies.

L'objectif principal de cette thèse est de mettre au point précis, le temps et l'emplacement de puissance efficaces et la gestion de handoff afin de mieux satisfaire les applications sensible des utilisateurs en dépendent au contexte dans lequel les utilisateur se trouvent. Pour obtenir une localisation à l'intérieur, le potentiel de réseau sans fil local (WLAN) et Radio Frequency Identification (RFID) comme une technologie autonome pour détection de location sont d'abord ont été étudiés par des expérimentations de plusieurs algorithmes et paramètres dans des plateformes réels ou par de nombreuses simulations, alors que leurs lacunes ont également été identifiés. Leur intégration dans une architecture commune est alors proposée afin de combiner leurs principaux avantages et surmonter leurs limitations. La supériorité des performances du système de synergie a été validée par des analyses profondes sur leur performance si elles fonctionnent d'une manière automne (sans intégration). En ce qui concerne la tâche de gestion de handoff, nous identifions que la sensibilité au contexte peut aussi améliorer la fonctionnalité du réseau. En conséquence, deux types de systèmes qui utilisent l'information obtenue à partir des systèmes de localisation one été proposées. Le premier schéma repose sur un déploiement tag RFID, comme notre architecture de positionnement RFID, et en suivant la scène WLAN analyse du concept de positionnement, prédit l'emplacement réseau de la prochaine couche, c'est à dire le prochain point de fixation sur le réseau. La deuxième méthode repose sur une approche intégrée RFID et réseaux de capteurs / actionneur Network (WSAN) de déploiement pour la localisation physique des utilisateurs et par la suite pour prédire leur prochaine point de handoff aux niveaux des couches de liaison et le réseau. Etre indépendant de la technologie d'accès sans fil sous-jacent, les deux régimes peuvent être facilement mises en oeuvre dans des réseaux hétérogènes.

L'évaluation de la performance démontre les avantages de nos méthodes proposées par rapport aux protocoles standards concernant l'exactitude de prévision, le temps de latence et l'économie d' énergie. Les mots clés : mobilité, localisation, gestion de handoff, communication des réseaux sans fil, architecture des réseaux hétérogènes, analyse de performance, WLAN, RFID, WSAN.

Mots clés localisation, mobilité, gestion de la handoff, communications sans fil, hétérogénéité, conception d'architecture réseau, analyse de performance, WLAN, RFID, WSAN.

Indoor Localization and Mobility Management in the Emerging Heterogenous Wireless Networks

Abstract is on page 9

Keywords localization, mobility, handoff management, wireless communications, heterogeneity, network architecture design, performance analysis, WLAN, RFID, WSAN.