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Introduction

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Over the past few decades, wireless communications have become essential in everyone's daily life. The world has become mobile, and continuous access to information has become a requirement. Owing to this necessity for fresh, real-time, first-hand information, devices such as mobile phones, computers, pagers, data cards, sensors and data chips have been entering our lives as typical technology "buddies". For this reason, wireless services have gained popularity, and location information has become useful information in the wireless world. The continuous demand for information has created a huge potential for business opportunities and it has promoted innovation towards the development of new services. As a consequence, the infrastructure that enables communication among wireless devices has been rapidly growing towards higher coverage, higher flexibility and higher interoperability. This reality is so visible that it is nowadays unthinkable to envision our lives without these technologies. Furthermore, with the rapid deployment of wireless communication networks, positioning information has become of great interest. Because of the inherent mobility behavior that characterizes wireless communication users, location information has also become crucial in several circumstances, such as rescues, emergencies and navigation. This position dependency has boosted research, development and business around the topic of positioning mechanisms for wireless communication technologies. The result is a wide variety of integrated and built-in solutions that can combine and interoperate with communication and position information. Thus, this book covers the topic of positioning mechanisms for wireless communication technologies. It explains in detail the services, wireless communication protocols, positioning and tracking algorithms, error mitigation techniques, implementations used in wireless communication systems, and the most recent techniques of cooperative positioning.

Positioning or location can be understood as the unambiguous placement of a certain individual or object with respect to a known reference point. This reference point is often assumed

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to be the center of the Earth coordinate system. In practice, the reference point can be any point on the Earth[1] that is known to the system and which all the coordinates can relate to. Although the position itself is obviously a very important source of information, this position must be related to a specific time to be even more useful. In particular, when we consider tracking systems, time information is a key necessity, not only for knowing the position of a certain device at a specific time, but also for inferring higher-order derivatives of the position, that is, speed and acceleration. Thus, "tracking" is a method for estimating, as a function of time, the current position of a specific target. "Navigation" is a tracking solution that aims primarily at using position information in order to help users to move towards a desired destination.

Although enabling position estimation with communication technologies is currently a hot topic, the necessity for determining the position of individuals, groups, animals, vehicles or any type of object is an ancient necessity that can be seen as a basic need. This necessity has been present in human life for many centuries and it is so important that humans and animals have in-built biological mechanisms that permit individuals to localize and orient themselves in many situations. When we consider the actual methods for obtaining position information, the history is long and the systems are numerous. During the early years, a few millennia ago, orientation and positioning were already possible using devices that resemble present-day magnetic compasses, using maps of sea currents and winds, or using celestial navigation techniques. For centuries, celestial navigation, by means of observations of the positions of stars and the Sun, was the most important technique for estimating position information. By knowing, for instance, the position of the Sun or well-known star constellations, people were able to determine their orientation and navigate on the Earth. This technique is so important that it is still used today to provide a rough sense of one's orientation when no other tool is available. Although the mechanisms for orientation based on star position readings and compass readings have been used for at least two millennia, these mechanisms were widely used and improved during the period of sea exploration in the 15th and 16th centuries. This was an important period in the history of positioning systems. Several objects, such as the cross-staff and astrolabe (and, later, the quadrant and the sextant, invented in the 17th and 18th centuries), permitted sea explorers to read the position of the stars and subsequently calculate their own position, often supported by the incomplete maps that were available at that time. Associated with these tools were other techniques for predicting and inferring future positions based on the analysis of past movements. These techniques were often used to navigate when, for instance, the sky was not clear and they were generally complemented by anchor points of known location, such as points on the shore. In the 18th century, the chronometer was invented. This tool, widely used in ship navigation, permitted calculations of position to be connected more efficiently to corresponding timestamps. By the end of the 19th century, wireless communications emerged and, along with this remarkable discovery, the first position solutions based on electromagnetic waves started to be developed. This period marked an important turn not only in the history of positioning systems, but also in the entire history of communication technology. The first positioning system to be invented was the radio direction finder, a device which was able to determine the direction from where radio waves were being generated. The basic concept of this device was to find the null (i.e., the direction which results in the weakest signal) in the signal observed with a directional antenna mounted on a portable support. Only by the mid-20th century were the first radars invented. Ever since, these systems have been used and enhanced, and they are still widely used for several positioning

[1] Or in space, if the system is meant to be used in outer space.

purposes. Radar is a system that transmits radio waves towards a target and is able to read the signals that are received back after they have been reflected from the target itself. From this period onwards, great development in positioning systems has occurred, culminating in the wide variety of systems currently available. One of the most famous systems is the long-range navigation (LORAN) system, proposed in 1940, which was characterized by beacons radiating synchronized signals that were then read by target receivers. The receivers had to be able to measure time differences in the arrival of the signals in order to calculate their positions. Later on, by the 1960s, satellite positioning systems started to be deployed, and space exploration began. Currently, Global Positioning System (GPS) is the best known and most used satellite positioning system. Over the past 30–40 years, several other positioning solutions have been deployed for use in various scenarios, based on various approaches, using infrared, ultrasound, image processing or electromagnetic waves.

In parallel with the deployment of positioning and communication systems during the last decade, research has evolved in the direction of integrating communication and positioning into a single system. Some examples are the current standards for the Third Generation Partnership Project (3GPP) and ultrawideband (UWB), which include information about positioning mechanisms in the communication specifications. The combination of these functionalities has leveraged new services, namely location-based services (LBSs). In contrast to the earlier dedicated solutions that were designed to simply provide positioning, the new solutions for wireless networks are able to provide the combined benefit of both communication and positioning. As a consequence, the whole network, as well as the end user and the service providers, can benefit from position-enabled communication capabilities: the network operator can manage all the network's resources in a more efficient way, the service provider is able to deliver new services based on the user's position, and the user can enjoy new personalized, location-dependent services. Many of the services proposed in research documents assume location information as a basic requirement for deployment of new protocols (e.g., routing and clustering), new technologies (e.g., cooperative systems) and new applications (e.g., navigation and location-aware advertising). Furthermore, in the industrial environment, location information has also been widely used in applications such as navigation, location-dependent searching and social networks. Since wireless communication networks are nowadays almost present anywhere at any time, any new location-dependent networking enhancement, service or application can be spread rapidly and used globally.

The location information mechanisms in wireless communication technologies can be classified into positioning systems and positioning solutions, as shown in Figure 1.1. A positioning system concerns the hardware and software necessary to measure the properties of wireless links and to subsequently process those measurements in order to estimate the user's position. Positioning systems are typically integrations of entire systems into communication technologies, such as the GPS integration into mobile phones and cellular base stations (BSs). In contrast, a positioning solution is typically a software-based implementation, where indirect measurements of the user's position are obtained in an opportunistic fashion from the adaptation of mechanisms existing in communication technologies. The enablement of location information in current wireless communication networks can be done either by integrating a positioning system into the network or by implementing a positioning solution that extracts location information, thus exploiting the potential of the network. By integrating a positioning system into the network, it is usually possible to obtain better accuracy than what is obtained by a direct implementation in the network. The disadvantage is that integrating

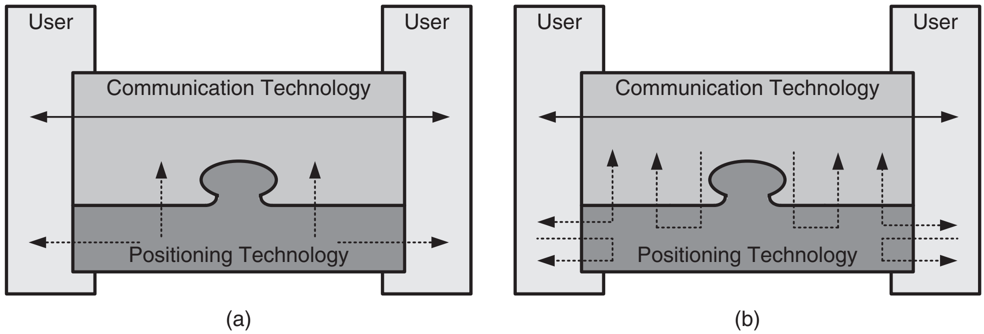

Figure 1.1 Schematic representation of a positioning system (a) and a positioning solution (b). The solid arrows represent the flow of communication and the dashed arrows represent the flow of position information. In (a), it is possible to see that position is always generated in a positioning technology. In contrast, a positioning solution is often calculated based on opportunistic information obtained from communication technology.

additional hardware necessarily implies additional costs, higher power consumption and higher complexity. For this reason, a direct software-based positioning implementation that opportunistically exploits the existing hardware and extracts location information is commonly preferred. Typical positioning solutions make use of mechanisms present in most of the current advanced wireless technologies, such as power control and synchronization schemes. The requirement is that the positioning solution is able to perform measurements of the wireless channel that can be used as indirect observations of the user's position. Examples of such measurements are the received signal strength and the propagation delay of signals.

The possible scenarios and conditions where location information is needed are numerous, and no localization system is able to perform localization under all conditions. For this reason, several localization systems and solutions are available and many others are still under research. For instance, the traditional satellite-based GPS represents a solution with worldwide coverage; however, it is not usable in some specific situations, such as in dense urban areas, indoors, underwater and underground. For these cases, many other systems are being developed or are even already available on the market.

The book is organized as follows. Chapter 2 introduces location-based services as the main driver for wireless positioning. Chapter 3 then introduces the basics of wireless communications. The foundations of positioning are presented in Chapter 4 and are extended to more complex data-processing algorithms in Chapter 5. Tracking algorithms are explained in Chapter 6. As none of the previous chapters reviews the actual preprocessing of raw data, Chapter 7 introduces some algorithms for mitigating propagation effects in wireless positioning. The systems and solutions for wireless positioning currently existing in the market are described in Chapter 8, while Chapter 9 presents the topic of ultra-wideband positioning and tracking. Wireless local area network (WLAN) approaches in indoor positioning are presented and discussed in Chapter 10. In Chapter 11 theoretical and experimental approaches are discussed for cooperative multi-tag localization in RFID systems and, finally, some novel cooperative schemes for wireless positioning are introduced in Chapter 12. The sections below give some insight into each of the chapters.

1.1 Application Areas of Positioning (Chapter 2)

Location-based services are introduced in this chapter as a motivational engine for combining communication and positioning information, and then integrating wireless systems and positioning technologies. Owing to the increasing number of services and systems using location and the even larger number of services envisioned for the future, it has become mandatory to have a framework for layering positioning systems in a similar way to what has been done for the open system interconnection (OSI) stack in the communication world. This framework defines several layers, each of which has clear, defined purposes. This framework, apart from other benefits, will allow services to run independently of the overlaid technology. This chapter concerns mostly the applications of LBS and the entities involved in the services. These entities are, for instance, service providers, users, network operators, location infrastructure operators, developers and portals. The applications are categorized according to the service that is being provided: emergency services, automotive applications, medical applications, monitoring, navigation, management and entertainment. Then, the major benefits of combining the two functionalities are pointed out: interoperability and enhancement of both positioning-based communication and communication-based positioning. Typical examples are radio resource management and radio planning.

1.2 Basics of Wireless Communications for Positioning (Chapter 3)

In this chapter, the basics of wireless communications and how they relate to mobile positioning are introduced. First, the radio propagation scenario is described by classifying the various physical phenomena that underlie wireless communications, that is, propagation loss, shadowing and multipath fading. Then, the possibilities and challenges of multiple-antenna techniques are discussed, focusing in particular on the two big families of *spatial diversity* and *spatial multiplexing*, and on the gains achievable with them. The other important family of multiantenna techniques, that is, beamforming, is discussed later in the chapter, when we will treat space division multiple access (SDMA), an access technique that is based on beamforming. The chapter reviews modulation and access techniques, focusing in particular on orthogonal frequency division multiplexing (OFDM) and orthogonal frequency division multiple access (OFDMA), which are the most relevant techniques for future wireless positioning systems. Moving up in the OSI stack, some radio resource management (RRM) techniques are illustrated, namely handoff, interference management, channel reuse, channel reservation and power control, and we illustrate how localization can benefit from them, and vice versa. Finally, we outline some important ideas about two emerging areas within wireless communications: cooperative communications and cognitive radio technology. Their interconnection with mobile positioning closes the chapter.

1.3 Fundamentals of Positioning (Chapter 4)

After reviewing some basics of wireless communications in the preceding chapter, we introduce the basics of wireless positioning. Systems are classified according to several aspects: topology, physical coverage and type of integration into communication technologies. Then, the various types of measurements are explained. The cell ID is identified as the simplest type of measurement to obtain and also the one that results in the least accurate solution. Range measurements such as time of arrival (TOA) and received signal strength (RSS) measurements are introduced as having, apart from the effect of propagation impairment, the potential to provide more accurate positioning information than what is possible with Cell ID measurements. Two alternatives are measurements of the time difference of arrival (TDOA) and the angle of arrival (AOA). These measurements enable several basic positioning techniques that are explained in detail. Proximity-sensing techniques rely on measurements of proximity or coverage. Triangulation techniques rely on trigonometric theory and channel measurements in order to obtain the positions of mobile stations (MSs). Finally, fingerprinting techniques require an extensive precalibration phase that is aimed at collecting measurements of the wireless channels at several predefined positions. Then, while in operation mode, the measurements obtained are correlated with information from the calibration in order to localize the MSs. As none of the positioning systems are error-free, due to channel noise, the chapter also introduces several of the most important types of errors existing in the measurements. These errors are mostly due to propagation effects, geometry and the technology used, and the consequent topology and communication protocols. Owing to the errors, it is necessary to define the metrics of positioning. The most common metrics are the circular error probability (CEP), the dilution of precision (DOP) and the Cramér-Rao lower bound (CRLB).

1.4 Data Fusion and Filtering Techniques (Chapter 5)

Because of the various error sources, it is necessary to implement mechanisms capable of handling this noise. The first approach explained in this chapter concerns the least squares (LS) method. This approach aims at determining the position that minimizes the squared error between the actual measurements from the channel and the expected measurements. In order to execute the algorithm, it is necessary to define a model to approximate the relation between the position coordinates and the measurements. In this context, linear and nonlinear methods are explained. While the linear LS methods present a closed-form solution and a derived method for recursive calculations, the nonlinear LS (NLLS) methods must be solved by numerical optimization algorithms. An alternative to the LS methods is the Bayesian framework. This framework defines a recursive mechanism to calculate the position based on the least mean squared error. Kalman filters (linear and nonlinear), particle filter methods and grid-based methods are illustrated as implementations of the Bayesian framework, each to be used depending on the properties of the system. As commonly happens in wireless positioning, there may be several parameters that are unknown, even though the model relating the measurements and the positions is known or at least can be approximated. For this reason, these parameters are determined by means of either precalibration or on-line combined estimation of parameters and positions. The chapter closes by describing some alternative solutions, such as fingerprinting and time series analysis.

1.5 Fundamentals of Tracking (Chapter 6)

As a first step towards tracking of MSs, this chapter starts by conceptually explaining the complexity introduced into systems when time is considered, that is, when users move. Then, as a further step in complexity, cooperative schemes are also introduced. Mobility models are presented as an essential aspect of tracking applications. The first class of movement models is that of conventional models, which is given by the well-known physical laws of the straight-line movement. Then, several stochastic models for individual mobility and group mobility are presented. While individual mobility models tend to permit unconstrained movement or are constrained only by scenarios or boundaries, group mobility models tend to be constrained by the mobility of other individuals belonging to the same group. The final class of mobility models is that of cooperative or social-based models, which resemble not only group behavior, but also the social behavior of individuals. The latter models provide some of the foundations of cooperative wireless positioning presented in Chapter 12. After presenting the models, the chapter presents a sequence of components commonly present in a tracking solution. The first phase is to treat the raw measurements in order to exclude some possible destructive effects that can be detected at this early stage. The measurements are then used as an input for tracking algorithms; we first present non-maneuverable and then maneuverable algorithms. Finally, at the output of the tracking algorithm there exists an intelligent platform capable of learning users' positions and tracking patterns; two important algorithms are presented in this context.

1.6 Error Mitigation Techniques (Chapter 7)

Non-line-of-sight (NLOS) situations are commonly encountered in modern wireless communication systems in both indoor and outdoor environments. They result in biased time-of-flight estimates, which, if not handled properly in the localization algorithm, may considerably degrade the localization accuracy. In this chapter, common techniques that can be employed for the mitigation of NLOS effects in a wireless positioning system are reviewed for time-based positioning systems. After providing a generic system model for time-based location estimation, we summarize fundamental lower bounds and maximum likelihood (ML) solutions for line of sight (LOS) and NLOS scenarios. Various NLOS mitigation methods are classified into four different categories and reviewed: (1) least-squares estimators, (2) constraint-based estimators, (3) robust estimators and (4) identify-and-discard estimators. Least-squares algorithms improve the localization accuracy by giving less emphasis to NLOS measurements in the mobile location's solution. Constrained-based estimators use NLOS measurements to define certain constraints on the location estimate; under these constraints, they typically evaluate the location of the mobile station by using LOS measurements. Robust estimators make use of the rich body of literature and methods available in robust estimation theory for detecting and discarding outliers in a given set of data (i.e., NLOS measurements are treated as outliers and discarded). Finally, the identify-and-discard estimators aim to accurately identify NLOS measurements and determine the location of the mobile station by using only LOS measurements. The key contributions in the literature associated with each of the above categories are summarized and compared with each other.

1.7 Positioning Systems and Technologies (Chapter 8)

This chapter presents in a concise way the positioning solutions commonly used in the various wireless communication technologies. The first class of systems to be introduced is satellite-based systems. The basic principle relies on measuring the propagation delays that signals are subject to when traveling from the satellites to the users on Earth. Then, cellular positioning solutions are introduced, with Global System for Mobile Communications (GSM) and Universal Mobile Telecommunications System (UMTS) communication systems the main ones considered. While GSM typically relies on methods based on cell identification and range measurements, UMTS relies on differences of range measurements. The next class of systems introduced in this chapter is WLAN systems. These tend to use both cell identification techniques and measurements of received signal strength (RSS). UWB technology is a special case in which time measurements are preferred, as such a wide frequency band permits time measurements to reach a higher accuracy than what is permitted by RSS measurements. Some dedicated solutions are also presented: radio frequency identification (RFID), infrared and ultrasound. The chapter closes by summarizing some hybrid techniques that combine more than one technology in order to achieve better results in terms of position estimation accuracy. The combination of cellular and WLAN positioning with the Assisted Global Navigation Satellite System (A-GNSS), for example the Assisted Global Positioning System (A-GPS), has become of great interest.

1.8 Ultrawideband Positioning and Tracking (Chapter 9)

In previous chapters the use of RSS, TOA, AOA or carrier phase measurements from different technologies was discussed to infer the position of a mobile node. Such measurements have several geometric constraints, allowing the location engine to estimate a node's position according to some methods. Unfortunately, RSS might not be always correlated with position/distance due to the random nature of radio propagation, especially in indoor environments and in NLOS conditions, thus leading to poor localization performance. In contrast, time-based measurements are in general better suited when high-accuracy positioning is required due to the fact that the larger the signal bandwidth the higher will be the resolution of time measurements. This might be enough to justify the adoption of wideband signals in the GPS and the interest in UWB signals in indoor positioning applications. Besides active positioning, UWB technology enables a plethora of novel applications such as multi-static radar for non-collaborative localization, life signs detection systems, and through-wall and underground imaging. In this chapter, the main issues and methods for obtaining high-resolution ranging and localization in UWB technology are presented and discussed, and the most successful applications of UWB, that is, those related to positioning and tracking, are identified.

1.9 Indoor Positioning in WLAN (Chapter 10)

WLAN data represent at the same time the most suitable and the most challenging signals to exploit in mobile positioning. The location estimation might be easily provided in different ways, making it one of the most adopted solutions for localizing and tracking people indoors. For this reason the very exploitation of WLAN signals is a tempting approach for researchers and service providers. When the signal strength of nearby hotspots is the adopted solution, we can define three main categories: cell identifier (Cell-ID), fingerprinting and pathloss-based. In this chapter, in addition to the description of the conventional approaches and characteristics or WLAN positioning, we describe how human-induced errors should not be ignored when performing experimental activities for indoor positioning using RSS. Specifically we emphasize that although environmental and human-induced perturbations generate systematic errors, if correctly accounted for and cognitively exploited it is possible to somehow mitigate the negative effects and to obtain enhancements in terms of positioning accuracy.

1.10 Cooperative Multi-tag Localization in RFID Systems (Chapter 11)

RFID is a wireless technology used to identify objects. It is mountable or attachable to a product, animal or a human being, enabling the transfer of its stored data using radio waves. In its simplest architecture it comprises RFID tags and RFID readers. RFID readers broadcast queries to tags in their wireless transmission ranges to obtain information stored in the tags such as their unique serial identification number, enabling contactless identification, even for RFID-tagged objects in motion and/or in NLOS with respect to the RFID reader. There are three types of tags: passive, semi-passive or active. Existing RFID localization mechanisms in literature assume that the object contains only a single tag. In order to increase the localization accuracy, multiple tags can be deployed on a target. Consequently, the RSS information obtained from the tags may be combined with the known information about the physical distance between the tags showing that cooperative multi-tag localization does exhibit higher localization accuracy over single-tag localization.

1.11 Cooperative Mobile Positioning (Chapter 12)

Based on the knowledge acquired in the previous chapters, this chapter introduces cooperative schemes for wireless positioning. As a concept borrowed from the context of robotics, these schemes are described within that context and examined further within the context of sensor networks. As a natural requirement of cooperative schemes, nodes are required to cluster so that cooperative links are known within the cluster members and also within the entire network. With this in mind, wireless mobile networks are considered from the cooperative point of view. The estimation algorithms, previously introduced as based on individual positioning methods, in particular the LS and Kalman filter approaches, are augmented in order to consider several users and the influence between them. These algorithms are used as the core estimation process in the Cooperative Mobile Positioning System (COMET) framework, a cooperative infrastructure which provides location information on a group of users by taking into account the user-to-user communications and the proximity relations among them. The architecture is based on the concept of clustering the users and then gathering the measurements from all the links between users and between users and BSs in order to jointly estimate the positions. The various mechanisms and the entire COMET concept are analyzed based on simulations.