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Introduction

It is now over 100 years since Marconi first demonstrated a practical radio system at transcontinental distances, and in the intervening years radio technology has become increasingly important to modern life. This book is focused on an emerging application of radio technology, namely short to medium-range positioning, particularly for indoor applications. The history of the development of radio technology shows that the initial applications tend to be for business and military use, but the most rapid development occurs when the technology becomes a consumer product.

As the short to medium-range indoor positioning technology is in its infancy, it is interesting to review the adoption of radio technology in the twentieth century as a rough indication of its likely development trajectory. Initial applications of radio technology were concentrated in the area of simple text communications, but analog modulation soon allowed the transmission of voice and later vision. In the general consumer area, ‘wireless’ initially came to mean analog AM radio, with the ‘wireless’ term being used to distinguish it from wired voice communications using the telephone. Over time, the term ‘wireless’ in this context became out of fashion, being replaced by the more generic term ‘radio’, only to become a popular term again for the description of short-range radio systems. Developments during World War II expanded radio technology into new areas, such as radar and radiolocation, but with no extension into consumer products. The development of mobile phone technology commenced as early as the late 1940s, but the uptake of the technology [1] was much slower than other consumer products, such as the telephone, automobiles, radio and television. The development of cellular telephone technology initially had little impact on this situation. Indeed, as late as 1987 the growth of customers in the USA appeared to have stalled [1], but with the advent of digital cellular telephone technology the growth exploded. However, it took some 50 years for the penetration of the mobile/cellular phone to reach saturation, far longer than other consumer electronics.

The development of radiolocation technology can be traced back to the late 1930s with the invention of radar, and with the development of navigation aids for aircraft during World War II. Early systems included the instrument landing system (ILS) and wide-area navigation with LORAN [2]. Such systems were restricted to aircraft and to a lesser extent shipping. While the theory of hyperbolic radiolocation was developed in the 1940s [2], little further occurred
until the advent of the global positioning system (GPS) by the US Department of Defense in the late 1980s. Although GPS is based on satellites rather than terrestrial stations, the general principles are the same as those used in LORAN, and indeed much of what is described in this book. While initially GPS was mainly intended for military use, the utility of global position determination was soon realized, so that civilian applications from surveying to in-vehicle navigation were developed in the 1990s. However, explosive growth in GPS is now occurring with the marriage of the cellular/mobile phone technology with GPS, which was made feasible by the increasing availability of low-cost GPS chipsets. The integration of location databases, the Internet, digital radio communications and radio positioning into mobile devices is poised to expand into the future. Perhaps the status of radio positioning technology today could be summed up by the English mathematical physicist Sir Oliver Heaviside, who in 1891 said

‘Three years ago, electromagnetic waves were nowhere. Shortly afterward, they were everywhere.’

GPS and other similar technologies such as the European Galileo system are mainly intended for navigation outside of buildings, whereas many of the potential applications are indoors, including security applications, health care, emergency services and inventory management [3]. These indoor applications require a tracking system rather than a navigation one, whereby knowledge of the location of an object is required remotely. Further, the indoor radio propagation environment is much more complex than the outdoor counterpart. Consequently, accurate but economical position location systems over large indoor areas is current not commercially feasible. Nevertheless, with the availability of ever more powerful radio and digital signal-processing chips, and more sophisticated position determination algorithms, such short to medium-range positioning systems are on the threshold of commercial viability.

The key difficulty in implementing short to medium-range radiolocation is the complexity of radio propagation, particularly in an indoor environment. It is interesting from a historical perspective that the very first experimentation [4,5] with radio waves in the late 1880s by Heinrich Hertz was indoors at frequencies close to those of modern indoor radiolocation technology. In the time before electronics, Hertz performed a surprisingly comprehensive investigation into radio propagation, including the speed of propagation, polarization, reflections, diffraction and mutual interference between paths. From the details of the equipment (a tuned dipole of length 26 cm, with a parabolic reflector for extra gain), the inferred frequency used in the experiments was about 500 MHz. Using spark excitation and the natural resonance characteristics of the antenna, Hertz obtained line-of-sight (LOS) ranges up to 20 m within his laboratory by using a similar receiving antenna and observing small sparks. Hertz’s original observations remain valid today. In particular, Hertz observed that radio waves propagate at the same speed as light (30 cm per nanosecond) and are reflected by surfaces (particularly metallic), but will pass through other materials such as those in walls. Thus, the indoor environment is dominated by multipath propagation, and the path length is likely to be longer than the straight-line path assumed in position determination. A more thorough understanding of these propagation effects is of key importance in the design of positioning systems. This book provides an introduction to radio propagation and signal processing, with particular emphasis on theoretical and algorithmic aspects of position determination, and design of

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1 Heinrich Rudolf Hertz website: chem.ch.huji.ac.il/history/hertz.htm.
2 It need hardly be pointed out that hertz (abbreviated Hz) has now replaced ‘cycles per second’ as the standard term for frequency.
ground-based (non-GPS) radio positioning and tracking systems. In particular, it covers some key topics in the field which have not been discussed in other books. These include the time-of-arrival measurements in multipath environments, positioning performance analysis and accuracy limitations, positioning techniques for wireless sensor networks, identification of non-LOS (NLOS) radio propagation, NLOS mitigation techniques and practical issues in designing wireless positioning systems.

1.1 Introduction to Radio Positioning

Radio positioning can be broadly defined as a method of determining the geographic position of a radio device using the properties of radio waves. Various methods have been developed over the years, including the measurements of time-of-flight (TOF), signal phase, signal strength and angle of arrival. Traditionally, the architecture of positioning systems was based on the concept of ‘fixed’ nodes and ‘mobile’ nodes whose position is required. Even GPS with satellites can be considered in this category, as a satellite’s position at any time, even though moving relative to the Earth, is accurately known. For short to medium-range applications, a logical development would be to enhance the existing wireless local-area network (WLAN) technology to incorporate positioning capability. Many other technological solutions are also possible, but it appears that the general thrust will be towards position determination incorporated into small, cheap nodes which are organized as an ad hoc network. Such networks are not centrally organized, but using radio transmissions to neighboring nodes allows both data communications and position determination.

The main difficulty with developing short to medium-range positioning systems is related to the characteristics of radio propagation indoors and the requirement for accurate position determination. Because of the smaller scale of the indoor environment, most applications require an accuracy of 1–2 m or better; this is in contrast, for example, to the typical GPS accuracy of around 10 m. Indoor radio propagation is usually NLOS with multiple scattering of the signal from the transmitter to the receiver. This multipath propagation causes both additional loss of signal strength and additional propagation time above the straight-line path assumed for radio position determination. While in theory the solution could be a high-powered and wide-bandwidth system, limitations by regulatory authorities on the availability of suitable spectrum and transmitter power mean that other more complex solutions must be sorted.

Radio positioning can be based on many properties of radio waves, but most accurate systems have been based on determining the TOF, or the closely similar concept of the time-of-arrival (TOA). In principle, if the time of the start of a transmission and the time of reception are both known, then the TOF can be used to determine the range from the transmitting node to the receiving node. If two or more of these measurements are made using three or more nodes, then a two- (2D) or three-dimensional (3D) position can be calculated from basic geometry, assuming straight-line propagation. As radio waves propagate at about 0.3 m per nanosecond, and given the above-defined accuracy of an indoor positioning system of (say) 1–2 m, timing measurements must be made to the order of 1 ns. This precision of time measurement is very challenging, particularly when using small, cheap radios.

Although position determination based on TOF is straightforward in principle, there are implementation issues that make it impractical in most situations. First, the TOF method requires the clocks in all the nodes to be synchronized; this is particularly difficult in mobile nodes and requires special design features in fixed nodes. Second, the elapsed time from the
transmitter to the receiver includes delays in the radio equipment. Again, for fixed nodes, calibration procedures can be devised to determine these delays, but this is difficult in mobile nodes. Thus, many positioning systems, including GPS, use TOA data for position determination and do not require time synchronization in mobile nodes. In this case, the receiver effectively measures a pseudo-range, which is the true range (estimate) plus an unknown range offset. This principle also applies to other positioning methods. For example, if the round-trip time (RTT) delay is measured between two nodes, one fixed and one mobile, then the time delay in the mobile node radio (transmitter and receiver) should be considered as an unknown parameter. While these delays are approximately known, the requirement for sub-nanosecond accuracy in specifying these delays means that even very small variations in the equipment delays cannot be tolerated. In fact, equipment delays in short-range systems represent the vast majority of the measured round-trip delay, so variations as small as a few parts per thousand, which could be due to effects such as temperature fluctuations, cannot be tolerated. If received signal levels are used for range estimation, then uncertainties in the effective transmitted power again result in the measurement of pseudo-ranges. In this case, the uncertainty is due mainly to antenna effects when the transmitter is close to an object, such as the ground or a body.

Because of the common occurrence in positioning systems of measuring pseudo-ranges rather than ranges, techniques for determining positions based on pseudo-range measurements at a number of fixed nodes is of prime interest. In the 2D case, the position determination has a simple geometric interpretation. If two pseudo-range measurements at two fixed nodes are subtracted, the common offset is eliminated, so that the locus of points with the differential TOA (DTOA) constant is a hyperbola. Similarly, with another pair of fixed nodes the DTOA defines another hyperbola, and the position of the mobile node is at the intersection of these hyperbolas. For this reason, positioning systems based on pseudo-range measurements are sometimes called ‘hyperbolic navigation’ systems. The analysis of position determination based on the intersection of hyperbolas is given in Appendix A, together with a summary of important characteristics of hyperbolas. However, this method is mainly of historic interest only, as more sophisticated methods are used in actual systems, as described in later chapters in this book.

While classical positioning systems are based on fixed and mobile nodes, many of the developments in short to medium-range systems are associated with ad hoc networks where all the nodes are essentially the same. In such systems, nodes exchange radio messages with data and timing information. If a node can communicate with sufficient neighboring nodes, thus sharing information, the relative positions of all the nodes can be determined. Further, if a few of these nodes have absolute positional data by some independent surveying process, then the positions of all the nodes can be determined in absolute coordinates. In some simple networks, such as wireless sensor networks (WSNs), only rather crude positional information may be required. In such cases, simple positioning strategies can be adopted. For example, the simplest methods are based on estimating position using knowledge of the surrounding neighbors’ positions, and (say) defining the position at the centroid of the neighboring nodes; the known positions of neighbors may be from ‘anchor’ nodes with accurate positional data, or from other nodes which have previously determined their positions. More accurate positions can be obtained if the signal strength data, available in even the simplest of radio receivers, are used to estimate range. For more sophisticated ad hoc networks, TOA data can be used in a manner akin to the hyperbolic method with fixed receiving nodes, thus allowing more accurate position fixes.

The above brief introduction to radiolocation can only touch on the various aspects and methods used in positioning systems. Because there are a wide variety of applications and
requirements, no one method is applicable; thus, this book attempts to cover a wide range of the major techniques. These are outlined in Section 1.3 as a guide to using this book. However, before summarizing the chapters in this book, it is useful to review the types of short to medium-range radiolocation technologies that have been used in the past and the possible future developments.

1.2 Short and Medium-range Radiolocation Technologies

While much of the theory and analysis in this book can be applied generally to all radio positioning systems, the main focus is on ground-based short (say less than 100 m) to medium-range (say up to 2000 m) systems, and more particularly indoor positioning systems. Within this definition there are many existing radio systems which currently are mainly used for data transmission, but these systems could also be used for position determination. When considering short to medium-range positioning, there is no one technology which suits all applications and situations, so it is useful to review the weaknesses and strengths of various technologies. From a technical performance point of view there are two main characteristics of practical interest, namely the positioning accuracy and the range of the radio link. However, for practical implementation, other factors are also of major importance, including the cost and size of the mobile units, the associated costs of the fixed components, such as base stations, and infrastructure costs for cabling and installation. As one might expect, there is no one technology that has all the desirable characteristics; a long-range, accurate positioning system is likely to require sophisticated and expensive hardware. Nevertheless, the processing power of the integrated circuits for both the analog radio and the digital signal-processing parts are increasing over time, while their cost is decreasing simultaneously. Thus, while an ideal indoor system may not be available at the time of writing (2009), one can define the characteristics of such a system and provide some performance estimates. However, developments in the technology are constrained by fundamental physics and other constraints, such as the availability of radio spectrum, so the performance of a positioning system is bounded, and these bounds will not change over time. Thus, while this book is not aimed at any one particular technology and implementation, the overall thrust is aimed at next-generation short to medium-range positioning systems which are comparatively cheap and which have good positioning accuracy and range.

The starting point in defining potential future systems is current technology. The following list is not comprehensive, but represents the range of possible positioning technologies.

1. WLANs  WLAN technology currently is based almost exclusively on the IEEE 802.11 specification, which defines a number of different physical layers for data transmission operating in the 2.4 GHz industrial, scientific and medical (ISM) band and at 5.2 GHz.

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3 http://standards.ieee.org/getieee802/802.11.html
4 The ISM bands are unlicensed, but all users must share the band. The potential of mutual interference limits the radio transmissions to spread-spectrum types (frequency hopping or direct sequence) which have an ability to resist the effects of interference.
5 The 802.11a WLAN operates in a specially allocated band at 5.2 GHz, but is restricted to indoor data transmission applications. The 5.8 GHz ISM band is not currently used for 802.11 WLAN systems, so this band would be an ideal candidate for a positioning system.
Position determination is not part of the standard hardware; but, as the transmissions are based on spread-spectrum modulation with bandwidths of 1–20 MHz, depending on the specific version of 802.11, positioning capability could be added. The simplest implementation currently is based on signal strength measurements, but techniques using TOA could also be implemented. The range of current WLANs is typically limited to about 50 m indoors, and a similar range could be expected for a positioning application. While the cost of the hardware, particularly the mobile unit, is modest, the system is based on fixed base stations installed in a building, with typically connections to a wired local-area network (LAN). For a positioning system, many more base stations would be required, thus leading to higher infrastructure cost.

2. **Ultra-wideband (UWB)**

UWB technology is a response to the limitation in available spectrum, which in turn limits the data transmission rates and the accuracy of positioning systems. UWB uses very wide bandwidths (at least 550 MHz), but is limited to a very low transmitter power density (watts per hertz) to minimize the interference to other existing radio systems which use part of the same frequency band (3–10.7 GHz) [6]. UWB technology is mainly aimed at short-range, high data-rates links. However, the large bandwidths are ideal for indoor positioning systems, as the large bandwidths mitigate the effects of multipath propagation by allowing very fine (sub-nanosecond) time resolution. The indoor positioning accuracy for UWB is of the order of 20 cm, but typically the range is limited to about 10 m. As a consequence, the number of base stations required to cover an area will be large, so the wired infrastructure costs would be high, at least for the first-generation systems. However, the hardware costs in future-generation UWB systems will be lower, but the short range and high base station spatial density means that other, cheaper technologies are likely to be used in preference unless the superior positioning accuracy is required.

3. **Field strength systems**

The simplest method of estimation radio propagation range is by signal strength measurements. Such methods have been implemented using WLAN hardware [7] and more recently in WSNs and ad hoc networks. While signal strength measurements are available in even the simplest of single-chip radios, the accuracy of such measurements is limited, partly due to the simple implementation of the radio, but more importantly due to effects such as interaction with the human body when worn by a person and indoor propagation effects. For indoor applications the signal strength varies in a complex fashion, so there is no simple function between loss and range. One method to improve the accuracy is by generating a radio-loss map of the building, which allows a database-matching algorithm to improve the accuracy of the position fix. However, even with these techniques, and particularly when using cheap body-worn mobile units, the positioning accuracy is likely to be of the order of 5 m. Thus, signal strength methods are likely to be limited to applications where only crude positional accuracy (such as in WSN applications) is sufficient.

4. **Radio frequency identification (RFID)**

RFID is a simple radio technology mainly aimed at providing identification of objects based on a unique multidigit identifier, usually associated with inventory management. RFID tags are small and very cheap, but their range is limited to about 1 m. Normally, a special tag reader, often hand held, is used to identify the tag. Such technology is not particularly aimed at position determination, but a simple adaptation would allow its use for position determination to a limited extent. For example, tag readers at key locations, such as doorways, can be used to identify people moving through a building.
While the tags are cheap, the infrastructure costs would be high if a large number of readers are employed to provide a good positioning coverage. For example, in an office building, one reader located at the entrance of each office may be necessary. In such a case the positioning accuracy would be typically a few meters (the size of a room), but the infrastructure costs to interconnect the readers would be high.

5. **Next-generation indoor positioning system** To provide some idea of the next generation of indoor positioning systems, a general specification can be devised, in part based on the strengths and weaknesses of the existing technology solutions summarized above. Thus, the system radio should have a typical indoor link ranges of at least 30 m, and a ranging accuracy of 1–2 m. Ideally, the positioning system should be ‘piggybacked’ onto an existing data system and the analog radio should be based on a single chip. To minimize infrastructure costs, the system architecture should be based on the ad hoc concept, whereby nodes communicate with their neighbors for position determination, and there is no central organization of the network. In such a system there is no distinction between base stations and mobile units. To minimize infrastructure costs, wired communications should be limited to a few interconnections to a wired LAN. Ideally, the hardware is battery powered with a long battery life.

To further investigate the relationships between these various radio technologies, Figures 1.1–1.3 show the ‘operational region’ of each technology plotted in three different domains. Note that these diagrams represent the various technologies when employed for radio positioning, which typically is not their main use currently. Note also that these diagrams are indicative of the technologies rather than being an accurate representation.

![Figure 1.1](image-url) **Figure 1.1** Representation of the range and positioning accuracy of various indoor radiolocation technologies. The ideal future technology (F) will provide a good compromise between range and accuracy.
Figure 1.1 is a plot of the positioning accuracy versus the link range. To some extent, existing technologies either have good positioning accuracy or long link ranges, but not both. Thus, these technologies would tend to be limited either to applications where good positioning accuracy is required over a relatively small area, or alternatively a large coverage area is required but with lower positioning accuracy. The suggested area of operation of the

Figure 1.2 Representation of the range and system costs of various indoor radiolocation technologies. The ideal future technology (F) promises to provide the lowest system costs, with significant improvements over time.

Figure 1.3 Representation of the cost of a tag and infrastructure costs of various indoor radiolocation technologies. The arrows show the expected trend over time.
next-generation location systems has similar or better range than current WLAN systems and an accuracy intermediate between those of UWB and WLAN systems. Thus, from an operational point of view, the next-generation positioning system should cover a wider range of applications.

Figure 1.2 shows a plot of system cost versus the positioning accuracy. The system cost is defined as the cost of the ‘fixed’ components (base stations) and any central network controller, but not the cost associated with the deployment. The system cost is based on installing nodes in a building to cover an area of 2000 m² to an accuracy broadly defined in Figure 1.1. Current system costs tend to be too high to provide economical coverage in large buildings. Unlike coverage for data systems, for correct operation the mobile unit must communicate simultaneously with typically four or more base stations (or neighboring nodes in an ad hoc network), so the spatial density needs would be much greater, typically 3–10 times of the data system. As a consequence, the system costs are much higher for a location system than a comparable wireless data system covering the same area. The short range of UWB (particularly first-generation systems) makes it expensive to cover a large area. For WLAN-type systems, particularly those based on field strength measurements, the cost is significantly less than UWB systems, but systems costs would still be too high to cover large areas economically. RFID technology can be cheap, but the costs are critically dependent on the required density and cost of tag readers. The suggested next-generation system costs should be quite low due to the ‘fixed’ and mobile units being essentially the same, and costing no more than $100. The arrow in Figure 1.2 shows the suggested trend over time, with costs decreasing significantly, and improved hardware and signal processing increasing the operational range. Thus, next-generation systems have the potential of covering large areas economically, resulting from a combination of lower unit cost and comparatively long operational range. Note that as the number of units required to cover a given area is proportional to the square of the link range, so link range has a big impact on system costs.

Figure 1.3 shows another representation of the performance of the various systems, this time the tag costs versus the infrastructure costs. In this context the infrastructure costs are defined as the cost of installing the ‘fixed’ nodes (base stations). As infrastructure costs are largely associated with the cost of labor, which is expected to rise over time, there is no benefit in infrastructure costs from the reducing costs of hardware, as is appropriate with the tags, whose cost is expected to fall rapidly over time. The number of tags required for a particular application would vary widely, so it is not possible to provide estimates of the total costs (total tags plus system plus infrastructure). However, for large systems with a large number of tags, overall costs would probably fall over time.

When comparing the various technologies in Figure 1.3 it is clear that technologies based on cheap tags operating in an ad hoc network are by far the most economical, as the infrastructure costs are low or nonexistent as there are only a few fixed base stations. Indeed, an ad hoc positioning system is possible with only two fixed nodes, so that position determination is largely based on communications between mobile nodes. Such a design can cover large areas at minimal costs. On this basis, the suggested next-generation system is clearly superior to the other technologies.

Thus, in summary, from Figures 1.1–1.3 it can be observed that next-generation indoor positioning systems promise good accuracy (1–2 m) and the ability to cover large areas at low cost. Given these parameters, such systems should find many applications in the future.
1.3 Overview of the Book

The book covers a wide range of topics associated with position determination in short to medium-range systems, with particular emphasis on indoor positioning using networks of simple nodes. Because of the diversity of topics, it is not expected that the reader would progress serially through the book, but would access areas of particular interest. Each chapter is written such that it can be read in a standalone fashion, although the material in a general area of interest may involve more than one chapter. The book is broadly divided into two groups of chapters, with Chapters 2–5 providing an overview of radio propagation, signal processing (particularly relating to spread-spectrum signals) and systems’ aspects of positioning systems. Chapters 6–13 are focused on methods of position determination, with mathematical development, details of specific algorithms and performance charts. These chapters are loosely grouped into sub-topics, according to positioning accuracy and type of positioning system architecture. Finally, Chapter 14 provides methods of identifying LOS and NLOS propagation, mainly based on statistical analysis of the received radio signal.

Thus, to provide some guidance to using the book, the following subsections provide a brief summary of the content of each chapter.

1.3.1 Radio Propagation (Chapter 2)

The performance of any radiolocation system is ultimately based on the propagation characteristics of radio waves. Radio propagation for outdoor large-scale systems is close to free space, so that the performance of such systems is relatively easy to determine. However, radio propagation associated with short-range systems in an urban environment, particularly indoors, is very complex and places challenges on the design of positioning systems. Chapter 2 provides an overview of indoor radio propagation, with particular emphasis on loss and delay excess relative to free-space propagation. The material is presented without deep mathematical analysis, but rather in the form of charts based on measured data. The information provided allows the radio propagation performance to be estimated for indoor situations, based on the properties of materials in the building and the architectural layout. In addition, Appendix B provides an overview of measurement techniques for determining the radio propagation characteristics in a multipath environment.

1.3.2 Signal Detection by Correlation (Chapter 3)

The most common method of radio positioning is based on the measurement of the TOA of the radio signals. However, because of the requirements for multiple access to the radio channel, radio pulse methods are restricted to very low powered UWB short-range systems, so that most common technology is based on spread-spectrum signal modulation. The key to this method is the pseudo-random modulating signal, which spreads the radio energy in a manner akin to the truly random noise in nature. The detection of such a signal requires the received signal to be correlated with a copy of the code used for modulating the transmitted signal. Thus, the properties of this correlation process are vitally important in determining the performance of spread-spectrum-based positioning systems. Chapter 3 analyses the relevant characteristics of the correlation process in relation to direct-sequence spread-spectrum signals, including the effective generation of a narrow time-domain pulse (signal despreading) used for TOA
estimation, multiple access properties, resistance to interference and the multipath mitigation properties. The topic of spread-spectrum is described in a vast amount of literature [8,9], so the specific topics discussed in this book are limited to the important practical areas of correlators, accumulators, interference performance and the concept of process gain.

1.3.3 Bandlimited Time-of-Arrival Estimation (Chapter 4)

The key technique used in positioning systems is based on the estimation of the TOA of a radio signal at a receiver. Because of the spectral limitations by regulatory authorities on radio transmissions and the need for wide bandwidths for ranging accuracy in a multipath environment, the most accurate positioning systems are based on direct-sequence spread-spectrum signals. Chapter 4 provides algorithms for estimating the TOA from these bandlimited signals and estimates their performance in the presence of both Gaussian noise and multipath signals. Simple analytical formulae are developed to allow designers to estimate the accuracy of TOA measurements.

1.3.4 Fundamentals of Positioning Systems (Chapter 5)

Chapter 5 provides an overview of the most important aspects of radio positioning, particularly in an indoor environment. The chapter briefly describes the effects of radio propagation on the performance (propagation range and TOA measurement accuracy) of a radio positioning system. Two broad types of positioning system are described: navigation systems and, the focus of this book, tracking systems. An introduction to important design aspects is described, including such topics as time synchronization of nodes and how the internal delays in the radio equipment are measured or compensated for by the design of the system. The chapter also briefly reviews the various methods of position determination, including TOA methods, TOF methods, received signal strength (RSS) methods, and hybrid radio/ultrasonics systems.

1.3.5 Position Determination

Chapters 6 and 7 describe methods of position determination based on using TOA, angle-of-arrival (AOA) or signal strength measurements. However, the main emphasis is on the processing of TOA data, as these provide the most accurate position determination. As these measurements are the arrival time at the receiver rather than the TOF, the effective measurement data are pseudo-ranges (range plus an unknown offset), rather than ranges. The algorithms in these chapters are based on processing pseudo-range data in a classical system architecture with fixed base stations used to determine the location of a mobile node.

1.3.5.1 Noniterative Position Determination (Chapter 6)

Chapter 6 focuses on noniterative position determination methods, where the raw measured data are processed using analytical formulae to provide the position of a mobile node directly. The particular algorithms comprehensive analyzed are spherical interpolation (SI), quasi-least-squares (QLS), and linear correction least-squares (LC-LS). From simulations with various
arrangements of base stations, and ranging errors based on models introduced in Chapters 2 and 5, it is shown that there is no one ideal algorithm. While these methods directly produce a position fix, the analytical equations can be computationally intensive and, thus, may not be suitable for simple network nodes with limited computational capability.

1.3.5.2 Iterative Position Determination (Chapter 7)

Chapter 7 provides numerical computational alternatives to the analytical methods of Chapter 6. In particular, iterative methods are used to solve the nonlinear equations which describe the position determination problem. The algorithms described include the Taylor series least-squares (TS-LS) method, the iterative optimization method and the maximum likelihood (ML) method. Iterative methods based on filtering the data (particularly the use of Kalman filters) are also discussed. These iterative methods require an initial ‘guess’ of the position, and in some circumstances, particularly when large measurement errors are present, the algorithm may not converge. However, in applications where continuous periodic updates are required, the previous position can be used as the initial position, which usually results in rapid convergence and position determination with less computation than the noniterative methods.

1.3.6 Positioning Accuracy

Perhaps the most important performance aspect of a positioning system is the accuracy of the position determination. The positioning accuracy has two broad aspects, namely geometric factors relating the position of the fixed and mobile nodes and the statistical performance due to random measurement errors. Chapters 8 and 9 describe various statistical metrics for determining the accuracy of a positioning system.

1.3.6.1 Positioning Accuracy Evaluation (Chapter 8)

Chapter 8 introduces various accuracy metrics, including Cramer–Rao lower bound (CRLB), geometric dilution of precision (GDOP), root-mean-squared error (RMSE) and cumulative distribution probability (CDP) of the location errors. The CRLB method is then used for the analysis of LOS and NLOS scenarios and the performance of the least-squares (LS) estimator; the iterative optimization-based location algorithm is evaluated against the CRLB. Also, the impact of the anchor location errors (see also Chapters 11 and 12) is investigated. The results of these methods are illustrated through simulations.

1.3.6.2 Geometric Dilution of Precision Analysis (Chapter 9)

One important aspect that affects positioning accuracy is the relative geometric relationship of the fixed nodes to the mobile node whose location is to be determined. The most common method of describing these geometric effects is GDOP, which is the ratio of the statistical position error to the standard deviation (STD) of the measurement error. Chapter 9 provides the statistical background to GDOP and provides relatively simple analytical formulae for its calculation for geometries typical of short-/medium-range positioning systems. The chapter also describes the limitations in the use of GDOP in short-range systems, where the measurement errors are a substantial fraction of the propagation range.
1.3.7 Multipath Mitigation (Chapter 10)

For radio positioning systems, particularly those operating indoors, the main degradation in performance is due to multipath propagation of the radio waves. Because of the scattering of the signal, the TOA and other measurements are corrupted, resulting in positioning errors. Chapter 10 considers various methods of mitigating these effects, including the residual weighting of the data, constrained optimization, Kalman filtering, smoothing data to exclude ‘bad’ measurements, error statistics to perform ML estimation under a number of scenarios and database-based pattern-matching position determination methods. The various methods are demonstrated through simulations, with graphical representation allowing comparison between the techniques.

1.3.8 Anchor-based Localization

Unlike classical positioning systems, which have ‘fixed’ (base stations) and ‘mobile’ nodes, ad hoc and wireless sensor networks have nodes with similar characteristics. By transmitting and then receiving messages from its immediate neighbors, each node can determine its relative position within the network. However, if at least two of the nodes have known absolute positions (for example, from an independent survey), then all the nodes with relative positions can also determine their absolute positions. The nodes whose absolute positions are known thus play an important part in any positioning scheme in ad hoc networks; such nodes are referred to as ‘anchor’ nodes. Chapters 11 and 12 investigate the characteristics of such ad hoc networks which include a few anchor nodes.

1.3.8.1 Anchor-based Localization for Wireless Sensor Networks (Chapter 11)

Chapter 11 describes position determination techniques in ad hoc networks with simple nodes, such as WSNs. The general characteristics of WSNs are first described and then some basic position determination methods are discussed, which at the simplest only require the identity of nearby anchor nodes. Other techniques are also described, including multihop localization algorithms and TOA-based localization. A number of practical parameters are also briefly considered, including the clock frequency offsets, internal delays in the equipment and clock time offsets.

1.3.8.2 Anchor Position Accuracy Enhancement (Chapter 12)

The localization accuracy in a WSN depends not only on the accuracy of ranging measurements, but also on the positioning accuracy of the anchors. While independent surveying of anchor nodes is possible, ideally the WSN infrastructure itself should perform the surveying of the anchor points. Chapter 12 considers various possible methods of determining anchor node absolute positions, including low-cost GPS receivers and wideband and UWB ranging. However, the main focus of this chapter is on more accurate anchor-to-anchor parameter estimates to enhance the anchor location accuracy. This accurate anchor location information is also helpful in localizing ordinary sensor nodes. The particular topics discussed include modeling LOS and NLOS propagation, accuracy improvement algorithms based on both distance and AOA measurements and CRLB as a performance benchmark. The techniques are illustrated through simulations.
1.3.9 Anchor-Free Localization (Chapter 13)

In Chapter 11, node localization was studied for scenarios where some nodes are anchors whose absolute positions are known a priori. In some circumstances there are no anchor nodes in the network, so that no absolute location information is available at any node. For such anchor-free networks the key issue of localization is how to determine the relative positions of the nodes accurately and to determine the graph of the node configuration accurately. Chapter 13 considers techniques for determining relative positions based on exchange of radio transmissions with neighboring nodes. Both single-hop and multihop techniques are considered, as well as localization accuracy measures, including the CRLB and the approximate distance error lower bound.

1.3.10 Non-Line-of-Sight Identification (Chapter 14)

In radio positioning, one of the dominant factors that affects the positioning accuracy is the NLOS radio propagation which happens when the direct, straight radio path between the transmitter and receiver is blocked. Compared with the LOS condition, the signal travels an extra distance and time under the NLOS condition. The NLOS propagation also results in an extra power loss and an AOA bias. To achieve improved location estimation accuracy, it is desirable to determine whether the measurements come from LOS propagation or NLOS propagation. The methods investigated in Chapter 14 include identification based on calculating the error variance through data smoothing, a number of well-known statistical distribution tests, level crossing rate and fade duration of the received signal envelope, nonparametric methods, a joint TOA and RSS-based method and AOA-based methods.

References