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Indoor Location-Based Services

Prerequisites and Foundations

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Martin Werner
Ludwig-Maximilians-Universität München
Munich
Germany

ISBN 978-3-319-10698-4 ISBN 978-3-319-10699-1 (eBook)
DOI 10.1007/978-3-319-10699-1
Springer Cham Heidelberg New York Dordrecht London

Library of Congress Control Number: 2014952609

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

To my family.

Preface

The rise of powerful smartphones equipped with many sensors has led to a huge amount of location-based services for the outside world. These applications provide orientation, navigation, and information to users in unknown locations. However, these services have long been limited to the outside of buildings, either because GPS is unavailable inside buildings or because alternative positioning based on cell towers or Wi-Fi access points is too inaccurate. The high information value of these applications, however, has triggered a lot of research towards extending the service experience from the outside into the inside of buildings. From a computer science perspective, this has led to a beautiful area of research in which many previously isolated domains converge towards new ideas and results. This book intends to bring together some of these aspects for students and researchers in a way, such that the aesthetics of indoor location-based services becomes evident. However, writing this book was quite challenging: It is sometimes hard to correctly distinguish the relevant and the irrelevant. However, I really enjoyed writing this book, and I hope that it will be helpful in making the domain of indoor location-based services accessible and attractive for others. Due to the chosen approach of covering the basics of many previously isolated domains in one book, this book cannot serve and is not intended to be a reference or state-of-the-art review. Instead, it provides readers with the needed background to enter the research area themselves.

This book would not have been possible without the help from my colleagues, my friends, and my family and without a university, which provides me with the freedom of investing a lot of time into this project. For their outstanding support and their helpful comments and discussions, I want to thank (in alphabetical order) Ulrich Bareth, Michael Beck, Florian Dorfmeister, Michael Dürr, Sebastian Feld, Moritz Kessel, Helge Klimek, Hans-Peter Kriegel, Claudia Linnhoff-Popien, Marco Maier, Philipp Marcus, Chadly Marouane, Valentin Protschky, Peter Ruppel, Lorenz Schauer, Mirco Schönfeld, and Kevin Wiesner.

Munich, Germany
May 2014

Martin Werner

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Chapter 1
Introduction

A journey of a thousand miles begins with a single step.

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Positioning and navigation as well as their related areas of mapping and guidance have been a central and widely recognized problem for human societies for centuries. Still, a lot of efforts are made towards more precise, reliable, and ubiquitous positioning systems. Nowadays, GPS and other navigation satellite systems are sufficient for navigating a car inside the complete world. The limitations, that GPS does not work inside tunnels and buildings, are not severe to that application. However, the widespread use of smartphones equipped with GPS leads to a lot of smart services using location as ingredient, and soon the aim for providing better service quality inside buildings comes up. Up to now, there is no system comparable to GPS for the inner of buildings. This is due to the fact that global radio-based infrastructures such as GPS cannot be observed with sufficient quality inside buildings. This is due to the fact that radio propagation of high-frequency signals in buildings faces a lot of multipath situations in which the propagation path is not the direct line between the mobile device and a base station or satellite which is a central assumption for GPS. On the other hand, low frequencies can penetrate buildings on the direct line of sight. However, they cannot be sent from satellites and only provide coarse time information and location. Therefore, a lot of local techniques based on a multitude of different technologies have been proposed to reach the same service quality inside buildings, which is offered outside using GPS. Some systems reach incredible accuracy of localization including recent UWB-based systems. However, they are often limited by their complexity and cost. Other systems reach global availability such as indoor positioning based on Wi-Fi measurements or cellular networks. However, their accuracy is often problematic for providing sufficient service quality. Note that the accuracy demands of personal navigation systems inside buildings are often claimed in the order of 1 or 2 m. This would suffice to distinguish doors located next to each other and enable a person to read off door signs located inside the error radius easily. In contrast to that, the expected error of GPS is around 10 m, a much higher value. Hence, even when a system with performance comparable to GPS is made available inside buildings, this does not imply that location-based services become easily possible. This is one of the main motivations for treating indoor location-based services fundamentally

M. Werner, *Indoor Location-Based Services*, DOI 10.1007/978-3-319-10699-1_1

differently and one of the main reasons for writing a book dedicated to the indoor situation. The high amount of uncertainty of location to be expected inside buildings brings a much higher influence of map information, filtering, and reasoning for providing acceptable overall service quality as compared to the outside. It is to be expected that fulfilling the demand for positioning with errors below 1 m is not possible without integrating map information and probabilistic techniques. This is quite different for GPS navigation: for GPS, a closed system with a single standardized interface and with very limited data access provides location estimates with errors in the magnitude of 10 m. A basic GPS system uses only almanac data defining the current location of satellites, and this data is transmitted via a satellite link. Therefore, no terrestrial network access is needed for basic GPS positioning.

This isolation of the positioning system and the location-based service is impossible for indoor location-based services. One reason for that is that the coarse position returned by simple GPS leads to high-quality locations using pretty simple map matching especially for the application domain of vehicle navigation.

To illustrate this, consider the following example of a car navigation system. The positioning system provides location fixes from time to time, while the navigation backend is interested in the current street segment inside a map of streets. Consider the situation of Fig. 1.1.

A car is driving upwards on the middle road labeled C, and GPS locations with large errors are shown.

A simple map matcher based on tracking multiple hypotheses of the current street segment over time is described as follows: from the first measurement, three hypotheses will be generated. The car is driving on A, B, or C, and these are scored according to their distance to the fix and their previous weighting. Hence, A and C are scored higher from this fix compared to B. For newly arriving measurements 2, 3, and 4, these hypotheses are updated, and possibly, new hypotheses are generated. The hypothesis of lowest score is dropped when the number of hypotheses exceeds a preconfigured limit. Altogether, this deals successfully with GPS uncertainty in most cases as the number of possible movements is low enough to track each individual possible movement due to the low degree of the street network and the small number of streets within the uncertainty of GPS fixes.

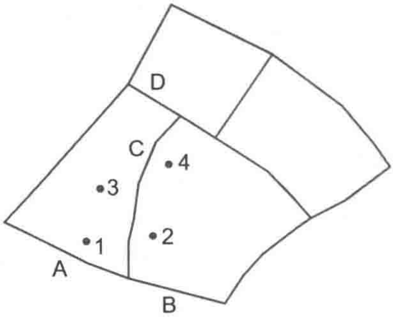

Fig. 1.1 Map matching example for car navigation

In contrast to that and even when assuming a perfect positioning system without any errors, the indoor area contains a lot of equivalent ways and free space leading to completely different traces of coordinates. Tracking all possible indoor movements quickly becomes infeasible. There is an approach called particle filter, which essentially tries to accomplish this. However, particle filtering applied to some indoor area has to track thousands of particles in order to be able to keep track of most sensible hypotheses. Furthermore, the inherent symmetries of buildings render the removal of hypotheses more difficult and lead to the huge amount of hypothetical locations.

In the last decades, indoor location-based services have often been reduced to solving the indoor positioning problem. While this is one of the most important problems for indoor navigation, it is not the only one, and this makes this book different from many other books dedicated to positioning. This book is intended to also shed light onto the problems waiting in the background when positioning has been solved completely. Moreover, it is to be expected that the problems related to indoor location-based services cannot be solved in isolation as was possible for the outside space, and the book will show examples on how to integrate map information or movement constraints into position determination.

Another perspective on location-based services is given by looking into the organization and communication of devices with location awareness. This includes communication patterns for different location-based service classes. From this perspective, the transmission, coding, storage, and retrieval of location-based information and the model of interaction including push and pull services are discussed. However, this area of research is very similar for location-based services indoors as well as outdoors. Though indoor geolocation is basically more uncertain, optimizations with respect to energy consumption and privacy render outdoor location-based services into similarly uncertain by leaving out available information such as shutting down the GPS to save energy in specific situations. Complicated middleware constructions have been long discussed including the Tracking and Exchange platform which might serve as an example on this area of research.

For the purpose of this book and in order to keep the description concise, we will omit details of service management, deployment, and energy optimization in cases where they do not differ too much from the treatment of these topics for general location-based services. Furthermore, we restrict the discussion of indoor location-based to the most advanced example of navigation. This is based on the observation that a system that is able to provide turn-by-turn guidance to a mobile device including map information, semantic models of the surroundings, and the associated capabilities of a geographic information system (GIS) is sufficient to provide the most relevant other classes of location-based services.

Overall, this book intends to collect results and ideas from very different domains, which are all relevant to providing indoor location-based services in the future.

1.1 Location-Based Services (LBS)

Location-based services are based on the need of people to orient in unknown environments. A location-based service is a computer service, which provides a specific functionality based on the current location of a mobile entity. In some cases, the mobile entity is a mobile device whose location is identified with the location of the person using the device. In other cases, the location of some objects is to be determined and tracked, for example, in fleet management applications or logistics.

There are several definitions of location-based services in literature. In essence, as we will observe in the following examples, location-based services contain three aspects: location, communication, and geoinformation.

Early definitions stem from the telecommunication standardization and usually bring the value of location into the definition. The GSM Association, for example, defines LBS roughly as a service using the location of a target in order to add value to a service. Note that the target is not necessarily a person but is defined to be the entity whose location is to be inferred. This definition includes the aspect of location explicitly. The aspect of communication is included implicitly as the GSM Association is a standardization gremium for mobile communication networks. The geoinformation aspect is given by the requirement of adding value to a service. It is clear that a service that adds value based on positioning needs to derive service information from location.

A more restrictive definition from the research domain reads a bit different as it—unfortunately—restricts location-based services to services in which the service users location is being used:

> In the general case, the location-based services can be defined as services utilizing the ability to dynamically determine and transmit the location of persons within a mobile network by the means of their terminals [6].

This definition also contains the three basic aspects: Firstly, location-based services are services utilizing the ability to dynamically determine the location of persons. This part of the definition is related to the aspect of location. The aspect of communication—though slightly restricted to the communication of location, actually—is included, too. Finally, the geoinformation aspect or the value aspect is included through the word "utilizing."

In order to further illustrate location-based services from a more concrete perspective, consider the following three abstract questions whose answer is utilizing location information:

- *Where am I?*
  The problem of finding a location of the mobile device.
- *What is surrounding me?*
  The problem of giving sense to the inferred location depending on the surroundings.
- *How do I get somewhere?*
  The problem of navigation and guidance in unknown environments.

For the purpose of this book, we will define location-based services as follows: *A location-based service is defined to be a service relying on the following three aspects: the ability to* ***infer the location*** *of one or more mobile entities, the ability to* ***communicate*** *information, and the ability to* ***use location data*** *in order to provide the service.*

This definition is perfectly aligned with the location-based service triangle which can be found in several discussions of location-based services and which is depicted in Fig. 1.2.

Sometimes it is reasonable to fix some roles in location-based services in order to better understand the preconditions and interactions of different entities when designing and developing location-based services. Four such roles are of sufficient universality to further illustrate definitions of location-based services. From this perspective, location-based services are services constructed from the concrete instantiation of systems accomplishing the following tasks:

- *Terminal:* A mobile terminal providing the ability to change location.
- *Location Enabler:* A system enabling the inference of the location of mobile terminals.
- *Service Provider:* A service provider which can generate additional value by utilizing location information
- *Service User:* A user which utilizes the service.

All of these systems can be deployed in different locations and domains. For example, a cellular network can provide a location enabler inside an infrastructure, while a GPS chip can be seen as a location enabler for a smartphone. A terminal can be a smartphone or tabled—the most common case—or an embedded system comprised of nothing more than being mobile and being identified such as a passive RFID tag. A service provider is the entity which is interested in exploiting available location information in order to provide a service, and the service user is the entity using the service.

In practice, a lot of additional roles come up in different scenarios; however, these four roles are always needed to build a location-based service.

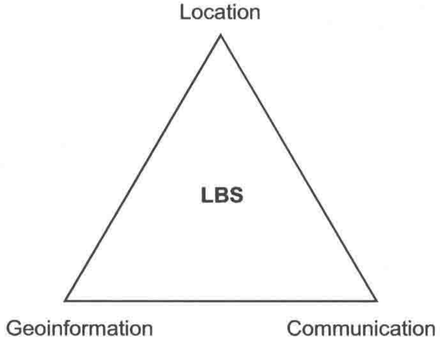

Fig. 1.2 The location-based service triangle

1.2 What Is Special About Indoor LBS

The success of location-based services outside has led to the desire for extending this service experience into the inner of buildings. However, a lot of open problems have to be solved, before a comparable service quality can be achieved inside buildings and position determination (e.g., an equivalent to GPS outside) is only one of them. For the indoor area, the complete value chain of location-based services needs to be addressed, and the diversity of stakeholders as compared to the outside world is often challenging. For example, a simple navigation application needs access to sufficient map information about a building. While it is possible to buy high-quality navigation datasets covering the outside world from a vehicle navigation perspective including streets, ferries, and point-of-interest information from map companies, such a company is not yet available for mapping indoor areas. This is linked to the complexities of creating and maintaining indoor maps as compared to outdoors: outdoor maps can be created from satellite imagery as well as from traces collected using GPS. For the indoor area, however, no such accessible and automated source of information is available, today. The only source of information is often given by a floorplan or drawings used during construction which are full of symbolism and difficult to understand for a computer service. Furthermore, indoor location-based services need a position determination service of sufficient accuracy. In many cases, this can only be provided in cooperation with the building owner unless crowdsourcing techniques have evolved to provide and organize map information.

This whole situation leads to a very fragmented landscape of isolated applications. As it is still impossible to globally deploy an indoor location-based service using some standardized data source, it becomes less likely for actual application providers to accept limitations or additional overhead induced by adopting a proposed standard. Therefore, each application does similar things in quite different ways each time providing the best relation between modeling effort and achievable service quality.

Moreover, mobile platforms tend to limit applications access to sensitive data which clearly includes all data which might enable positioning or other forms of context awareness. This data is to be considered private, and hence a modern smartphone operating system will provide tools and mechanisms to prevent applications from using this information.

The block diagram in Fig. 1.3 depicts a minimal set of components needed to provide a nontrivial indoor location-based service. In comparison to the outside world, the interrelation of different entities involved in providing a location-based service is much more complicated in many cases:

One large building block of indoor location-based services is about the map information and semantic representation of buildings. There is not even a suitable global coordinate system in which indoor location-based services can be performed. Rather, any environmental model provides an own coordinate system. As a result, a positioning system cannot provide any location information without referring to an environmental model in which the location can be interpreted. This relation

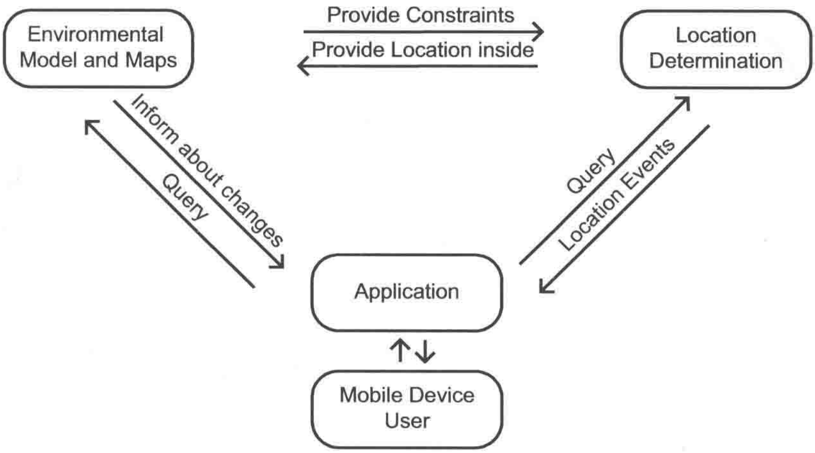

Fig. 1.3 Building blocks of indoor location-based services

between environmental model and positioning becomes critical for positioning systems, which use map-matching techniques to overcome inherent inaccuracies in position determination and for coordinate-free positioning systems. Coordinate-free solutions might provide a room name or some other semantic labels describing the use of the room and possibly a graph describing their topological relationships. This type of location can be inferred much more reliable and is of more use for an application than a set of numbers representing an uncertain three-dimensional spatial location inside an environmental model consisting of a three-dimensional scene composed of solid objects. Moreover, the operation principle of the application is a central question for indoor location-based services. As some positioning systems are based on a dedicated, distributed infrastructure, this infrastructure can take over active parts and, for example, signal the application with a message, when a given situation occurs in the location data or environmental model. This type of service is often called *proactive* service, as the service gets activated only when a situation of interest is detected in the background and independently from the user. More classical services get active on user request. These are called *reactive* services and can provide the integration of environmental models and positioning through the application itself. From a user perspective as well as for energy efficiency inside a mobile device, proactive services are more interesting than reactive services. However, they are also more difficult to realize: they depend on a flexible and powerful interconnection of services from different domains and on mechanisms rating the relevance of location events with respect to the user or a group of users which is a hard problem for itself.

In a classical indoor location-based service setup, the building owner might provide some infrastructure such as Wi-Fi access points and some map information. Then a service on the Internet might provide the mapping of Wi-Fi sightings to locations inside these maps to applications. For a proactive service, however, some