Assisting Multimodal Travelers: Design and Prototypical Implementation of a Personal Travel Companion

Karl Rehrl, Stefan Bruntsch, and Hans-Joachim Mentz

***Abstract*—Increasing the share of multimodal journeys is becoming more and more urgent in our society in order to guarantee a high level of mobility in the long term. While car drivers are already assisted by advanced guidance and navigation facilities, continuous on-trip assistance for multimodal travelers is still in its infancy. Especially when it comes to situations of modal change, travelers get discouraged by the increased complexity and the lack of adequate information and guidance. Thus, the goal of our research over the past three years has been to integrate existing information systems and to design and implement the prototype of a digital personal travel companion for multimodal travelers. This paper discusses typical travel situations and possible barriers for people traveling on multimodal journeys. To address these challenges, functional requirements for a personal travel companion are derived from the analysis of the situations. The main sections of this paper describe our results focusing on personalized multimodal journey planning, mobile multimodal trip management, and smart-phone-based pedestrian orientation and guidance in complex public transport transfer buildings.**

***Index Terms*—Digital assistants, multimodal transport, navigation systems, pedestrian guidance, public transport, travel information systems.**

I. Introduction

One of the most important needs of society today is mobility, and this need is likely to grow in the future. The continuously increasing demand for mobility has so far resulted in exceptional growth rates for motorized individual transport. Increased motorized transport requires a powerful road infrastructure and intelligent traffic management systems. However, to guarantee a high level of mobility in the long term, a shift toward multimodal transport is necessary. Policy makers, transportation experts, and decision makers claim that a shift from individual to public transport will have to occur and that a significant share of journeys of tomorrow will be multimodal, implying the usage of more than one means of transport on a single journey. This claim is confirmed by a survey among Austrian travelers [39], which showed that about 20% of travelers would be willing to use alternative means of transport if they had access to multimodal travel information.

While more and more car drivers are assisted by advanced guidance and navigation facilities, travel assistance typically ends when travelers leave their cars and continue the journey with other means of transport. Looking at public transport, continuous personal travel assistance is often poor or not available. Orientation and guidance in unknown public transport systems require time-consuming planning processes and the study of different maps, timetables, and information terminals. Smooth and fast movement along public transport routes with a personal digital assistant (PDA) at hand is still an open issue. Current information systems are typically built from many heterogeneous systems that lack integration. Whereas multimodal journey planning in the pretrip phase is at least available via web access for urban regions, the planned journey can typically not be used in the in-car navigation system nor can the journey be accessed via a mobile terminal. Multimodal trip planning systems and in-car navigation systems are at present non-interoperating domains.

Over the last three years, a consortium of Austrian and German transport associations, research organizations, and companies led by the largest Austrian public transport association, known as the Verkehrsverbund Ost-Region,[1] has worked on the integration and extension of existing travel information systems in order to achieve continuous personal on-trip assistance for multimodal travelers. The goal is to overcome the deficiencies of heterogeneous nonintegrated systems and to provide new approaches to passenger guidance and information on public transport systems in order to encourage more people to take advantage of multimodal transport.

This paper focuses on aspects of improving information and orientation for travelers along such multimodal journeys. The main questions answered are how to personalize multimodal trip planning, how to provide continuous on-trip information to multimodal travelers, how to integrate in-car navigation and multimodal trip management, how to provide information on when to change from individual motorized transport to public transport, how to provide guidance and orientation in situations of modal change in the public transport system, and how to assist travelers in finding their way to the destination address once they get off at the last stop provided by public transport.

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[1] http://www.vor.at/.

II. MULTIMODAL TRAVELING: TASKS AND BARRIERS

Multimodal traveling requires extensive pretrip planning, continuous on-trip information, and end-trip assessment. The multimodal traveler model, which was developed in the Infopolis 2 project [20], describes the tasks and activities from a user's perspective. This model was taken as a basis for analyzing travel situations, traveler needs, and potential barriers along multimodal journeys.

A. Tasks

We classify typical tasks according to the pretrip or on-trip phase of a multimodal trip.

1) Pretrip: Before starting a trip, people determine key parameters such as travel purpose, the time frame, price expectations, or preferred means of transport. People can use web-based travel planners in order to get information and then plan how to travel from point A to point B. Besides route planners for motorized individual transport (e.g., Map24[2]) or public transport (e.g., Austrian Federal Railways[3]), recently, multimodal web-based journey planners (e.g., intermodal journey planner (IJP)[4] or EU-SPIRIT[5]) have also reached some maturity and thus have gained considerable attention. Research projects like EU-SPIRIT [10], DELFI [31], ISCOM [22], or INTREST [21] defined the basics of multimodal route planning.

The significant change to previous travel planners is that these multimodal journey planners are able to calculate trips between two addresses consisting of different trip parts, e.g., one by car, one by underground, one by bus, and at least a pedestrian path to the destination address. According to user preferences, the calculated route alternatives (a route alternative is a possible connection between start and end points that meets the travelers' needs) are weighed. Parameters for the personalization of the routing process are time, number of transfers, price, and preferred transport means, or Park&Ride (P+R) facilities. Information about the calculated routes has to satisfy traveler needs. Relevant information needs in the pretrip phase include the connection, the start and end parts, transport means, number of transfers, public transport schedules, transfer descriptions, map visualizations of the route, and prices. The key benefit of multimodal journey planners is the "door-to-door" information logic and the possibility to compare different route alternatives [20].

2) On-Trip Tasks: After starting the trip, information about the travel tasks along a selected route is necessary. Travel tasks include multimodal trip planning in cars, searching for P+R facilities, navigating to P+R facilities, changing from car to public transport, orientation in public transfer facilities, orientation along public transport routes, and orientation on the last mile from the public transport stop to the destination address. Especially, the last mile of a multimodal journey is often difficult to accomplish for travelers. For example, catching the wrong underground exit makes it difficult to find the right address. The lack of end-trip information is one of the typical barriers in the context of multimodal travel.

B. Barriers

Barriers in multimodal travel situations are frequent, and this prevents people from changing means of transport. Typical examples of such barriers are listed as follows:

1) Lack of Public Transport Information in Cars: Web-based multimodal trip planners and in-car navigation systems are totally independent systems. The preplanned route cannot be transferred to the in-car navigation system. Instead, the car part of the journey has to be planned a second time. This means that the user has to enter the name or the coordinate of the P+R manually. Also, digital road networks as used for car routing typically ignore public transport. Thus, it is most likely that the P+R is not known to the in-car navigation system, and it is difficult to find a routing endpoint near the P+R. Timetable information, real-time information about the status of the public transport network, and information on the availability of free parking lots at the P+R are missing.

2) Complexity of Public Transport Systems and Difficult Transfers: Public transport systems are complex [18] and often provide obstacles especially for travelers who are not used to public transport. Using a public transport system for the first time requires a number of questions to be answered [20]. These questions typically arise before or on entering an unknown public transport system. When it comes to situations of modal change [34], people often get lost. Typical situations of modal change are from car to public transport, from public transport to public transport, or from public transport to walking. Transfer situations within the underground network are typically easier than changing from underground to bus or tram. Barriers for travelers include finding the right exit from the underground station and finding bus or tram stops over ground.

3) Lack of Information System Integration and Personalization: Typically, information systems for individual motorized transport or public transport are heterogeneous, and people have to be prepared for different modes of user interaction. Especially when leaving the car, people are confronted with a broad variety of new information systems including local guidance systems, orientation plans, electronic timetables, scoreboards for real-time information, or onboard information systems. All these information systems are standalone and do not provide personalized trip information. Thus, travelers have to do the integration in their heads, which leads to an increased cognitive load. A personal travel companion at hand could bridge the information gap between car, P+R, and public transport information systems.

4) Lack of End-Trip Information: Having reached the final public transport stop, the last barrier is to find the right address. Whereas car travelers are often navigated exactly to the destination address, multimodal travelers exiting from a public transport network are left alone at the final stop. Information about the final stop, where to find the exit, and how to get oriented in the surrounding area of, e.g., the bus or tram stop, is needed.

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[2] http://www.map24.com/.

[3] http://www.oebb.at/.

[4] http://195.30.232.155/bay/index_en.htm.

[5] http://euspirit.vbb-fahrinfo.de/.

5) Lack of Return-Trip Information: A frequently arising barrier is the missing information about the return trip. This includes navigation and guidance back to the public transport stop, different route possibilities, and detailed information on the possible sections of the overall route.

Considering the aforementioned aspects, it seems obvious that the missing link is an integrated traveler assistance system for palm use that should provide on-trip information for typical travel situations along multimodal journeys. With the results of the analysis in mind, we derived functional requirements for a personal travel companion, as described in the next section.

III. FUNCTIONAL REQUIREMENTS FOR A PERSONAL TRAVEL COMPANION

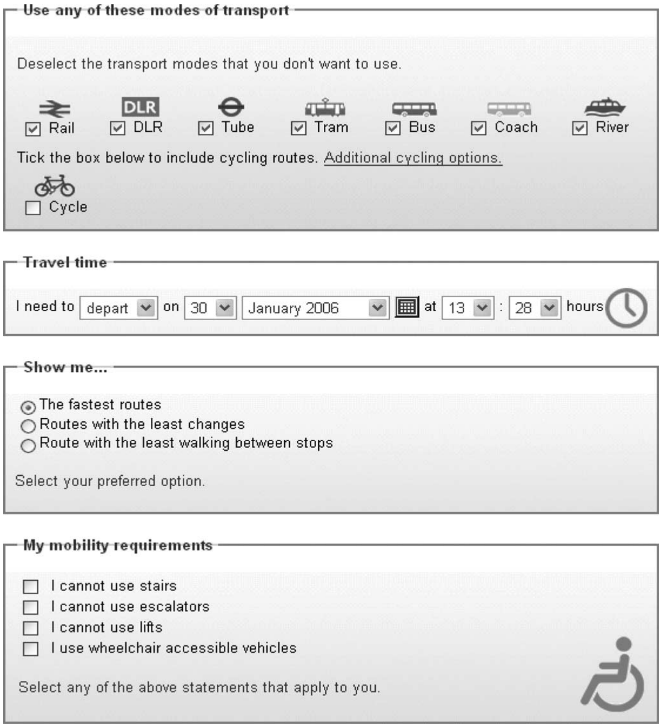
For the definition of the requirements (i.e., Sections III-A–III-D), we considered the barriers described above and the four key properties, namely 1) personalization, 2) continuity, 3) mobility, and 4) seamlessness, which according to Heuwinkel [17] are the key characteristics of digital assistants.

Personalization of digital assistants means that the information provided is directly related to one person. This is in contrast to information systems for public transport, which provide general information. Continuity implies that the digital assistant is always active and can be used in whatever situation the traveler is in. Mobility describes the characteristic of digital assistants to be always near the person, e.g., the digital assistant can be carried in the palm or elsewhere on the body. Seamlessness is reached when the digital assistant not only provides information for one location or situation but also informs the assisted person independently from the current location.

A. Personalized Multimodal Trip Management

With this requirement, we focus on extensions of existing multimodal journey planners. The two key aspects are personalization and trip management. Personalization of journey planning means that personal preferences are considered in the journey planning process. This is a key requirement for the acceptance of the service. Multimodal journey planning is a complex process with many different parameters that have significant impact on the quality and thus on the acceptability of the suggested route. In order to get optimized routes out of the planning process, the consideration of personal preferences and settings is important. Personalized settings should allow the selection of preferred means of transport, to exclude unwanted means of transport, to set personal walking options, to select mobility requirements, to select a maximum number of transfers, to select time constraints, or to select waypoints. An example of personal travel preferences selection is given in Fig. 1.

Another key aspect is personal trip management. Trip management encompasses the functionality of storing personal routes, accessing these personal routes later via different information systems, keeping a personal history of planned routes, or preferred travel locations, and of centrally storing routes planned on different travel information systems like in-car navigation, web-based journey planner, or mobile journey planner. Personal trip management guarantees the integration of pretrip travel planning and on-trip assistance. Moreover, it provides convenient access to the system for frequent travelers.



Use any of these modes of transport

Deselect the transport modes that you don't want to use.

☑ Rail ☑ DLR ☑ Tube ☑ Tram ☑ Bus ☑ Coach ☑ River

Tick the box below to include cycling routes. Additional cycling options.

☐ Cycle

Travel time

I need to depart on 30 January 2006 at 13 : 28 hours

Show me...

● The fastest routes
○ Routes with the least changes
○ Route with the least walking between stops

Select your preferred option.

My mobility requirements

☐ I cannot use stairs
☐ I cannot use escalators
☐ I cannot use lifts
☐ I use wheelchair accessible vehicles

Select any of the above statements that apply to you.

Fig. 1. Example of personal travel preferences selection in the London IJP. Transport for London.

B. Continuous On-Trip Access to Multimodal Trip Data

A key requirement for a personal travel companion is the continuous on-trip access to multimodal trip data. Starting with travel planning in the pretrip phase, it is important to have access to trip data along the whole journey, no matter whether a person is traveling by car, bus, train, underground, or walking. For continuous mobile access, different prerequisites have to be fulfilled. First of all, data for the whole multimodal route have to be available. This includes data from the street network, data from the public transport network, data from transfer facilities, and data from pedestrian networks. Only the acquisition and integration of these data sets for arbitrary geographical areas can contribute to continuous trip information. End-user devices used along the multimodal route have to be equipped with personal travel companion applications reading the trip descriptions and extracting the right section of the trip, e.g., an in-car navigation system has to be able to access the trip data, interpret the trip sections, and accept the car section as the current route. In order to achieve continuity, it is necessary to make the description of a multimodal trip interoperable, exchangeable, accessible from everywhere, and self-describing.

C. Personal Orientation and Guidance Along Trip Sections as Well as in Transfer Situations

Increased complexity [18], information overload, and being uneasy about unknown situations often prevent people from choosing multimodal travels. Whereas in-car journeys are assisted by navigation systems, there is nothing similar available for public transport or pedestrians, although orientation within unknown public transport systems is not easier than in road networks.

From a technical point of view, providing guidance and orientation in complex transfer buildings or from public transport stops to target addresses and vice versa is a challenging task. Pedestrian navigation in combined indoor/outdoor environments is still an open issue. The key questions address positioning, description of buildings, transition between indoors and outdoors, and the generation of route descriptions in the surrounding environment of public transport stops.

D. Interoperability of Travel Information Systems

Interoperability is one of the biggest problems in the domain of multimodal travel information. As can be expected, different modes of transport result in heterogeneous information systems to be involved in providing data. Problems arise at different levels. First of all, focusing on the data, there is the problem of nonintegrated digital transport networks. Digital road networks as typically used for in-car navigation do not include the public transport network. The same is true for infrastructure related to the public transport network like transfer points for motorized individual transport (e.g., P+R) or transfer buildings. For multimodal route planning, public transport networks and road networks have to be integrated. Another problem arises from different geographic reference systems. Experiences with different travel planners have shown that coordinates, although in the same coordinate reference system, do not point at the same objects, e.g., the same coordinate in one system points to a different road in another system or a coordinate in one system points to a P+R, whereas in the other system, it points to a street near the P+R. Recent projects (e.g., INTREST [21] in Germany) have addressed these shortcomings and have developed integrated multimodal geographic reference systems.

At the service level, significant efforts toward standardized service descriptions and interfaces have been made. International standards like XML, OpenGIS, and OpenLS[6] or DELFI [31] have brought significant advancement; however, currently used route planning, navigation, gazetteer, and map services are still quite far away from being interoperable. Services from different domains (e.g., route planning for cars, route planning for public transport, timetable information, parking information, real-time traffic data) are typically not interoperable. For achieving interoperability, an additional interoperability layer for integrating these services has to be provided.

Concerning end-user devices and applications, web standards have brought a good degree of interoperability to web-based clients. However, when it comes to mobile devices, heterogeneity is prevalent. In-car navigation systems are typically standalone applications tailored to one specific device. Open interfaces and possibilities for data exchange are rare. Experience has shown that bringing multimodal route information to in-car navigation systems is a challenge. Mobile devices like smart phones suffer from incompatible characteristics such as heterogeneous functionality, limited resources, display properties, or interaction modes, and are error prone. Similar user interaction on different devices is a requirement in order to cope with usability issues.

IV. RELATED WORK

According to the key research questions described in Section III, we classify related work along the following categories: multimodal journey planning, theory of way finding in public transport buildings, pedestrian navigation pilot systems, and indoor-positioning technologies.

Multimodal journey planning is a relatively well-researched area, and some of the research prototypes are already in commercial usage. EU-Spirit [10] is a European travel information system offering the calculation of door-to-door travel itineraries between European cities or regional areas. Beside the operational system, results include open interface definitions and harmonized metadata. The main goal of the ISCOM [22] project was to model the ways to and from public transport stops in a geographic reference system in order to integrate these paths into the multimodal routing network. Results from the ISCOM project are the basis for the IJP provided by Mentz Datenverarbeitung GmbH,[7] which was used for our prototype applications. Personalization of routes was one goal of the German research project “Der orientierte Mensch” [8]. One of the results was the possibility to store public transport or car routes (a combination is not possible) in a personal travel map for on-trip access on mobile devices. The Smartkom Mobil [16] project combines car and pedestrian navigation and includes the search for parking facilities near sights. A special emphasis is given to different interaction possibilities with digital maps. To summarize, none of the above projects focuses on the combination of mobile multimodal trip management and guidance along multimodal routes.

The human navigation and way-finding process in public transport buildings is based on concepts of human spatial cognition [7], [15]. Rüetschi and Timpf [37], [38] developed a conceptual model for describing the way-finding process in public transport stations. We used this conceptual model for modeling transfer buildings. Fontaine and Denis [12] analyzed spatial human cognition in subway stations. One of the results of the study with several users is that directing signs are important elements for the navigation and way finding in public transport stations. This result is also confirmed by May *et al.* [27] in a requirements study of pedestrian navigation. Our approach builds upon theoretical concepts of way finding, focusing on the design and implementation of navigation aids. Especially, the consideration of path segment types and signs in the generation of maps and guidance instructions addresses spatial human cognition.

There are many pilot projects that address different topics of pedestrian navigation, like user interaction, positioning, cartographic visualization, and data transfer. REAL [1] and M3I [25] are developed for indoor and outdoor environments. REAL describes a hybrid navigation system that adapts the

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[6] http://www.opengeospatial.org/.

[7] http://www.mentzdv.de/.

presentation of route directions to different output devices and modalities. M3I presents an approach that connects a variety of specialized user interfaces to achieve a personal navigation service spanning different situations. The NAVIO project [13] analyzes important aspects of designing a pedestrian navigation system for indoor and outdoor environments. The main parts of the project are integrated positioning technologies, multicriteria route planning, and multimedia route communication. LoL@ [28] is a pedestrian navigation system for tourists, which operates on smart phones. LoL@ focuses on the cartographic visualization of multimedia content. As far as we know, there exists at present no pilot system that focuses on guidance of public transport passengers in transfer facilities.

Addressing the field of positioning, Retscher and Thienelt [36] discuss suitable location technologies for pedestrians. In their study, they test and demonstrate different positioning technologies like satellite positioning, cellular phone positioning, dead reckoning sensors for measurement of heading and traveled distance, and barometric pressure sensors for height determination. For indoor positioning, most of the prototypes are based on Infrared, wireless LAN (WLAN), or Bluetooth [11], [19], [25], [40]. Whereas Infrared needs line of sight, WLAN positioning needs costly calibration and cannot be accessed by typical smart phones. Existing Bluetooth positioning systems are mainly server based and thus require a costly installation procedure. In our approach, the requirements were to support an easy and cheap installation procedure and the use of off-the-shelf smart phones.

V. DESIGN OF A PERSONAL TRAVEL COMPANION

On the basis of the requirements outlined above, our design for a multimodal personal travel companion focuses on integrated information systems for multimodal journey planning and on-trip assistance. While the multimodal journey planner provides comprehensive functionality for personalized route planning in the pretrip phase, the mobile travel companion allows on-trip multimodal trip management, orientation, and guidance.

A. *Multimodal Journey Planning*

Multimodal journey planning is possible in the pretrip phase using a web application and in the on-trip phase using the personal travel companion on mobile devices like smart phones or on in-car navigation systems. Personalized multimodal routes can be stored centrally on a server and accessed during the journey. The central storage and mobile access on different end-user devices addresses the requirements for personalized trip management and continuous mobile access. In the following sections, we describe the essential features concerning multimodal route calculation and personalization in order to cope with the requirements.

1) Multimodal Route Calculation: Multimodal route calculation is done "door-to-door." The reference points may be addresses, entrances to a point of interest, or public transport stops. If the journey planner is accessed in the on-trip mode, the start point can also be determined via a coordinate from an automatic positioning system. The route is calculated on integrated public transport, road, and pedestrian networks. The networks are connected at defined transfer points and are based on a common geographic reference system. The output of the route calculation is a detailed overview of possible connections between route sections for cars, public transport, and sections for walking. The personal preferences are considered in the route calculation process. The whole route is also visualized on a map. Detailed maps for transfers can be requested (Fig. 2).

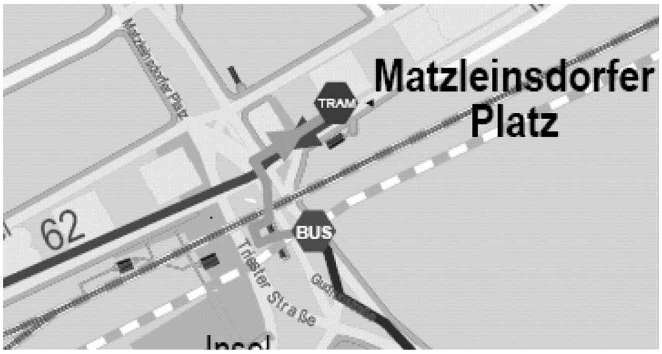


Fig. 2. Detailed map of transfer point Matzleinsdorferplatz, Vienna.

The calculation of detailed transfer routes is one concrete innovation of our multimodal journey planner. The prerequisite for this calculation is a model for transfer buildings including a routing-enabled pedestrian network. For modeling transfer buildings, we have adapted and extended a conceptual model originally proposed in [37] and [38]. The model distinguishes between the network space (the public transport network itself) and the scene space (the nodes of the public transport network, e.g., transfer facilities). Scene space describes the space where way finding takes place in public transport transfer facilities. This space is modeled by the schematic geometry, which is based on image schemes [23] and affordances [14]. The nucleus of the model is a hierarchical logical representation describing transfer buildings. Our adapted model builds on the main data categories: buildings, floors, regions, gateways, and items. Transfer buildings are cut into different floors with a hierarchical order. Floors are logically structured in different nonoverlapping walkable regions. For the connection of floors and regions, gateways are used. Typical representations of gateways are stairs, elevators, escalators, or ramps. For better orientation, it may be necessary to collect data for certain items. These items may be signs, ticket machines, shops, etc. Items can either afford a user interaction like ticket machines, or they can be used as orientation marks like signs. Items are linked to regions and are mainly used to provide a better interaction between way finders and the surrounding environment.

The second important part of our model of transfer buildings is the pedestrian routing network. This graph-based network consists of nodes and segments and has to be linked to the logical model of buildings and to road and public transport networks. To each node or segment, we are able to assign certain attributes that are used for route computation and generation of routing instructions. Nodes are marked with a floor number. When a path is computed, the order of floor numbers provides details whether the segment between two nodes leads up or down. Segments have type attributes. Type attributes can be an ordinary path (even level), stairs, escalators, elevators, or ramps. With this information, we are able to realize a selective route computation based on personal demands in order to optimize transfer time, route complexity, or walking effort [18]. Especially for wheel chair users, it is also important to know about single steps on an otherwise level floor or about the steepness of ramps. Another important attribute is the time needed to traverse a certain segment. The complete time for the transfer has to be considered for continuous route calculation. In order to provide personalized transfer times, we use time factors for each path segment. During the route calculation, these time factors are multiplied by the default velocity settings in the traveler's personal profile.

2) Personalization: Personalized route calculation means that personal preferences are considered by the multimodal routing service. Possible parameters are transfer options like how many transfers are preferred or the average walking speed during transfers, transport mode options like which modes should be excluded or which modes are preferred, mobility options like "I cannot use stairs" or "I need wheelchair accessible vehicles," time constraints like "I only want to walk for 10 minutes or less," and travel options like via stops (e.g., known P+R facilities). Calculated routes can be personalized and stored for later use. Moreover, the journey planner keeps a history of recently planned routes and entered locations.

B. On-Trip Assistance

For on-trip information and guidance, we propose two integrated applications, namely 1) multimodal extensions to in-car navigation systems and 2) a mobile personal travel companion on smart phones. The main goal of the research was to provide continuity and seamlessness. Mobile multimodal trip management on different end-user devices, navigation and orientation in transfer buildings, and navigation and orientation to the destination address, and continuous positioning are the approach we took to address these requirements.

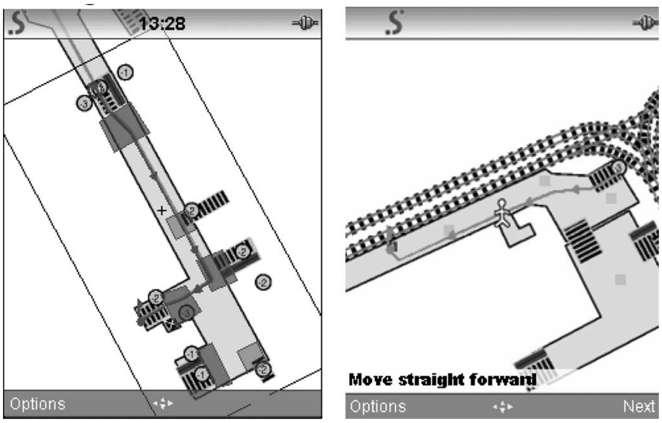
1) Mobile Multimodal Trip Management: Mobile multimodal trip management means that multimodal trips can be planned on mobile devices and that personalized preplanned multimodal trips stored on a central server can be accessed from different mobile devices. We considered in-car navigation systems, PDA-based car navigation systems, smart-phone-based car navigation systems, and a smart-phone-based travel companion. For car navigation systems, we found it useful to integrate the multimodal trip management as an extension to available navigation systems rather than replacing the systems. With these extensions, people can still use their preferred car navigation system but can also make use of multimodal functions such as loading pretrip planned routes, plan multimodal routes, or get information about nearby P+R and public transport schedules. The extensions to existing navigation systems guarantee the continuity and seamlessness of multimodal information and are considered as a valuable contribution to the convergence of information systems for motorized individual transport and public transport.

For personal assistance in public transport networks, we provide multimodal trip management on a smart-phone-based travel companion for palm use. Leaving the car at the P+R, the travel companion can be taken along which addresses the requirement for mobility and continuous mobile access to multimodal trip data. The same functionality as provided for in-car navigation is also available on the smart phone client: access to personalized preplanned routes, planning of multimodal routes between two addresses, planning of multimodal routes from the current position to a destination, and storing of routes on the central server. Moreover, due to personalization, the mobile client is able to track travelers and inform them about congestions on the route.

2) Navigation and Orientation in Transfer Buildings: Navigation and orientation in transfer buildings and on pedestrian routes are still in an early stage of research. There is some conceptual work on way-finding behavior in public transfer buildings [37], [38], but as far as we know, there is no existing pilot system that focuses on guidance of public transport passengers in transfer facilities. We define guidance as an information-technology-based tool assisting pedestrians in the process of way finding, which means a purposeful interaction with an environment with the defined aim to reach a certain place or goal [37], [38]. Our guidance system provides the following services.

- Select the optimized pedestrian route according to the user's profile in transfer buildings (e.g., from the car to the platform or from one platform to another).
- Give instructions for pedestrians in order to optimize their transfer and to improve their orientation.
- Select the most relevant information out of the scene space based on the calculated footpath in order to improve the interaction between way finders and the environment.
- Reduce complexity of the pedestrian's navigation task by providing detailed timetable information of public transport connections, detailed floor plans of transfer buildings, automatic positioning, and thus filtering of information from the individual's point of view [28].

The process of guidance in transfer buildings can be described as follows [35]: Travelers changing from car to public transport turn ON the personal travel assistant after leaving their car. The active route is automatically loaded on the smart phone. If the transfer building is equipped with an indoor-positioning system, the appropriate route section is activated. Information provided for this route section includes a detailed description of the transfer building, the logical model of the building, floor plans, the calculated transfer route, route instructions, and positioning information. The activation of the route section initiates the loading of the floor plan, zooming to the user's current position, and giving instructions on how to walk to the next decision point. Floor plans are simplified representations of the scene space, including floor numbers, walkable regions, calculated route segments, gateways, signs, and optional orientation marks. Beside general information on the building, floor plans typically only show data relevant for the calculated path. Thus, floor plans have to be generated dynamically from the model. Examples of floor plans are shown in Fig. 3.



Move straight forward

Fig. 3. Screenshots showing the map-based guidance in transfer buildings (manual and automatic navigation mode).

Regarding route instructions, it is important to avoid simple turn-by-turn instructions that are solely based on geometric information of the form “Walk nine meters straight and turn left.” Instead, instructions should refer to observable physical objects in the scene space in order to improve the interaction of pedestrians and the environment [33]. Referenced objects can be gateways, signs, or orientation marks. The generation of route instructions is based on a set of standardized text building blocks that allow us to create appropriate path descriptions for most cases. For complex scenes, it is possible to link manual route directions to specific path segments. This basic path description is combined with information from nearby landmarks and signs that are stored in the database. In doing so, it is possible to reference signs that do not explicitly refer to the traveler’s destination but point them in the right direction. In this fashion, we are able to automatically generate instructions like “Walk to the lower end of the stairs marked with the sign ‘Neubaugasse.’ Walk up the stairs.”

3) Navigation and Orientation to the Destination Address: As described in Section II-B, finding a destination address from the last public transport stop is challenging. For pedestrian routing and navigation, the road network as well as separately modeled pedestrian networks can be used. Pedestrian networks can either be extensions to street networks (e.g., sidewalks, pedestrian crossings, or pedestrian underpasses) or road-independent networks (e.g., transfer buildings, parks, or pedestrian zones). The important difference between road and pedestrian networks is that the routing network and the surrounding environment have to be modeled in a different scale. Whereas, for car navigation, it is sufficient to model roads in a large scale (e.g., coarse-grained road segments with attributes), for pedestrian navigation, paths and the surrounding environment have to be modeled in more detail in order to be of use for navigation and orientation purposes. Because of the slow movement of pedestrians, the perception of the environment is significantly increased, and thus, local landmarks and detailed walkable regions in scales of $1:500$ have to be shown on maps and referenced in route instructions. For example, the modeling of overground transfer facilities has to include public transport platforms, public transport infrastructure like tracks or bus stops, walkable pedestrian regions, nonwalkable regions, prominent buildings or other objects, connections to sidewalks of nearby streets, and pedestrian crossings. Maps or instructions generated on the basis of road network data cannot meet these requirements; thus, it was a challenging task to adapt the models and to generate fine-grained maps and routing instructions. For example, one significant adaptation had to be made to the precision of the coordinate reference system: For the generation of detailed pedestrian maps, the granularity had to be changed from a precision of meters to a precision of centimeters. Otherwise, it would not have been possible to generate a sufficiently precise map of geographic objects.

4) Positioning: The basis for navigation in outdoor as well as in indoor environments is positioning. Although our guidance system provides manually navigable maps and a list of step-by-step route instructions that can be manually acknowledged, the maximum convenience for travelers can be achieved with automatic positioning. In order to cope with the requirements for continuous assistance, we had to provide continuous positioning no matter whether users are indoors or outdoors. Whereas outdoor positioning is available in variable quality through the use of global positioning systems (e.g., GPS), indoor positioning has not yet reached the same level of maturity. For indoor positioning, numerous different approaches that vary greatly in terms of accuracy, cost, and used technology exist [19], [27]. In order to be applicable for our scenario, we determined the following acceptance criteria:

- to provide high enough accuracy to determine the region in which the user currently is;
- to have broad support of end-user devices;
- to work without cellular network connection;
- to be cost effective;
- to require little installation effort.

We opted for a Bluetooth-based solution because it met our requirements most closely. First of all, a great share of smart phones sold today incorporate this technology and thus will support automatic positioning without additional hardware on the client side. Furthermore, pretests showed us that we should reach a high enough accuracy for providing orientation and useful instructions for the way-finding process.

Most of the commercially available location systems based on Bluetooth (e.g., [2], [3], and [26]) use an infrastructure of interconnected Bluetooth access points. These access points permanently execute inquiries in order to detect nearby Bluetooth devices. Once discovered, their location is determined on the server side, and appropriate information is pushed onto the detected device. In large public transport stations, however, it would be very resource consuming or even impossible to install an LAN interconnecting the access points.

Our approach to a cell-based positioning system makes use of a client-side query and a set of passive Bluetooth beacons. The smart phone clients are constantly looking for beacons in the proximity that broadcast their unique ID. After receiving a beacon ID, the client looks up the associated position information in a list that is part of the building description. If all the relevant data for a transfer building are cached on the device, navigation will work without any network connection. This

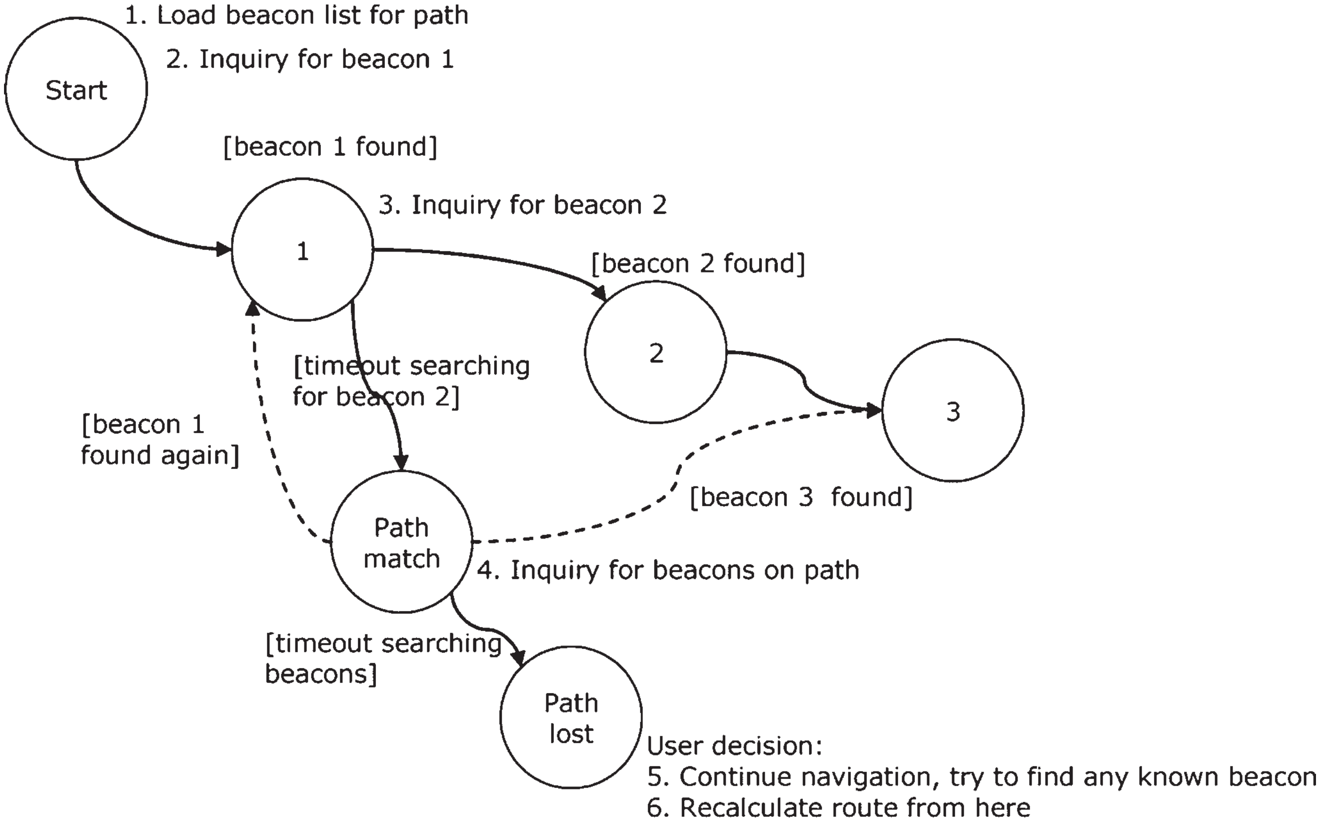


Fig. 4. State transitions of indoor navigation algorithm.

offline capability is a crucial requirement for, e.g., underground stations suffering from low cellular network coverage.

The beacons utilized for the pilot system (BlueLon Bodytags BT-002 [3]) have adjustable transmission power that allows for adjusting cell sizes. In this way, we are able to adapt it to the needed accuracy or to the room topology at hand (i.e., hall, room, or corridor). Ideally, cell sizes should be selected in a way that the covered area is not overlapping with the other beacons; otherwise, this would result in an ambiguous position.

Due to the signals' spherical propagation behavior, it is not always possible to completely separate individual cells (i.e., signals crossing floor bounds). To overcome this problem, we exploit the data model's hierarchical nature and use knowledge from the calculated path as well as information known from history. In a first step, we discard detected beacons that are outside of the current region.

Furthermore, we can determine a sequence of beacons that will be passed when walking along the calculated route. If still more than one beacon is seen and one of them is the next expected beacon, it is assumed that the user most probably moved one step further along the way. Likewise, if the next logical beacon is not found but the one following thereafter is, we consider one beacon to have been skipped (Fig. 4).

Another challenging characteristic of the Bluetooth technology is the rather long delay from entering a device's transmit range until its actual detection. This can take up to 13 s and imposes a lower bound to the usable cell sizes, because a user may have passed the beacon without detecting it. However, most of the time, beacons are found within the first 5 s [29]. Practical tests have shown that reissuing the query after this duration yields higher detection probability. Together with the fault tolerance mechanism outlined above, we achieved a usable cell size of down to 4 m, which is sufficient for providing useful route instructions.

As described in the requirements above, a crucial requirement for the personal travel companion is continuity. Continuity in positioning means that transition from indoor to outdoor or vice versa is done automatically.

In our approach, automatic transition is achieved through tagging regions with the positioning mode. Outdoor regions are mostly tagged with GPS, whereas indoor regions are tagged with Bluetooth. This approach works well for outdoor to indoor transitions, where the navigation application simply disconnects from the GPS receiver and starts searching for Bluetooth beacons. Having found the first beacon, the personal travel companion knows the indoor position and continues to give route instructions for the indoor route.

Transitions from indoor to outdoor are done in a similar fashion: when the last beacon before an exit is found, the smart phone client stops querying and connects to the GPS receiver. However, as commonly known, we are also facing the problem that currently available GPS receivers need an initialization time of about 30 s up to several minutes to deliver a reliable position. We try to address the problem by pretending that the user is constantly moving along the calculated path until we are able to determine the exact location. In most of the cases, this behavior will lead to better results, because there is a higher chance of walking out of the GPS signal shadowed area near

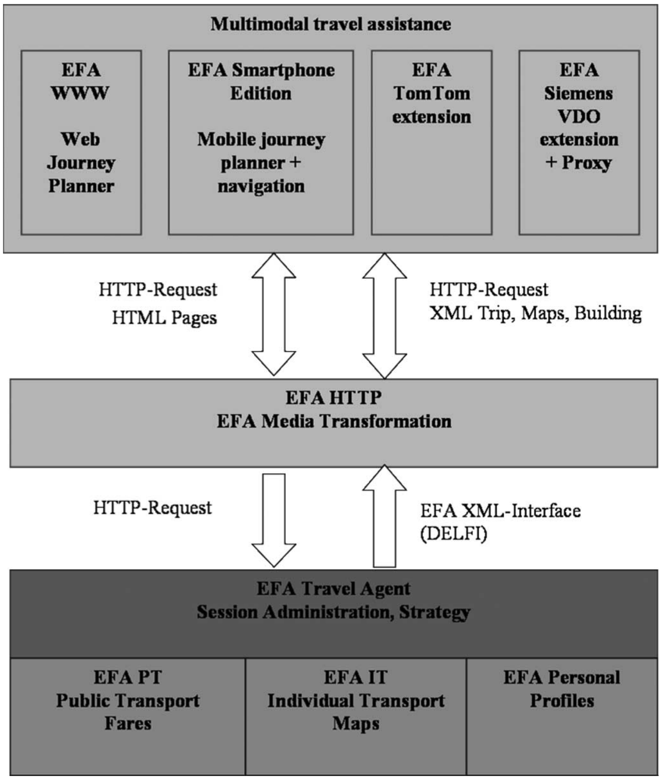


Fig. 5. Overview of the system architecture.

the building. We expect significantly better results once A-GPS [9] becomes more widely available.

VI. PROTOTYPE APPLICATIONS AND IMPLEMENTATION

In this section, we give some implementation-specific details on the prototype applications. An overview of the system architecture is given in Fig. 5. The system architecture is built of three layers, namely 1) a client layer, 2) an interoperability layer called Media Transformation, and 3) the multimodal journey planner on the server side. For multimodal journey planning, we use the IJP from Mentz Datenverarbeitung GmbH. This service provides all the personalization functions described in the requirements above. Adaptations were necessary for calculating personalized pedestrian routes and for requesting trip information, maps, descriptions of route segments, and descriptions of transfer buildings. The IJP provides a standard access interface based on XML and the DELFI protocol. An interoperability layer called Media Transformation ensures compliance with different client applications.

Different client applications were implemented for the pilot system. The applications include a proxy-based extension for a Siemens VDO in-car navigation system, an extension module for TomTom Navigator, and a personal travel companion application on smart phones. The Web Journey Planner was adapted in order to show detailed transfer maps and transfer descriptions.

The car navigation systems were extended in a way that made it possible to load preplanned multimodal routes from a server, to show the different sections of the trip on the device, and to load the car section into the navigation system. Moreover, it was possible to plan multimodal routes from a current location to the destination address entered in the car navigation system, to find a suitable P+R, to get information on the public transport route, and to store the route on a server for later use on the smart-phone-based personal travel companion [4], [5].

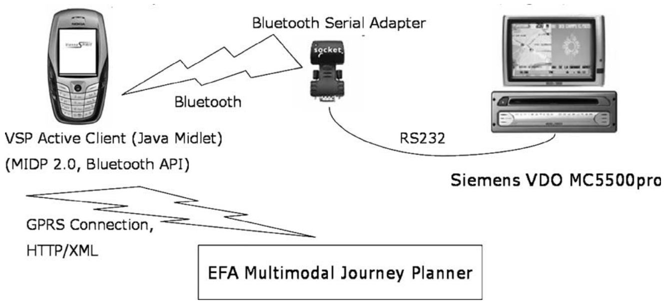


Fig. 6. Connection of the Siemens VDO PC 5510pro navigation unit and the multimodal journey planner.

The Siemens VDO PC5510pro in-car navigation device offers a serial interface for data exchange and remote access. This gave us the opportunity to extend the user interface with additional menu items pushed from a proxy application running on a smart phone. The smart phone was connected via Bluetooth to the navigation system and communicated with the server system via a cellular network [5] (Fig. 6).

As a PDA-based car navigation system, we used TomTom Navigator. TomTom Navigator offers an API, which can be used to read the current position, the destination, and to integrate custom functionality for multimodal trip management. The PDA communicated with the server via the cellular network and an HTTP/XML-based protocol [5].

The smart phone client was realized with the mobile Java platform J2ME. The reference device is the off-the-shelf smart phone Nokia 6630. The building blocks on the client are as follows:

— a microbrowser for interaction with the multimodal journey planner and presenting server-calculated trip information;
— a plugin mechanism for the microbrowser to start specific extension modules (Smartlets and Services);
— a navigation plugin (Navigation Smartlet) for handling all navigation-specific user interactions;
— a location service and two different location providers for automatic location acquisition;
— a local data cache for caching trip and navigation relevant data (necessary for offline use).

The main interaction concerning trip planning and browsing trip information on the client is done via a microbrowser. This microbrowser allows rendering of server-generated pages similar to xHTML pages. However, advanced functionality on the client cannot be handled appropriately by a standard xHTML browser. Thus, the browser is enabled for handling small extension modules called Smartlets. The Smartlets are referenced in the markup language by proprietary tags. Upon activating a Smartlet link, the microbrowser starts the corresponding Smartlet and hands over the control to the appropriate module. This mechanism constitutes a tradeoff between server-generated user interfaces, where the design is easily

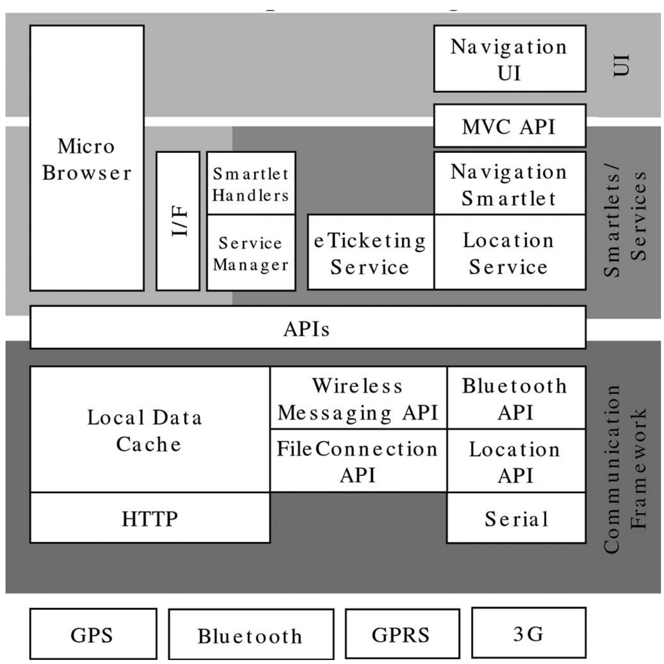


Fig. 7. Overview of the J2ME client architecture.

exchangeable, and additional functionality, which allows using local resources like positioning infrastructure on the smart phone device.

One of these Smartlets is the Navigation Smartlet. The Navigation Smartlet asks the local data cache for the journey data of the current trip including route descriptions, building descriptions, and maps. Maps are delivered as geo-referenced bitmaps or vector graphics. Bitmaps can be split up in multiple tiles in order to improve loading times (Fig. 7).

The local data cache either uses locally stored data or fetches data from the server. This mechanism allows for preloading all the data for a whole journey or at least for one transfer building. Different strategies for preloading of data are possible.

Navigation Smartlet performs the entire map rendering and communicates with locally available positioning providers like GPS and/or Bluetooth providers. Communication with Bluetooth is implemented using the Java Bluetooth API (JSR-82), which is available on recent smart phones like the Nokia 6630. Communication with the GPS receiver is done via the NMEA protocol over a serial Bluetooth connection. Without automatic positioning, the user has the possibility of scrolling maps manually and to switch to other floors by interactively selecting gateways on the map. Moreover, users can also jump step-by-step through the instruction list and match the instructions with their actual position manually.

VII. EVALUATION

The prototypes of the described system were developed and tested over the last three years. We demonstrated the prototypes in different pilot systems and organized test settings in the field.

The development of the Siemens VDO proxy application on a smart phone was cumbersome, since no simulation toolkit was available. We had to continuously test the proxy application in combination with the navigation device.

With field tests, we tested the system for applicability in real-world scenarios. We installed the in-car navigation system and the PDA-based navigation system in a Chrysler Voyager Concept Car. We selected two test regions in Salzburg and Vienna. We identified the main corridors from each direction leading to the city centers and predefined four test trips covering the corridors. For the test trips, we selected start points and target addresses. Within the route corridors, we identified relevant P+R facilities and car parks with public transport connection. For all of the test trips, we determined the ideal and all the possible transfer points from car to public transport. The test scenario was to drive along the test routes with the concept car according to a predefined test plan. In the test plan, we planned the routes exactly, including the expected duration for going along the routes, the locations, where to start the request to our multimodal journey planner, and the expected results. During the test trips, we logged relevant parameters, including the location of the car at the time of request, the exact time of request, the round trip time of requests, the result of the request, or error messages. We used the test results to optimize the prototype applications and did several reruns of the tests. The test phase for the in-car navigation systems was going on for one month. Relevant outcomes from the tests were the following.

- Requests to the multimodal journey planner were successful in about 60% of the test cases.
- About 25% of the requests terminated without results because no P+R or no public transport connection could be found.
- About 15% of the requests terminated because of a timeout caused by poor network connection in the moving car.
- Poor network connection and high latencies also caused long round-trip times (about 30–60 s).
- Long round-trip times had the effect that in many situations, we had already passed the suggested P+R by the time we got the result.
- Slight changes in the location information caused unexpected and irreproducible variations of the results.

In addition to the system tests, we also did user tests of the in-car multimodal extensions during public events around Vienna and Salzburg. During AGIT 2004,[8] we provided hourly round trips with the concept car for five visitors each, demonstrating multimodal trip planning on the Siemens VDO and TomTom navigation systems. People found the multimodal extensions useful. Especially, people who were not familiar with the local public transport system found the suggested P+R facilities and the public transport connections useful. However, most of the people criticized that using the system while driving would probably take up too much of the driver's attention and would therefore be hazardous.

For testing the navigation in transfer buildings, we followed a three-step testing strategy. First, we developed and tested the application on a simulator. Second, we simulated an underground station in our office building and tested the navigation in this simulated environment. Third, we installed test

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[8] AGIT: Conference and Exhibition for Applied Geoinformatics, Salzburg.

environments in two different buildings for field tests. During AGIT 2005, we implemented a test installation of the Bluetooth-based indoor navigation system, which was publicly accessible and thus tested by approximately 60 persons. With the pilot system, people were able to plan multimodal routes from any address in Salzburg to selected locations at the conference venue (e.g., a lecture auditorium or a specific exhibitor). The multimodal route included the pedestrian route from the nearest public transport stop to and inside the building. We tested outdoor as well as indoor pedestrian navigation. Important evaluation results could be generated from the automatic transitions between outdoor and indoor. Although the proof-of-concept was approved, we got some hints on the weaknesses, e.g., inaccurate GPS positions could prevent timely transition, and long setup times of the GPS receiver could prevent people from continuing the navigation after transition from indoors to outdoors. We tried to cope with these shortcomings in later prototypes, e.g., allowing for manual acknowledgement if automatic transition cannot be done reliably. Altogether, people assessed the multimodal route planning as well as combined indoor/outdoor navigation as useful.

In autumn 2005, we installed a test environment in the Vienna underground tram station Matzleinsdorfer Platz. The whole station was equipped with 30 Bluetooth beacons on the ceiling at a distance of about 10 m. The installation of the test beacons took about 1 h. Afterwards, the positioning system was ready to use. During the time frame of one week, we thoroughly tested the personal travel companion application. Although the application was tested in the office building before, we found a number of malfunctions. It was a challenge to calculate optimized transfer routes, to provide reliable positioning, to cope with transitions from indoor to outdoor and vice versa, and to provide meaningful maps of buildings as well as guiding instructions. After one week of testing, the application was prepared for the user tests. Travelers were guided by the prototype of the personal travel companion on smart phones along six predefined test routes. Twenty test persons participated in the test setting; the average assessment was 2.43 on a scale from 1 (best) to 6 (worst). Four persons found the travel companion very good, nine persons good, two persons satisfying, and five persons not useful. Points of criticism were the complicated input of addresses for route planning and orientation problems with the maps provided. One important outcome was that orientation of people can be improved by turning the digital floor plan on the mobile phone in a way that the route is leading ahead in walking direction. Another important outcome concerning Bluetooth positioning was the proof in principle that this is a viable approach; however, many fine tuning concerning the adjustment of the beacons was necessary in order to improve positioning accuracy to a sufficient level. In order to further improve positioning accuracy, reliability, and usability, more research on this topic has to be done in the future.

VIII. CONCLUSION

In this paper, we described typical travel situations during multimodal journeys and barriers preventing people from choosing multimodal travel options. To address these barriers, we stated four requirements for a multimodal personal travel companion. With these requirements in mind, we proposed the design of digital multimodal travel assistance applications focusing on personalized and integrated multimodal trip management, continuous on-trip access to multimodal trip information, navigation, and orientation in transfer buildings as well as on outdoor pedestrian routes. Our approach of personal travel assistance makes a considerable contribution to the integration of in-car navigation and multimodal trip management, mobile multimodal trip management, and advanced guidance in complex transfer buildings.

The field tests, on one hand, successfully demonstrated the integration of different information systems and the resulting benefit for travelers. On the other hand, still many open issues have to be solved in order to transfer the prototype into a product for the mass market. For future research and development on the way to continuous multimodal travel assistance, we have identified the following key success factors.

- Car navigation systems are not prepared for multimodal extensions. It is necessary to call upon manufacturers to integrate multimodal extensions or at least to open navigation systems for third-party extensions.
- Navigational data sets are mainly targeted at car navigation. Standards for multimodal data acquisition and exchange, especially for the last mile, are missing. These standards will be a necessity for area-wide multimodal travel assistance systems.
- The key success factor for developing location-based services on mobile devices is to design applications strongly in accordance with user needs and to build on experiences of users at a very early stage of development.
- Systematic and standardized approaches for developing and testing mobile applications have to be established in future research. The lack of approved methodologies results in new applications without any guaranteed quality for users. The lack of quality is an inhibitor to broad user acceptance of digital assistants.
- Well-designed field tests for location-based services are a crucial success factor. The continuous change of context parameters obviously leads to a number of test cases in the field. These test cases are necessary in order to guarantee reliability of mobile applications and cannot be simulated in an office environment.

In the future, our research will focus on the open issues and on possibilities to transfer the prototypes into products together with commercial partners.

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