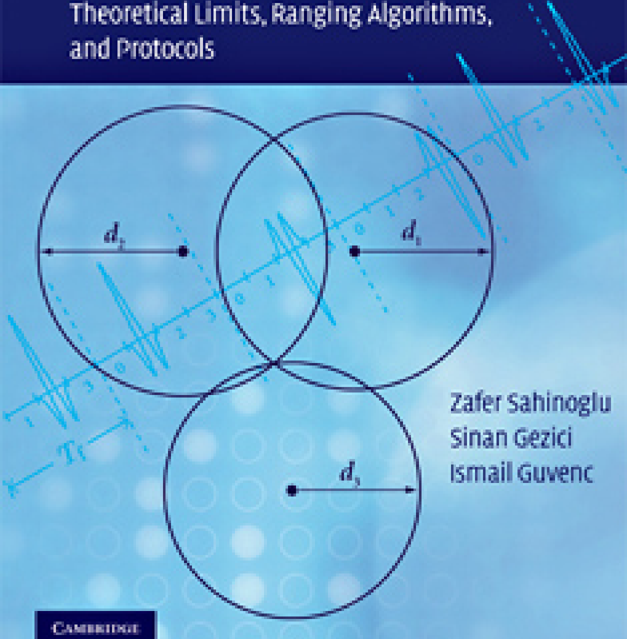
Ultra-wideband Positioning Systems

Theoretical Limits, Ranging Algorithms, and Protocols



Zafer Sahinoglu
Sinan Gezici
Ismail Guvenc

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Accurate determination of the location of wireless devices forms the basis of many new and interesting applications. Ultra-wideband (UWB) signals enable such positioning, especially in short-range wireless networks. This text provides a detailed account of UWB positioning systems, offering comprehensive treatment of signal and receiver design, time of arrival estimation techniques, theoretical performance bounds, ranging algorithms, and protocols. Beginning with a discussion of the potential applications of wireless positioning, and investigating UWB signals for such applications, later chapters go on to establish a signal processing framework for analyzing UWB ranging and positioning systems. The recent IEEE 802.15.4a standard related to UWB is also studied in detail. Each chapter contains examples, problems, and MATLAB® exercises to help readers grasp key concepts. This is an ideal text for graduate students and researchers in electrical and computer engineering, and for practitioners in the communications industry, particularly those in wireless communications. Further resources are available at www.cambridge.org/9780521873093.

ZAFER ŞAHİNOĞLU is currently working at the Mitsubishi Electric Research Laboratories as a Principal Technical Member, and is a Senior Member of the IEEE. He received his Ph.D. in Electrical Engineering from the New Jersey Institute of Technology in 2001, receiving their Hashimoto Prize the following year.

SİNAN GEZİCİ is an Assistant Professor in the Department of Electrical and Electronics Engineering at Bilkent University, Ankara, Turkey. He received his Ph.D. in Electrical Engineering from Princeton University in 2006, and is also a member of the IEEE.

İSMAİL GÜVENÇ is a Research Engineer at DoCoMo USA Communications Laboratories, Palo Alto, CA, and is a member of the IEEE. He received his Ph.D. in Electrical Engineering from the University of South Florida in 2006, receiving their Outstanding Dissertation Award in the following year.

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Dedicated to
my parents, Hakki and Saziye Sahinoglu, my brother Fatih and my sister Filiz, whose support I have always had from thousands of miles away.

Zafer Sahinoglu

Dedicated to
my parents, Ergül and Muammer Gezici, my sister Sevinc, my brother-in-law M. Bekir and my dear niece Sila.

Sinan Gezici

Dedicated to
my wife Zeynep, my daughter Beyza and my parents, Mehmet and Hatice Guvenc, and my brother Oguz.

Ismail Guvenc

Contents

Preface

Ability to locate assets and people will be driving not only emerging location-based services, but also mobile advertising, and safety and security applications. Cellular subscribers are increasingly using their handsets already as mapping and navigation tools. Location-aware vehicle-to-vehicle communication networks are being researched widely to increase traffic safety and efficiency. Asset management in warehouses, and equipment and personnel localization/tracking in hospitals are among other location-based applications that address vast markets. It is a fact that application space for localization technologies is very diverse, and performance requirements of such applications vary to a great extent.

The Global Positioning System (GPS) requires communication with at least four GPS satellites, and offers location accuracy of several meters. It is used mainly for outdoor location-based applications, because its accuracy can degrade significantly in indoor scenarios. Wireless local area network (WLAN) technology has recently become a candidate technology for indoor localization, but the location accuracy it offers is poor, and also high power consumption of WLAN terminals is an issue for power-sensitive mobile applications. Ultra-wideband technologies (UWB) promise to overcome power consumption and accuracy limitations of both GPS and WLAN, and are more suitable for indoor location-based applications.

The Federal Communications Commission (FCC) and European Commission (EC) regulate certain frequency bands for UWB systems. These have prompted worldwide research and development efforts on UWB. Another consequence was development of international wireless communication standards that adopt UWB technology such as IEEE 802.15.4a WPAN and IEEE 802.15.3c WPAN.

The writing of this book was prompted by the fact that UWB is the most promising technology for indoor localization and tracking. As of today there is no book with particular focus on theoretical and practical evaluation of the capabilities of various UWB localization systems. The book is written for graduate-level students and practicing engineers. Prior knowledge in probability, linear algebra, digital signal processing, and signal detection and estimation is assumed.

The scope of the book is not limited to time-based UWB ranging systems, because in addition to signal design and time of arrival estimation, most location systems should adopt a ranging protocol and perform certain position estimation and tracking techniques. For completeness of the course, in depth coverage from signal design to position solving and tracking techniques is given. Each chapter includes examples and problems to accelerate readers' understanding. Programming exercises allow readers to simulate various techniques in UWB systems and help them see impacts of various design parameters.

Although the main focus of all chapters is on UWB systems, Chapters 1, 4, and 9 are not limited to UWB. Current trends for location-aware applications and taxonomy of localization systems are given in the first chapter. Position estimation and tracking techniques, which are applicable to any location system, are discussed in Chapter 4. Recent developments and future research directions form the main topic of Chapter 9.

UWB-specific treatment starts with Chapter 2, in which various UWB signal waveforms are studied, international regulations for UWB signal emissions are presented, and various UWB standards are discussed. UWB channel models arising from channel measurements conducted for 2–10 GHz, below 1 GHz and 57–66 GHz frequency band regions are overviewed in Chapter 3. Also, differences between narrowband and UWB channels are highlighted in this chapter. Treatment of time based ranging via UWB radios is given in Chapter 5. Its content includes discussion of potential error sources and quantification of fundamental performance limits via Cramer–Rao and Ziv–Zakai lower bounds. Chapter 6 is devoted to the discussion of various ranging protocols, and their pros and cons. The ranging aspect of the recently published IEEE 802.15.4a UWB WPAN standard is studied in detail, including preamble and start of frame delimiter design, timing counter management, and clock frequency offset mitigation. Narrowband and multiuser interference mitigation techniques, ranging privacy mechanisms and the state-of-the-art coded payload modulation technique are the special topics covered in Chapter 7. Practical considerations for UWB system design are given in Chapter 8, including signal design under practical constraints, link budget analysis, and specific hardware issues.

Solutions for the problems at the end of each chapter and Matlab simulation scripts can be found by visiting the website for this book, which is currently at www.cambridge.org/9780521873093. The most up-to-date errata sheet and references to additional material can also be found at the same site.

We would like to thank experts in the field, who have reviewed and commented on the draft of the manuscript. Their inputs greatly helped us improve the presentation. Special thanks to Andreas F. Molisch from Mitsubishi Electric Research Labs for his suggestions about the channel modeling chapter, Davide Dardari from University of Bologna for his thorough review of Chapter 5, Henk A. Wymeersch from Massachusetts Institute of Technology and Qin Wang from Harvard University for their inputs in general and for helping organize Chapter 6 in particular, Yihong Qi from AMD for her inputs on Chapters 4 and 7, Rainer Hach from Nanotron Inc. for his review of Chapter 6, Chia Chin Chong from NTT DoCoMo Labs and Fikret Altinkilic from Syracuse University for their suggestions on Chapter 3, Philip Orlik from Mitsubishi Electric Research Labs for reviewing and providing suggestions and comments on Chapters 2 and 4, and furthermore Fujio Watanabe from NTT DoCoMo Labs, Huseyin Arslan from University of South Florida and Volkan Efe from Motorola for providing comments on various chapters.

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1 Introduction

Wireless communications are becoming an integral part of our daily lives. Satellite communications, cellular networks, wireless local area networks (WLANs), and wireless sensor networks (WSNs) are only a few of the wireless technologies that we use every day. They make our daily lives easier by keeping us connected anywhere, anytime.

Since more and more devices are going wireless every day, it is essential that future wireless technologies can coexist with each other. Ultra-wideband (UWB) is a promising solution to this problem which became popular after the Federal Communications Commission (FCC) in the USA allowed the unlicensed use of UWB devices in February 2002 subject to emission constraints. Due to its unlicensed operation and low-power transmission, UWB can coexist with other wireless devices, and its low-cost, low-power transceiver circuitry makes it a good candidate for short- to medium-range wireless systems such as WSNs and wireless personal area networks (WPANs).

One of the most promising aspects of UWB radios are their potential for high-precision localization. Due to their large bandwidths, UWB receivers can resolve individual multipath components (MPCs); therefore, they are capable of accurately estimating the arrival time of the first signal path. This implies that the distance between a wireless transmitter and a receiver can be accurately determined, yielding high localization accuracy.

Such unique aspects of UWB make it an attractive technology for diverse communications, ranging, and radar applications such as robotics, emergency support, intelligent ambient sensing, health-care, asset tracking, and medical imaging (see Fig. 1.1). Potential of UWB technology for future wireless communication networks was also recognized by the IEEE, which adopted UWB in the IEEE 802.15.4a WPAN standard for the creation of a physical layer for short-range and low data rate communications and for precise localization.

Various aspects of UWB ranging and localization systems are discussed in the subsequent chapters. In this chapter, first, general trends in location-aware applications are reviewed. Then, a taxonomy of localization systems is presented. This is followed by a discussion on UWB localization applications and available UWB localization technologies.

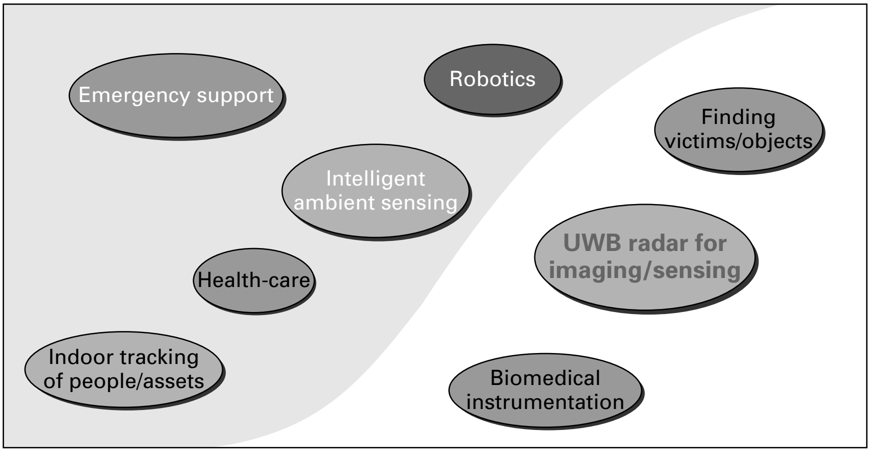

Fig. 1.1. Diverse business opportunities for UWB communications, ranging, and radar.

1.1 Trends in location-aware applications

1.1.1 Location-based applications and services

As wireless devices are becoming more and more integrated into our daily lives, they are also getting more and more intelligent. In other words, today's wireless devices are becoming more context aware. In [1], *context awareness* (or *context sensitivity*) is defined as the ability of the mobile device to be aware of the user's surrounding physical environment and state. Another related definition in [2] states that a system is *context aware* if it uses contexts[1] to provide relevant information and services to the user, where relevancy depends on the user's tasks. These services may be based on the context information such as time, location, temperature, speed, orientation, biometrics, audio/video recordings, etc.

Between these different variables that define a context, location and time are probably the two most important inputs that define a specific situation [3], and *location awareness* can be considered as a special and important form of context awareness. Localization serves as an enabling technology that makes numerous context-aware services and applications possible.

A location-aware wireless device may use the location information in different ways for different technologies. For example in cellular networks, location information can be used for Emergency-911 (E-911) services, location-sensitive billing, fraud detection, resource management, and intelligent transportation systems [4]. Location of the doctors/patients in hospitals, injured skiers on mountains, or fire-fighters and victims inside a building are a few examples on how location information can be used to save lives in emergency situations. While knowing your position will be handy to find the closest

[1] Context is defined as any information that can be used to characterize the situation of an entity [2].

printer in a wireless local area network, it may as well be used to locate your friend in a university campus. In warehouses, laboratories, and hospitals, location of portable and in-demand equipment may be needed [5]. A customer may receive location-based advertisements in a shopping mall, or personal digital assistants with location support can be used for guided tours in museums. Smart homes/offices/highways that exploit the location information are a few other examples of how our daily lives can be made easier [6].

The services provided to the user based on location information are commonly referred as location-based services (LBS). Some definitions of the LBS available in the literature are as follows [3].

- *"Network-based services that integrate a derived estimate of a mobile device's location or position with other information so as to provide added value to the user."*
- *"Recent concept that denotes applications integrating geographic location (i.e. spatial coordinates) with the notion of service. Examples of such applications include emergency services, car navigation systems, tourist tour planning, or yellow maps (combining of yellow pages and maps) information delivery."*
- *"Will allow mobile users to receive personalized and lifestyle-oriented services relative to their geographic location."*
- *"Most location-based services will include two major actions: (1) Obtaining the location of a user, and (2) Utilizing this information to provide a service."*

The classification and characteristics of different LBS are presented in [3], and summarized in Table 1.1, which also includes the business models ("C:" Customer, "B:" Business, "G": Government, "W": Workforce), location update specifications (Pull: Information is provided after a request by the mobile, Push: Network delivers the information to the mobile based on an event or trigger condition), and typical accuracy requirements.

The LBS are traditionally considered for cellular networks. This may be correlated with the fact that cellular technology has long been an integral part of our daily lives and has a wide consumer acceptance. Hence, killer applications are relatively obvious.

On the other hand, technologies such as WLANs and WSNs have only recently become widely deployed. As they become more integrated to daily practices, the killer applications for these technologies will become more obvious. As a matter of fact, we have already started seeing new LBS using these technologies. For example, LOKI software [7], developed by Skyhook Wireless Inc., uses the WiFi network to pinpoint a mobile user's location and provide services such as finding the closest restaurant to the user's location. Applications such as guided tours in museums, location-based advertisements, people/inventory tracking, etc. are possible through similar technologies. While such LBS are not widely deployed today, they are expected to become more common with the advances in different relevant technologies, wide consumer acceptance, and decreases in device costs.

The accuracy and precision requirements of location-based applications are highly dependent on the application characteristics. Accuracies on the order of tens of meters

Table 1.1. Classification and characteristics of location-aware applications and location-based services (After [3]).

Category	Description	Examples	Business Model	Pull versus Push	Accuracy
Location-based information services	User requests information related to its location	Local weather forecast, navigation, local maps, local bus schedules	C2B	Pull	< 1 km
Points of interest	The mobile user looks up stationary objects or facilities in the near area	Restaurant, hotel, etc. finder services, service look-up (e.g. printers)	C2B	Pull	< 1 km
Discovering other users	The mobile user looks up other users in the nearby area	Games, friend-finder, flirt-finder	C2C	Pull	< 200 m
Tracking services	A (likely stationary) user looks up the location of a mobile person or object	Fleet management, tracking children, patients, doctors, tracking assets	C2C, B2B, B2W	Tracking entity pulls	< 200 m
Assistance services	A service center receives the location of a mobile caller who needs assistance	Emergency calls, breakdown services	C2G, C2B	Push	< 20 m
Messaging and announcement services	Mobile users receive a message from another user broadcast to a certain area	Local advertisements, messages to nearby friends	C2C, B2C	Push	< 1km
Trigger services	A mobile user receives a trigger when entering a certain location	Location-based reminders, traffic warnings, weather warnings	C2C, C2B, B2C	Push	< 500 m
Location-based billing	A user is charged according to his/her location	Toll billing, home zones	B2C, B2B	Push towards billing side	< 500 m

Table 1.2. Accuracy requirements of potential localization applications (After [8]).

Applications	Accuracy
Automated handling	0.5 cm
Route-guidance for blind	1 cm
In-building survey	1 cm
Tool positioning	1 cm
In-building robot guidance	8 cm
Formation flying	10 cm
Recreation and toys	10 cm
Urban canyon (off-road)	30 cm
Urban canyon (marine)	50 cm
Incidence tracking/guidance	80 cm
Urban canyon (other)	80 cm
Exhibit commentary	1 m
Goods and item tracking	1 m
Hazard warnings	1 m
Pedestrian route guidance	1 m
In-building tracking (other)	1 m
In-building worker tracking	1 m
Urban canyon (rail)	1 m
Precision landing	1 m
Access control	3 m
Location-based services	3 m
Public services tracking	3 m
Docking	5 m
Parolee tracking	10 m
Local information	30 m
Train / air / bus information	30 m
Advertising	100 m

might be satisfactory for applications such as location-based handover in cellular networks. On the other hand, a meter of positioning error may mean a life-or-death situation for a fire-fighter depending on whether he is on the correct side of a building wall or not. In [8], tentative accuracy requirements of various localization applications are depicted, which are tabulated in Table 1.2. These show that the required accuracy of the location estimate can range from less than a centimeter to over tens of meters. Note that accuracy is only one aspect of the overall system; factors such as cost, range, and complexity are other issues to be considered, and no single localization system fits to all applications.

There are numerous localization technologies currently available which have different ranges, accuracy levels, costs, and complexities. While some of these technologies date back to World War II, significant improvements in localization technologies have been observed, particularly over the last few decades. Some of the important current localization technologies are classified and their key characteristics are summarized in Table 1.4 at the end of this chapter.

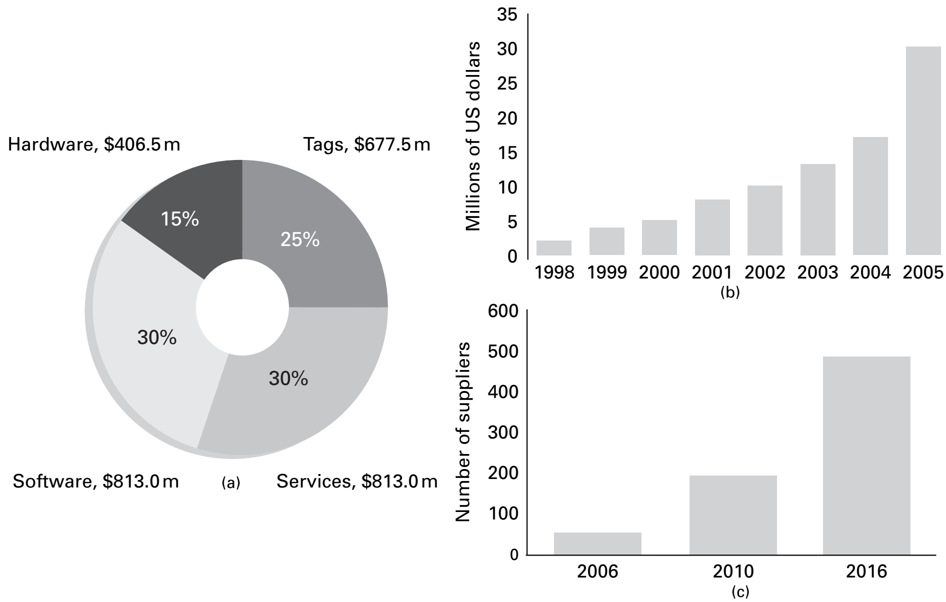

Fig. 1.2. (a) Share of spendings on RTLS in 2016 in millions of US dollars. (b) Global market on RTLS in millions of US dollars, from 1998 to 2005. (c) Trend in number of significant suppliers into parts of the RTLS value chain in 2006, 2010 and 2016 (After [9]).

1.1.2 Trends in real-time location systems

Due to its importance, there is a significant interest in the industry on real-time location systems (RTLS). In Fig. 1.2, estimated market share of spendings on RTLS in 2016 is depicted [9], which shows that software and services will dominate the total share rather than the hardware. Global market on RTLS and trend in number of significant suppliers is also seen to be exponentially increasing, indicating the importance and significance of the technology. While the number of significant suppliers into parts is 50 in 2006, it is expected to be around 200 in 2010, and around 500 in 2016.

According to IDTechEx forecast for RTLS [9], the global RTLS market will increase to 2710 million US dollars in 2016, while it is only 70 million US dollars in 2006. According to the same report, the major applications of RTLS in 2016 will be in military (44%, US$1.2 billion), health-care (30%, US$0.8 billion), logistics and other (26%, US $0.7 billion, including manufacturing, prison/parole service, and postal/courier sectors, etc.); however, there will be increasing interest from other sectors such as leisure, retail, and agricultural.

1.2 Taxonomy of localization systems

Different classifications of localization technologies have been previously presented in the literature [2, 10, 11]. In the following, some of the important classifications are briefly overviewed.

1.2.1 Signaling scheme

A fundamental classification is based on the signaling scheme that a localization technology uses. *Radio frequency (RF)* is probably the most commonly used signaling scheme for localization purposes. This is because RF signals can penetrate through obstacles and can propagate to long distances.

Infrared signals are low power and inexpensive; however, they cannot penetrate through obstructions (as opposed to RF), and they are susceptible against sunlight. Therefore, one usually has to install infrared sensors all over the indoor environment to pick up the signals from a transmitter.

Optical signals also require line-of-sight (LOS) conditions, are affected by sunlight, and require low power. They provide high accuracies and are typically more appropriate for short ranges (e.g. around 10 m).

Another inexpensive signaling alternative is *ultrasound* signals, which provide high accuracies in the short range. An advantage of acoustic signals is that the sound travels slowly. Hence, slow clocks are sufficient, and high accuracy can be achieved inexpensively in LOS conditions. On the other hand, acoustic emitters are power hungry, and they do not work well in non-line-of-sight (NLOS) scenarios.

1.2.2 RF signaling waveforms

Among different RF technologies, *ultra-wideband (UWB)*, *code division multiple-access (CDMA)*, and *orthogonal frequency division multiplexing (OFDM)* are a few of the RF technologies that may be considered for localization. Depending on their accuracy and range requirements, different versions of these technologies are used in various wireless systems such as *cellular systems*, *WLANs*, WPANs, *radio frequency identification (RFID) systems*, and *WSNs*.

1.2.3 Position-related parameters

Localization systems can employ various parameters/information obtained from received signal(s), such as the *time-of-arrival (TOA)*, *time difference of arrival (TDOA)*, *angle of arrival (AOA)*, and *received signal strength (RSS)*. Hybrid approaches that use combinations of the above are also possible. These different approaches are discussed in detail in Chapter 4.

1.2.4 Data fusion and localization methods

Different metrics of a received signal can be processed in various ways for obtaining a location estimate. The simplest way of estimating the target's location is the *cell ID* localization, where the target's position is approximated to be the location of the serving reference node (RN)[2], and the positioning accuracy is limited to the cell size. Alternatively, with *proximity detection*, the distance to a particular RN can be estimated.

In *triangulation*-based systems, the intersection(s) of the *at least* two lines (obtained e.g. from AOA information) from *at least* two RNs is/are used to estimate the terminal location.

On the other hand, in *trilateration* systems, at least three RNs are required for two-dimensional (2-D) localization, and at least four RNs are required for three-dimensional (3-D) localization. The intersections of the circles (or hyperbolas) obtained from TOA/RSS information (or TDOA information) are used to estimate the terminal location.

Fingerprint-based or *pattern-matching* localization technologies compare real-time measurements with a location database to infer the terminal's location. The positioning accuracy is limited to the granularity of the training locations, and an off-line calibration stage is required, which may need to be repeated if the propagation characteristics of the environment change.

1.2.5 Location estimation unit

Depending on where the localization is performed, localization technologies can be classified as *handset-based* (location aware), or *network-based* (location support) systems. In handset-based localization, the target receives signals from the RNs, and calculates its own location (also called *self-positioning*). It is more commonly used in military or public safety applications, such as a fireman trying to find his way out of a building. Global Positioning Systems (GPS) systems also fall under the same category.

In network-based localization, the RNs forward the received signal information, such as TOA, AOA, and RSS, to a central processing unit, where the target's location is estimated (also called *remote-positioning*). Note that privacy issues may be a big concern in this type of localization system, since the target may not always wish to be tracked by the network. In such a case, the target may estimate its own location, and may choose not to report its location to the central server.

1.2.6 Indoor versus outdoor localization

Due to significant differences in the propagation characteristics of the environments, it is common to classify the localization systems as *indoor* and *outdoor* localization systems.

A typical example of an outdoor localization system is the GPS. It uses TDOA information from four or more of 24 satellites around the world to estimate target's position with an accuracy between 1 and 5 m. It performs poorly indoors since buildings block GPS signals. Another widely used outdoor localization system is the E911 service in cellular networks.

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[2] A reference node may be a base station (BS) in cellular networks, an access point (AP) in WLANs, or an anchor node (AN) in WSNs.

Although GPS and E911 systems can provide location information outdoors, they are not designed for the indoor environments, where unique technical challenges exist and accuracy requirements are typically much higher. Indoor localization systems may require a completely different infrastructure installed within buildings (e.g. active badges [10]), or they may rely on the existing communications infrastructure such as wireless LANs (e.g. RADAR by Microsoft Research [21]).

1.2.7 Active versus passive localization

In *active* localization systems, the network sends specific signals to estimate the location of a target. *Passive* localization systems, on the other hand, use incumbent signals received from the mobile. In other words, as opposed to an active system, a passive system does not transmit any signal for location estimation purposes.

1.2.8 Centralized versus distributed localization

In *centralized* localization systems, position-related information (such as the TOA, AOA, RSS, etc.) is forwarded to a data fusion center, where the target location is estimated. The terminals that use a *distributed* localization system determine their location jointly by communicating with each other.

1.2.9 Software-based versus hardware-based localization

Software-based localization systems can be implemented by using the existing infrastructure, and there is no need for deploying extra hardware for localization purposes. As an example, Ekahau positioning engine [22] uses the existing WiFi infrastructure; it uses signal processing algorithms to estimate (and track) the target location from the RSS metrics obtained from different access points. *Hardware-based* localization systems need installation of extra hardware, such as in the case of SpotOn technology [23].

1.2.10 Relative coordinate versus absolute coordinate localization

Absolute location is the actual physical coordinate of a target with respect to a global reference; e.g. expressed as 24° 35′ 53.2″ North, 10° 45′ 11.5″ East. On the other hand, relative location is the position of a target with respect to a local reference within the network.

Another related term is the *semantic* (or *symbolic*) location, which is much easier to interpret by the targets. Absolute location, as discussed before, may be good enough for a missile but it is not much use for a taxi driver [1]. Examples of semantic location are “Topkapi Palace, Istanbul, Turkey’’, or “Stanford University Campus, Palo Alto, CA’’. Semantic locations have the advantage that they can be easily used as search keys in traditional databases [3].

1.2.11 Range-based versus range-free localization

If a localization system depends on the distances (or angles) between the nodes (e.g. the target and the base station), such a localization system is referred to as a *range-based* system. The distances are typically estimated using TOA, TDOA, and RSS metrics (or AOA for direction of arrival estimation).

On the other hand, there are localization systems which do not require estimation of absolute distances. Such approaches typically fall under two categories [2]: (1) techniques that rely on high density of anchors, such as the centroid algorithm, which calculates the position estimate to be the average location of all the *connected* anchors, and (2) hop counting techniques such as the DV-hop algorithm [24].

1.2.12 Accuracy versus precision

How well a certain localization technology performs is commonly measured with its *accuracy*, which is defined as how far the estimated location of the target is away from its actual location (e.g. 1 m accuracy). It is also desired that a certain localization accuracy is achieved with high probability; *precision* defines the percentage that a certain accuracy (or better) is achieved (e.g. 95% precision).[3]

1.3 Ranging and localization with UWB

1.3.1 Applications of UWB localization

As discussed earlier, there is not one localization technology that fits to all applications. For example, whereas GPS is an excellent technology for many scenarios and typically has fine precision outdoors, it fails to yield the desired accuracies in indoor environments due to multipath effects and blocked LOS. In addition, GPS devices are usually too expensive for many applications.

UWB is an excellent signaling choice for high accuracy localization in short to medium distances due to its high time resolution and inexpensive circuitry. It is also considered to be the unique signaling choice for short-range, low-data rate communications such as in WSNs. Some of the key applications for low-rate UWB communication and ranging systems are summarized in Fig. 1.3.

The low-rate UWB was standardized in 2007 under the IEEE 802.15.4a. The potential of UWB for high precision ranging, its possible applications, and implementation issues were extensively discussed and documented during the standardization process. Some key UWB localization applications as well as their range/accuracy requirements are tabulated in Table 1.3 based on [25]. The UWB technology is an excellent match that makes these exciting applications possible with sub-meter accuracies at distances smaller than 300 m.

[3] Some other performance measures in localization systems were listed in [2] as calibration requirements, responsiveness, self-organization, cost, power consumption, and scalability.

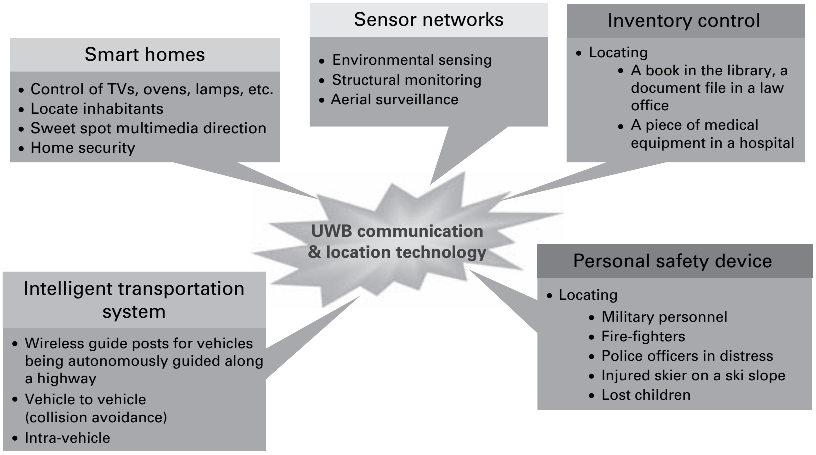

Fig. 1.3. Applications and business opportunities for low-rate UWB.

Probably the most suitable technology where UWB may be used as a physical layer signaling scheme is WSNs. Together with the advances in RF and MEMS IC technologies, wireless sensors are becoming cheaper, smaller, and more capable. We are probably living the last years in which furniture, buildings, cars, streets, highways, etc. are not dominated by WSNs. Localization of sensors in WSNs is important for a number of reasons, including: (1) in order for sensor data (e.g. temperature, humidity, and light intensity, etc.) to be meaningful, it is essential that the sensor's location is known, (2) some geographic routing algorithms can be enhanced if the location information is available, (3) location itself can be the data to be sensed, especially in logistics management [26].

Below, some of the recent applications of WSNs are briefly oveviewed.[4] The motivation is to make it clear that localization is a key component in many of the WSN applications.

- In the Great Duck Island project, 150 sensing nodes are deployed throughout the island, to collect and relay data such as temperature, pressure, and humidity, etc. to a central device. Then, these data are made available through Internet using a satellite link [28].
- In the ZebraNet project, WSNs are used to study the behavior of zebras, where special GPS equipped collar devices are attached to the zebras [29].
- In order to monitor the volcano activity in Ecuador, WSNs are used in the areas where human presence is discouraged [30].
- In agricultural monitoring applications (such as the wireless vineyard project), data are collected using WSNs and processed to make decisions, such as detecting parasites to automatically choose the right insecticide, or watering and fertilization only wherever and whenever necessary [26, 31].

[4] For some other applications and a detailed discussion on the design space of WSNs, the reader is referred to [27].

Table 1.3. Key localization applications, ranges, and accuracy requirements (After [25]).

Core RTLS applications	Range	Accuracy
High value inventory items (warehouses, ports, motor pools, manufacturing plants)	100–300 m	30–300 cm
Sports tracking (NASCAR, horse races, soccer)	100–300 m	10–30 cm
Cargo tracking at large depots including port facilities	300 m	300 cm
Vehicles for large automobile dealerships and heavy equipment rental establishments	100–300 m	300 cm
Key personnel in office/plant facility	100–300 m	15 cm
Children in large amusement parks	300 m	300 cm
Pet/cattle/wild-life tracking	300 m	15–150 cm
Niche commercial markets	**Range**	**Accuracy**
Robotic mowing and farming	300 m	30 cm
Supermarket carts (matching customers with advertised products)	100–300 m	30 cm
Vehicle caravan/personal radios/family radio service	300 m	300 cm
Military applications	**Range**	**Accuracy**
Military training facilities	300 m	30 cm
Military search and rescue: lost pilot, man overboard, coast guard rescue operations	300 m	300 cm
Army small tactical unit friendly forces situational awareness – rural and urban	300 m	30 cm
Civil government/safety applications	**Range**	**Accuracy**
Tracking guards and prisoners	300 m	30 cm
Tracking firefighters and emergency responders	300 m	30 cm
Anti-collision system: aircraft/ground vehicles	300 m	30 cm
Tracking miners	300 m	30 cm
Aircraft landing systems	300 m	30 cm
Detecting avalanche victims	300 m	30 cm
Locating RF noise and interference sources	300 m	30 cm
Extension to LoJack vehicle theft recovery system	300 m	300 cm

- Avalanche victims can be rescued by the help of WSNs [32]. The people at risk (skiers, hikers, etc.) carry wireless sensors with an oximeter (to measure oxygen level in blood), oxygen sensor (to detect air pockets around victim) and accelerometers (to detect orientation of victim), which are communicated to the PDAs of a rescue team.
- A prototype network of meteorological and hydrological sensors has been deployed in Yosemite National Park to monitor natural climate fluctuations, global warming, and the growing needs of water consumers [33].
- WSNs were used to monitor 44 days in the life of a 70-m tall redwood tree, at a density of every 5 min in time and every 2 m in space, where each sensor

reported the air temperature, relative humidity, and photosynthetically active solar radiation [34].

- A virtual fence application was presented in [35], where an acoustic stimulus is given to animals which cross a virtual fence line. It can be dynamically shifted based on the movement data of the animals, improving the utilization of feed-lots and reducing overheads for installing and moving physical fences.
- Example military applications: counter-sniper systems (detect and locate shooters as well as the trajectory of bullets) [36], self-healing land-mines (ensure that a certain geographical area remains covered with land-mines; if an enemy tampers with a mine, an intact mine hops into the breach using a rocket thruster) [27, 37], tracking of military vehicles (e.g. tanks) using sensors dropped from an unmanned aerial vehicle (UAV) [27], and UAV flock control [38].
- Example medical and commercial applications: damage detection in civil structures (such as smart structures actively responding to earthquakes and making buildings safer [26]), continuous medical monitoring [39], elder care [40], aware home [41], smart kindergarten [42], condition-based maintenance of the equipment [26], and active visitor guidance systems [43].

These examples prove that localization may be needed as a key enabling component for numerous WSN applications, and UWB is an excellent fit for communications and localization for WSNs.

1.3.2 Available UWB localization technologies

There are already a number of UWB ranging and positioning devices in the market. Together with the completion of the IEEE 802.15.4a standard, standard-compliant UWB localization technologies are also being announced. Some of the available UWB localization technologies and their key characteristics are overviewed below and listed in Table 1.4.

Sapphire DART

The Sapphire DART system from Multispectral Solutions, Inc. (MSSI) is an active RFID and RTLS system (see Fig. 1.4) and has the following characteristics [44].

- Tag read ranges in excess of 200 m. (650 feet) line-of-sight, and better than 50 m (160 feet) indoors through multiple obstructions.
- Real-time location (not just active RFID).
- Battery life of up to 10 years, even at one tag transmission per second.
- Real-time location accuracies better than 30 cm (10 cm with averaging).
- Immunity to ISM and WiFi interference, and multipath effects.
- Microminiature tag sizes (e.g. $0.5 \times 1.0 \times 0.25$ inches and 10 g).
- Tags certified UL1604 for use in hazardous locations.

Table 1.4. Current location technologies.

Technology	Location method	Accuracy	Remarks
GPS	Localization using time-of-flight information from four or more of 24 satellites	1–5 m (95–99%)	Expensive (US$100 receivers), does not work indoors
Loran	TDOA	Better than 0.25 nautical miles (460 m) within published areas	Loran-A developed during World War II, and Loran-C around 1950s. Land-based system operating at 90–110 kHz. More robust to jamming than GPS. Mostly used by mariners.
Enhanced Loran (eLoran)	Incorporates signals from all stations in range	8–20 m	Being installed in US in 2004, a variation is used in north-west Europe.
ARGOS [52]	Makes use of Doppler effect. Six NOAA satellites are currently in service with ARGOS instruments.	150–1000 m	May locate any platform equipped with a suitable transmitter, anywhere in the world. Average daily power consumption as low as a few milliamps, miniaturized models can be as compact as a small matchbox, weighing as little as 15 g.
Polaris Wireless [53]	Uses multipath signatures for localization	Well within 100 m	Fingerprint information compared with a database.
A-GPS (Assisted GPS)	Modified handsets that use a GPS receiver	Around 10 m	Works well in rural and suburban areas with unobstructed sky view. Specialized network server to assist in location estimation.
WLANs			
Ekahau [22]	RSS-based pattern matching, usage of Bayesian inference methods	Up to 1 m	No extra cost over existing wireless LAN structure, extensive utilities
Microsoft RADAR [21]	RSS-based pattern matching	3–4.3 m (50%)	Scalability problems, no extra cost over existing wireless LAN structure
Wireless Andrew [10]	Closest AP	802.11cell size	Poor accuracy
Aeroscout [54]	TDOA and RSSI	1–5 m with TDOA	Uses Wi-Fi-based Active RFID tags.

Table 1.4. (*cont.*)

Technology	Location method	Accuracy	Remarks
PanGo [55]	RF fingerprint technique	Room level accuracy (< 3 m)	Asset tracking system for companies. includes an integrated rules-based notification application that sends event-triggered alerts to users based on asset location, presence/absence duration and status.
LOKI (Skyhoow Wireless, Inc.) [7]	Closest AP	802.11 cell size	Installed as a free software. Used for locating the closest restaurant, etc. through a search engine.
WSNs			
Active Badges [56]	Infra-red-based proximity of wearable badges to predeployed sensors	Room size	Installation costs, cheap tags and sensors, sunlight and fluorescent interference, limited IR range
Active Bats [57]	Ultrasound time-of-flight lateration	9 cm (95%)	Ceiling sensor installation costs
Cricket [58]	RSS and ultrasound-based localization	4 x 4 feet regions	US$10 beacons and receivers, installation costs
SpotON [23]	RSS-based ad-hoc lateration	Depends on cluster size	US$30 per tag, inaccuracy of RSS metric
UWB			
Ubisense [45]	TDOA and AOA	30 cm in 3-D	Maximum tag-sensor distances greater than 50 m
PAL650 (MSSI) [47]	TDOA	Up to 1 foot	The world's first FCC-certified UWB-based active RFID tracking system.