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Methods, Framework and Architecture for Designing and Investigating Smart City Applications

Habilitation theses

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Abstract

Rapid technological development and the introduction of smart services make it possible for modern cities to offer an enhanced perception of city life for their inhabitants. This covers providing some ubiquitous information and communication technologies (ICT) infrastructure, and smart applications and services to the citizens. For example, providing broadband Internet access to citizens, communities, public institutions and developing businesses is a basic demand today. Smart services, like automated meter reading (AMR), support for intelligent parking or live public transportation timetables can make everyday life easier. AMR systems offer a convenient solution for collecting utility consumption data. An intelligent parking assistance system could alleviate the problem of finding free parking spaces in parking lots or in city centers especially during rush hours that is a really challenging if not an impossible task. By monitoring the occupancy of the parking slots and offering some aid to the drivers in selecting an available one and navigating to there can substantially reduce parking space seeking time, CO_2 emission and helps avoid driver frustration. A lively updated public transport information service can aid travel planning and save unnecessary waiting times.

However, the traditional solutions are usually not appropriate for designing and implementing such infrastructure and smart services, and/or may demand huge investments. New methods and approaches have to be explored and developed. For instance, participatory sensing, or often called mobile crowdsensing, is an alternative approach for environment monitoring in smart services. In this case, the power of the crowd has been exploited in data collection via the inhabitants' mobile devices because with the proliferation of smart-phones more and more computing and sensing power becomes available at the hands of urbanites. This paradigm provides an economic, and almost ubiquitous sensing infrastructure in urban environment.

In the recent years, we put the focus of our R&D work on examining and solving practical issues in the smart city domain. The achieved new research results are presented in this booklet in seven theses, which are organized into three thesis groups. The first thesis group contains contributions to network and system planning. Thesis 1.1 introduces a new design methodology to plan and build wireless community networks. Thesis 1.2 describes an evaluation method to facilitate wireless technology selection in AMR system planning. Thesis group 2 deals with indoor positioning and navigation. Thesis 2.1 proposes a new algorithm for placement optimization of wireless reference points to be used in triangulation based indoor localization. Thesis 2.2 proposes a new method for Wi-Fi signal fingerprint based indoor positioning and navigation. Thesis group 3 focuses on crowdsensing based smart city applications. Thesis 3.1 introduces a new communication model and framework to facilitate the development of crowdsensing based smart city applications. Thesis 3.2 proposes an architecture for crowdsensing based transit feed service. And finally, thesis 3.3 proposes a purpose-built simulation environment for investigating crowdsensing based urban parking. These results have been developed and successfully applied in national, international and/or industrial R&D projects. The developed solutions have been validated via prototype implementations for proof-of-concept purposes and/or applied in case studies.

Smart cities are huge and complex ecosystems, which provide still plenty of room for research, development and innovation. The results covered by the presented theses can contribute to and facilitate the design and implementation of smart city applications and services.

Kivonat

A gyors technológiai fejlődés és az intelligens szolgáltatásokban rejlő lehetőségek elősegítik, hogy a modern városok emelt színvonalú városi létet biztosítsanak lakóiknak. Ehhez szükség van egyrészt egy mindig, mindenhol elérhető kommunikációs infrastruktúrára, másrészt a városlakók életét megkönnyítő okos alkalmazások fejlesztésére. Például szélessávú Internet hozzáférés biztosítása a városlakók, közösségek, városi intézmények és a feltörekvő vállalkozások számára ma már alapvető elvárás. Az intelligens szolgáltatások, mint az automatikus mérőóra leolvasás, intelligens parkolás vagy egy valós időben frissülő tömegközlekedési menetrend, egyszerűbbé tehetik a mindennapi életet. Az automatikus mérőóra leolvasó rendszerek kényelmes megoldást biztosítanak a közművek (víz, villany, gáz) fogyasztási adatainak összegyűjtéséhez. Egy intelligens, parkolást támogató rendszer segítségével egyszerűbbé válik a szabad parkolóhelyek megtalálása parkolóházakban vagy belvárosi környezetben, ami elég nagy kihívás, olykor lehetetlen küldetés, különösen a csúcsforgalmi időszakokban. Ez a rendszer folyamatosan figyelemmel kíséri a parkolóhelyek foglaltságát, és támogatást nyújt a megfelelő szabad parkolóhely kiválasztásához és megközelítéséhez, ezáltal lényegesen csökkentve a parkolásra fordítandó időt, a környezetszennyezést és a sofőrök frusztráltságát. Egy valós időben frissülő tömegközlekedési menetrend szolgáltatás segítségével pontosabbá válik az utazás megtervezése és minimálisra csökkenthető a felesleges várakozás.

Azonban a tradícionális megoldások általában nem megfelelők ezen infrastruktúra ill. intelligens szolgáltatások tervezéséhez és megvalósításához, és/vagy jelentős beruházást igényelnek, így szükség van új eljárások és megoldások kidolgozására. Például a közösségi érzékelés egy megfontolandó alternatíva a környezet monitorizására okos város alkalmazásokban. Ilyenkor a közösségben lévő potenciál kiaknázásával történik az adatgyűjtés a városlakók mobil eszközein keresztül, mivel az okostelefonok robbanásszerű terjedésének köszönhetően egyre nagyobb számítási és érzékelési kapacitás áll rendelkezésre a városlakókhoz köthetően. Így a közösségi érzékelés egy költségkímélő és többé-kevésbé mindig és mindenhol elérhető érzékelési infrastruktúrát biztosít nagyvárosi környezetben.

Az elmúlt években az okos város témakörrel kapcsolatos gyakorlati problémák vizsgálatára és megoldására összpontosítottuk K+F tevékenységünket. Az így elért új eredmények hét tézis formájában kerültek megfogalmazásra három téziscsoportra bontva ebben a tézisfüzetben. Az első téziscsoport hálózat- és rendszertervezéssel kapcsolatos eredményeket tartalmaz. Az 1.1 tézis bemutat egy új tervezési eljárást vezetéknélküli városi közösségi hálózatok tervezéséhez és megvalósításához. Az 1.2 tézis egy kiértékelési eljárást ismertet, amely megkönnyíti a megfelelő vezetéknélküli technológia kiválasztását automatikus mérőóra leolvasó rendszer tervezésekor. A második téziscsoport témája beltéri pozicionálás és navigáció. A 2.1 tézis egy új algoritmust mutat be vezetéknélküli referenciapontok optimális elhelyezésére háromszögelést alkalmazó beltéri pozicionálás esetén. A 2.2 tézis ismertet egy új módszert Wi-Fi jelerősség térkép alapú beltéri pozicionáláshoz és navigáláshoz. A harmadik téziscsoport a közösségi érzékelésen alapuló okos város alkalmazások témakörével foglalkozik. A 3.1 tézis bemutat egy új kommunikációs modellt és keretrendszert közösségi érzékelésen alapuló okos város alkalmazások tervezésének és implementálásának támogatásához. A 3.2 tézis ismertet egy közösségi érzékelésen alapuló, valós időben frissülő tömegközlekedési menetrend szolgáltatás architektúrát. És végül a 3.3 tézis bemutat egy célirányosan kifejlesztett szimulációs környezetet közösségi érzékelés alapú városi parkolás vizsgálatára. Ezek az eredmények hazai, nemzetközi és/vagy ipari K+F projektek keretein belül kerültek kidolgozásra és alkalmazásra. A kifejlesztett megoldások prototípus implementációkon keresztül lettek validálva ‘proof-of-concept’ jelleggel, illetve esettanulmányokban kerültek felhasználásra.

Az okos városok nagy és komplex ökoszisztémák, amelyek számos kutatási, fejlesztési és innovációs lehetőséget tartogatnak még számunkra. Ezen tézisfüzetben bemutatott eredmények elősegíthetik okos város alkalmazások és szolgáltatások tervezését és megvalósítását.

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1 Introduction

1.1 Motivations

In the 21st century, environmentally sustainable living style more and more comes to the front. Cities attract an increasing population with their greater political and economical power. These cities also develop rapidly in technology as their core systems are getting interconnected and getting more intelligent. To seize this opportunity enhanced infrastructure is needed. However, the development of cites are not any more solely depend on the city's basic (physical) infrastructure but more and more correlated to the availability of information and communication technologies (ICT) supporting knowledge sharing about cities. More formally, Gartner defined smart cities as "multiple sectors cooperating to achieve sustainable outcomes through the analysis of contextual real-time information shared among sector-specific information and operational technology systems" [11]. In this context, real-time information is big data and the contextual sharing system is generally believed to be realized by the Internet of Things (IoT). IoT is visioned to become true with over 50 billion connected devices around 2020 [12]. As a conducent of this evolution intelligent applications are to be designed and developed which can exploit the collected huge amount of information and make our cities even smarter by enriching our everyday life.

Talking about smart cities providing some ubiquitous ICT infrastructure, and smart applications and services is a must today. For instance, providing broadband Internet access to citizens, communities, public institutions and developing businesses has become a strategic objective for governments and international organizations worldwide. Services, like automated meter reading (AMR), intelligent parking or real-time public transportation timetables are more and more common in cities providing high living standard for their inhabitants.

However, the design, development and investigation of such smart city ICT infrastructure, applications and services are usually a complex issue, which requires new methods and solutions. In the recent years, we put the focus of our R&D work on examining practical issues in the smart city domain and elaborating methods, solutions and prototypes which can be applied in implementing smart city applications and services.

1.2 Research Objectives

There are no unified methods and techniques to design and develop smart city applications and services. This domain is huge and overspans several sectors from public services to transportation with their sector specific properties. Motivated by the projects accomplished in cooperation with our industrial or research partners the basic goal was to gain insight into some specific areas, pick up practical issues and challenges, and develop methods and solutions which can be exploited at least in these areas.

The objectives covered by the presented theses were the following:

- Compared to traditional telecom networks, explore the differences and develop a systematic design methodology to plan and build wireless community networks or often called wireless municipal networks [13], which can serve as ICT infrastructure to provide digital public administration services to smart city inhabitants;
- Develop a systematic evaluation method to facilitate the appropriate wireless technology selection in AMR systems;
- Develop theoretical and practical methods to implement radio frequency based indoor positioning and navigation which can be used in indoor parking garage environment;

- Develop a generic communication model and framework which can facilitate the development of crowdsensing based smart city applications when the power of the crowd is used to collect environmental information;
- Develop a service architecture for crowdsensing based transit feed service which implements a live public transportation timetable;
- Analyze and investigate the properties of crowdsensing based urban parking to facilitate the design of such a service.

1.3 Research Methodology

The following tools and techniques were successfully applied in the numerous industrial and research projects I led or participated in the last ten years:

- Problem and state-of-the-art analysis defining a set of criteria to be fulfilled in designing a solution;
- Originate the task to be solved from a well-known problem and use an appropriately modified solution (method/algorithm) of this problem to derive a solution to the original task. For instance, one of the theses proposes an algorithm to find the optimal number and position of reference points to be used in indoor localization. This task is very similar to an NP-complete graph theory problem, which can be solved by heuristics like simulated annealing. This heuristic was also used with some modification successfully to solve the original task;
- Simulations on one hand to analyze the performance of the proposed method/algorithm; on the other hand, to analyze problems which are too complex to be investigated analytically;
- Prototype implementation and measurements as a proof-of-concept to validate the proposed method/solution in real environment when it is possible.

1.4 Organization of the Theses

The theses are organized as follows. The first thesis group (Section 2) contains contributions to network and system planning. Thesis 1.1 introduces a new design methodology to plan and build wireless community networks. Thesis 1.2 describes an evaluation method to facilitate wireless technology selection in AMR system planning. The proposed methods have been successfully applied in case studies of industrial projects.

Thesis group 2 (Section 3) deals with indoor positioning and navigation. Thesis 2.1 proposes a new algorithm for placement optimization of wireless reference points to be used in triangulation based indoor localization. Thesis 2.2 proposes a new method for Wi-Fi signal fingerprint based indoor positioning and navigation. The performance of the proposed algorithm was analyzed in simulations. The fingerprint based positioning method was validated via a prototype implementation in an indoor parking garage of a shopping mall.

Thesis group 3 (Section 4) focuses on crowdsensing based smart city applications. Thesis 3.1 introduces a new communication model and framework to facilitate the development of crowdsensing based smart city applications. Thesis 3.2 proposes an architecture for crowdsensing based transit feed service. Thesis 3.3 proposes a purpose-built simulation environment for investigating crowdsensing based urban parking. The validation and proof-of-concept implementation of the proposed framework and architecture were carried out in the frame of R&D projects.

2 Network and System Planning

2.1 Motivations and Goals

Planning ICT networks and systems requires a continuous innovation and adaptation of new methods and approaches due to the dynamic technological developments. This thesis group deals with issues related to planning wireless community networks and AMR systems.

Broadband Internet access is a must today for citizens, communities, public institutions, and developing businesses. A large number of initiatives, under the collective name community networks, have been launched in North America as well as in Europe. By creating telecom infrastructure in underserved regions, local governments can create a healthy climate for economic development, help startups grow, and bring new businesses into the region. A community network means the combination of the telecommunication infrastructure, the services provided on it, and the specific business model to operate the infrastructure and provide services. Since most community network projects are being initiated, implemented, or governed by city administrations, the term municipal network or municipal wireless network is also used. For building municipal networks wireless technologies offer handy solutions starting from the ubiquitous Wi-Fi through WiMAX and 3G/4G/5G mobile. However, planning, deployment and operation of municipal networks have been challenging tasks. As opposed to telco networks, there is a specific set of services cities or regions want to implement. The applications and services have to be made accessible to a wide range of geographically diverse users, no matter where they are located. Unlike in telco networks, cities can more freely choose communication technologies, including emerging ones, as they do not have the stringent business requirements the telcos have to meet, such as high return on investment (ROI) or totally risk-free adaptation of new technologies. With regard to this topic, our goal was to develop a systematic design methodology to plan and build wireless community networks.

On the other hand, automated meter reading (AMR) is the technology of automatically collecting consumption, diagnostic, and status data from different utility metering devices and transferring that data to a central database for billing, analysis and troubleshooting. AMR devices are basically water, gas, electricity, and heat meters. However, automatic meter reading requires the deployment of an appropriate infrastructure. An enhanced variant of such an infrastructure is called AMI (Advanced Metering Infrastructure) that, besides collecting metering data, also enables two-way communications with the meter. The AMR/AMI system saves utility providers the expense of periodic visits to each physical location to read a meter and the metering data can be collected remotely with arbitrary periodicity in an efficient and economic way. In addition to that, thanks to the continuous monitoring of the meters failures or misuse can be detected immediately making possible instant intervention. Moreover, billing can be based on near real-time consumption rather than on estimates. This timely information and its analysis can help both utility providers and customers to better control the production and consumption of public utility services. For communications between the meters and the concentrators, wired or wireless (e.g., ZigBee, Wireless M-Bus, Wi-Fi, proprietary radio) connections are typically used. With regard to this topic, our goal was to develop an evaluation method to compare systematically the candidate wireless technologies which can facilitate the selection of the most suitable technology to build AMR systems.

2.2 New Results

2.2.1 Thesis 1.1: Design Methodology for Wireless Community Networks

A systematic design methodology has been developed to plan and build wireless community networks. This method defines 6 steps and their relations.

The corresponding results have been published in [1, 2]. There are significant differences between planning of community networks and Internet or other service providers' design methodology. Key differences include the following requirements for wireless municipal networks:

- Ubiquitous Wi-Fi access covering the whole territory of the community (e.g., a city, a county, or a province), no matter if some parts are sparsely populated and/or geographically challenging;
- Users should be provided with other forms of access as well, depending on the application and the users' needs and economic possibilities. Thus, on one hand, the applications must be made accessible via cheap communication services, and on the other hand, bandwidth-demanding customers have to be served, too;
- Mobility or at least nomadic access across the covered area must be supported;
- Support must be provided for a multiplicity of user devices from simple mobile phones through PDAs and laptops to videoconferencing equipment;
- The network should support a specific set of government, business, and society-related applications.

Based on these requirements the proposed design methodology consists of the following steps:

1. *Identifying applications and services* [13] – First, we have to select the key applications and services that raise requirements on the network.
2. *Identifying network technology requirements, based on applications* [14] – We have to analyze the requirements of the applications and services selected in the first step. This analysis should contain Quality of Service (delay, jitter) and bandwidth parameters.
3. *Identifying coverage requirements, and the possibilities and limitations of the environment* [15] – Preparing the network technology selection, we should determine the area that is supposed to be covered by the network, with its topography, natural obstacles such as hills or trees as well as buildings, availability of support structures, towers, and so on.
4. *Choosing network technology and configuration* [15] – Selecting the right technology is one of the key parts of network planning. This decision should be based on identified requirements and conditions of the environment. We have to choose optimal solutions for both the access and backbone networks.
5. *Planning of network topology* [16] – This complex part of the methodology uses the results of the coverage requirement analysis as well as the network technology selection. We have to plan the network topology according to the topography and optimal station placement strategies.
6. *Verifying original requirements* – Last but not least, this step stands for verifying the results of planning. We have to recognize the differences between the original requirements and the capabilities provided by the planned network.

The outcome of the design is a network plan and the list of the required components on which the cost calculation can be carried out. The relations of these steps are illustrated in Figure 1.

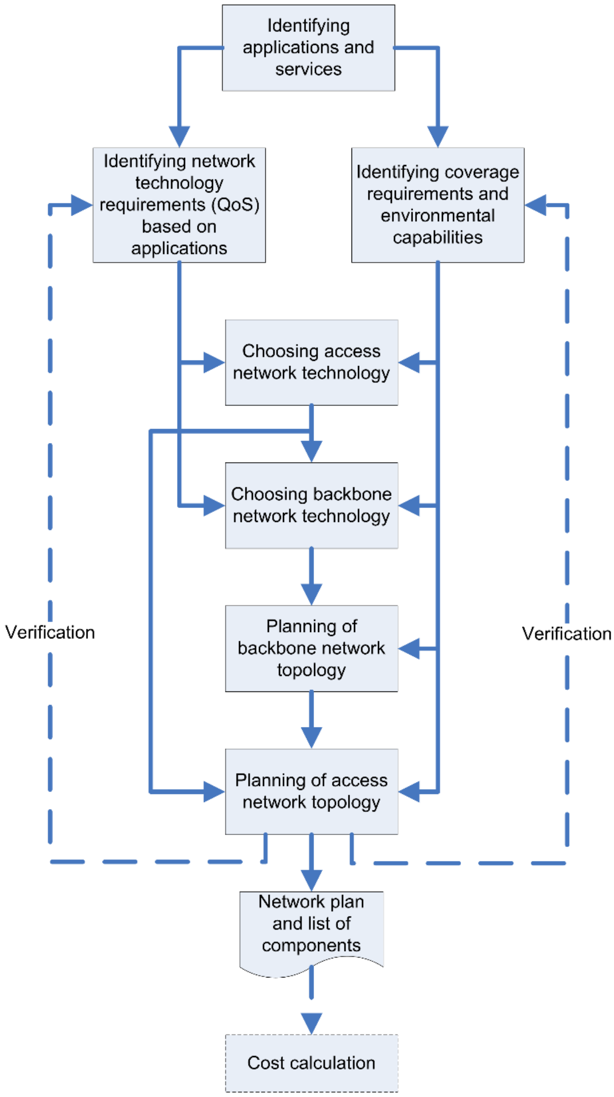


Figure 1: Illustration of the design process

2.2.2 Thesis 1.2: Evaluation Method to Facilitate Wireless Technology Selection in AMR Systems

An evaluation method has been developed to compare systematically the candidate wireless technologies that can facilitate the selection of the most suitable technology to build and implement AMR systems. It defines properties based on which a systematic comparison of the technologies can be carried out.

The corresponding results have been published in [3]. The evaluation method defines the following properties:

- *Network topology and architecture* – What type of network topologies and related architectures (e.g., infrastructure based, ad hoc, peer-to-peer) are supported?
- *Propagation properties and area coverage* – What are the wireless signal propagation characteristics and the communication range?
- *Possibilities for Quality of Service (QoS) provisioning* – What type of QoS guarantees (e.g., minimum transmission rate, delay, jitter) are available if any?
- *Manageability* – What type of management and control functions (e.g., device authentication, association, keep-alive beacons, power management) are available if any?

- *Security and privacy issues* – What type of security and privacy mechanisms (e.g., data encryption, user authentication, digital signature) are available if any?
- *Existing applications, products, vendor support* – What type of applications, products are available on the market? How many vendors do support the technology?

The outcome of the evaluation is a thorough comparison of the investigated technologies in a tabular format. The different properties can be weighted and numerical values (points) can be assigned to the properties according to the basic requirements and the evaluator's preferences. Thus, based on the sum of the gained points the final decision to select the most suitable technology can be easily done.

2.3 Application of the Results

The design methodology for wireless community networks has been developed and successfully applied in a national R&D project (Digital City – Győr, 2007). In this project, the goal was to develop and build a wireless community network in Győr, a medium size Hungarian city. We did the planning of this network [1]. Moreover, as a further case study we planned the wireless municipal network of another, smaller Hungarian city called Sopron in collaboration with the local administration of the city [2]. Figure 2 shows the relevant part of the Sopron city map with the planned network. On the other hand, we delivered three tutorials on this topic at international conferences [17, 18, 19] and published an on-line tutorial that was offered by IEEE [20].

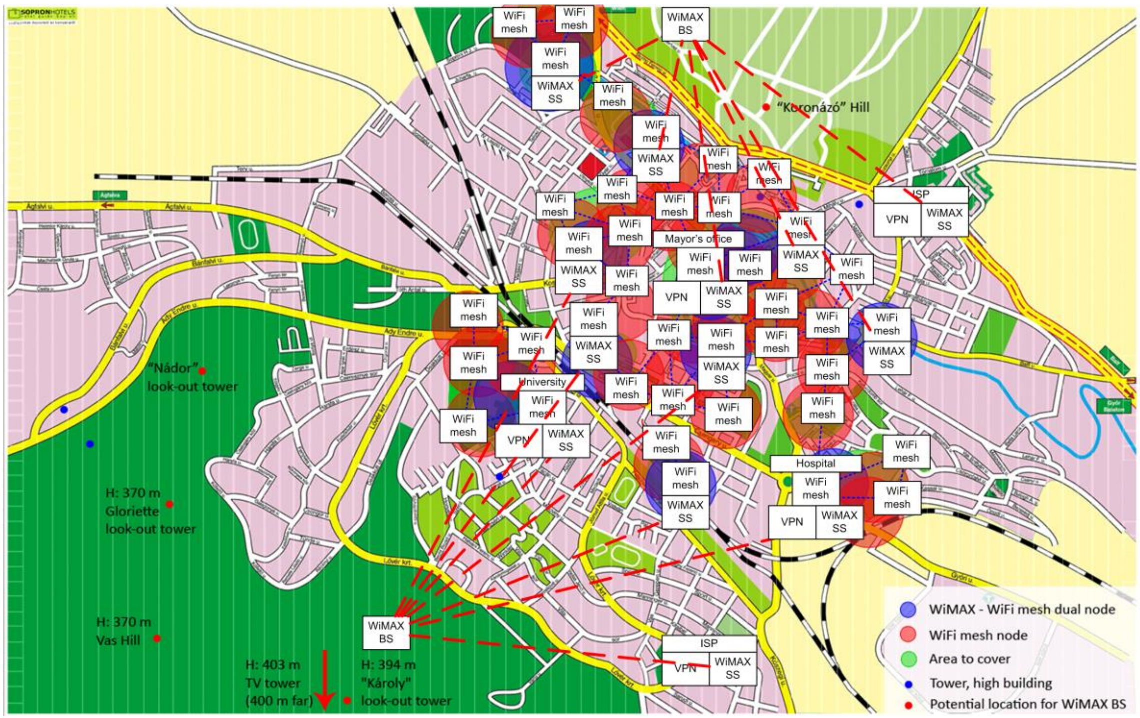


Figure 2: City map of Sopron with the planned municipal network

The proposed evaluation method to facilitate wireless technology selection in AMR systems has been developed and successfully applied in an industrial project (Hungarian Telecom, 2011). In this project, we systematically evaluated the suitability of three wireless technologies, such as Wi-Fi, ZigBee and Wireless M-Bus, for being used in AMR systems based on the developed method. Moreover, we carried out some measurements to see the performance of the investigated technologies under real conditions [3]. The developed method can be made even more attractive if the evaluation is automized and the evaluator has to provide only the basic requirements, the technology properties and the evaluation parameters.

3 Indoor Positioning and Navigation

3.1 Motivations and Goals

Developing location based applications are getting popular today because they can offer handy and useful services to their users (e.g., navigation, route planning, smart parking) and make everyday life easier. This thesis group deals with issues related to indoor positioning and navigation.

Using some location-aware service is more and more common during our daily routines. Such services are based on location tracking. Collecting the location data is straightforward in open-air environments, e.g., via a GPS (Global Positioning System) receiver. However, indoor position tracking is a more challenging issue and still an actual research topic today. In the last years, several wireless technologies and systems have been proposed for indoor positioning. Most of the wireless positioning systems operate in the license free ISM (Industrial, Scientific and Medical) radio band and are based on Wi-Fi, Bluetooth or ZigBee technologies. They use different methods for deriving the location information. One possible approach is deploying reference points or sensors into the indoor area and using triangulation technics to derive the position of the visiting node. Triangulation methods estimate the target location based on the geometric properties of triangles [21]. They have two variants, such as lateration and angulation. Lateration derives the position by measuring the object’s distances from multiple reference points. However, instead of measuring the distance directly some other characteristics of the signal are usually measured, like received signal strengths (RSS), time of arrival (TOA) or time difference of arrival (TDOA). Then, the distance is derived by computing the attenuation of the emitted signal strength or by multiplying the radio signal velocity and the travel time. Angulation locates an object by computing angles relative to multiple reference points. Regardless the applied variant of triangulation, the indispensable requirement for computing the location estimation is to receive the signal of at least three reference points everywhere within the given area. A challenging issue is how to place the reference points optimally.

On the other hand, location fingerprinting is also a widely applied technique besides triangulation [21]. In this case, signal fingerprints are collected in advance at a number of positions in the given area and later compared to the actual measurements carried out by the visiting node. The location belonging to the best fit is selected as the position estimate. In some scenarios, the signal fingerprint based positioning is easier to implement and requires less infrastructure, such as location tracking and navigation in an indoor parking garage. However, the traditional signal fingerprint based approaches cannot accurately handle nodes moving continuously, such as cars looking for free parking slots in an indoor parking garage environment.

With regard to this topic, our goals were twofold: i) investigate how to place, assuming the use of triangulation techniques, wireless reference points (sensors) optimally in a given indoor territory; ii) develop a Wi-Fi signal fingerprint based positioning method for indoor parking garage environment which can handle the continuous motion of the mobile nodes (vehicles) and can be used for implementing indoor navigation.

3.2 New Results

3.2.1 Thesis 2.1: Algorithm for Placement Optimization of Reference Points to Be Used in Triangulation Based Indoor Localization

An algorithm, called OptiRef, for triangulation based indoor positioning has been proposed to find the optimal number and placement of wireless reference points in a given indoor territory fulfilling the criterion of perceiving the signal with strong enough strength of at least three reference points everywhere within the territory. Moreover, a simulation tool has been developed to investigate the performance of OptiRef.

The corresponding results have been published in [4]. OptiRef is a top-down reference point placement algorithm to find the optimal reference sensor location setup(s). The initial step is to place a reference sensor in every discrete grid junction point of the territory map and compute the coverage area of each sensor using a wireless signal propagation model. In real environment, this can be almost any point of the continuous space, but we consider only discrete points with high density. The next step is to determine the number of perceived reference sensors, using the previously computed coverage maps, in each point of the territory where the visiting node can be located, and thus to verify the fulfillment of the criterion. If there is no point on the map where the number of perceived reference sensors is less than three, than one sensor can be removed randomly. The next step is to check the criterion again. If the number of perceived sensors still fulfills it in each point of the territory, then another sensor can be removed randomly and so on, otherwise the algorithm stops.

This simple method provides a solution, but in most of the cases not an optimal one. It can be modeled in a tree graph, where the states represent by binary numbers all the possible reference point combinations. After serializing the grid (creating from the 2D grid a 1D sequence by writing down the rows of the grid done after the other) the binary number determines which sensor is part of the given setup. The root state (every digit is a 1) is the initial setup containing in every grid junction point a reference sensor. The states one level below represent the setups where a reference sensor is deployed in all but one grid junction point, or from a different viewpoint one sensor is removed compared to the parent state, and so on. For instance, 1011..1 means that the reference sensor in the second position is removed compared to the initial setup. Figure 3 illustrates this graph containing the possible reference point combinations. Note, that the Hamming distance between the neighboring levels is one, and the graph consists of *n* levels if the number of possible reference point locations (grid junction points) is *n*.

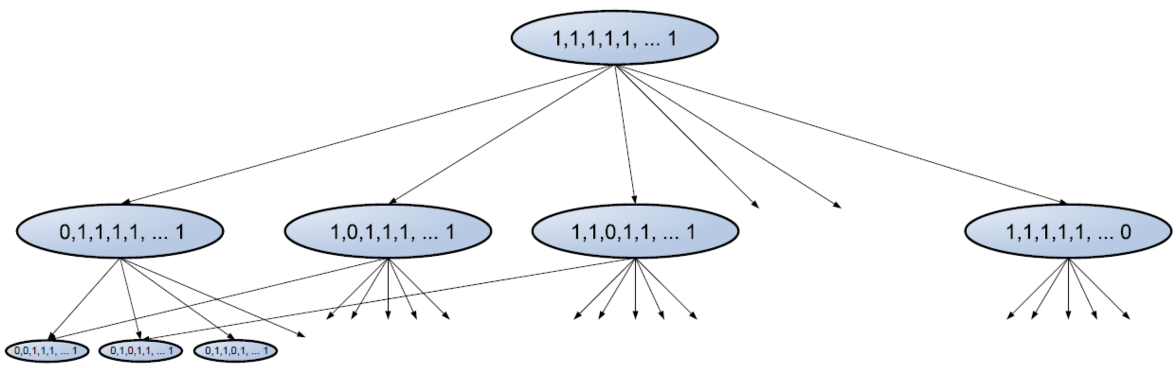


Figure 3: Graph representation of the possible reference sensor setups

With the graph representation the task can be originated in a graph theory problem. Thus, the goal is to find the state with the longest distance from the root, in which state the three perceivable reference sensors criterion still holds. On each level of the tree, the number of removed reference points is the same, therefore the deeper we are in the tree the less reference points are needed to cover the served territory. However, this "longest path" task is an NP-complete problem in graph theory [22]. Numerous heuristic optimization algorithms were developed to find the global optimum for such NP-complete problems, like hill climbing, swarm intelligence, integer linear programming, simulated annealing, etc.

OptiRef extends the above-mentioned simple reference point placement method with the simulated annealing algorithm that is a generic probabilistic algorithm for global optimization [22]. Hence, a previously removed reference point can be put back again with some probability. This probability is given by the equation *exp(ΔE/T)*, where *ΔE* stands for the cost function difference of the two neighboring reference sensor setups in question and parameter *T* is called temperature. The cost function, in this case, is the number of reference points in the given graph state. *T* is the sum of the number of perceived reference sensors for each position on the territory map. This number is decreasing as more and more sensors are removed (we are deeper in the graph), that can be interpreted as “cooling” in the context of simulated annealing. The possibility of putting a previously removed reference sensor back prevents the method from being stuck in a local minimum that is worse than the global one. Algorithm 1 shows the pseudo-code of the OptiRef algorithm’s main steps.

Algorithm 1: OptiRef Algorithm

```
initialization (add all ref. points, compute the coverage maps, set counter)
While counter > 0      # counter is the step limit, linearly dependent on n
   Choose neighbor state randomly (put back or remove a ref. point)
      Case putback
         putbackRef() with Pr (exp(ΔE/T))
      Case remove
         removeRef() with Pr (1− exp(ΔE/T))
         If perceivedRefs < 3 (check the criterion)
            restoreRef() (restore the removed ref. point)
   counter = counter − 1
```

The time required to get an appropriate reference point setup is an important issue that is affected by the complexity of the algorithm used. To find the global optimum with a brute force method all the possible reference point setups must be investigated. Thus, it has an $O(2^n)$ complexity, where *n* is the number of possible reference point locations. In case of the OptiRef algorithm, a step limit, linearly dependent on *n*, is used to determine how many times reference point can be removed or put back which limits the running time of the algorithm, too. Hence, OptiRef, having $O(n)$ complexity, is able to find a good approximation of the global optimum in real time showing linear run-time behavior.

To investigate the performance of OptiRef a simulation tool has been developed in the MATLAB [23] environment. In this tool, for modeling wireless signal propagation the ITU indoor model [24] was implemented and applied in the implementation of the OptiRef algorithm.

3.2.2 Thesis 2.2: Method for Wi-Fi Signal Fingerprint Based Indoor Positioning and Navigation

A Wi-Fi signal fingerprint based method has been developed for positioning and navigation in an indoor parking garage environment. The method is a modification of the K-nearest-neighbor (KNN) algorithm together with extensions applying some heuristics.

The corresponding results have been published in [5]. The positioning method is based on Wi-Fi signal fingerprints. The fingerprint database (signal vectors) of the given indoor parking garage is built in advance by measuring and collecting received signal strength (RSS) data of all the access points (APs) in predefined locations of the area. The visiting device (usually a smart-phone or tablet in a vehicle) to be located continuously measures any perceived signal from the APs. For its position estimation the actually measured signal value and the stored fingerprint information are used running the KNN algorithm [25].

However, the original KNN algorithm has been modified with weighted average calculation and extended with some heuristics, such as memory, motion change detection and road fitting methods. Thus, the position is calculated as the weighted average of the two nearest RSS neighbor coordinates and the previous returned position, shown in the following equation:

$$(x_t, y_t)' = w_1 \cdot (x_{KNN1}, y_{KNN1}) + w_2 \cdot (x_{t-1}, y_{t-1}) + w_3 \cdot (x_{KNN2}, y_{KNN2}),$$

where w_n is the applied normalized weight ($w_1 > w_2 > w_3$). The search for the two nearest RSS neighbors is restricted by implementing some heuristics. These are: i) memory of previous positions to avoid flipping between location candidates being far from each other in the area but showing similar signal fingerprint properties; ii) detection of changes in the direction and speed of motion using the orientation and accelerometer sensors of the visiting node; iii) road fitting to keep the position estimates within the coordinates of the given road segment. The calculated $(x_t, y_t)'$ is used to find the closest reference point within the search area in the fingerprint database. This position calculation method smooths out the effect of sudden RSS variations due to false measurements and keeps the estimated visiting node (vehicle) position on the route. Moreover, these position estimations provide the basis for navigation.

In the evaluations, the proposed positioning method showed an accuracy in the range of 2 – 3 meters which is acceptable, assuming a maximum 30 km/h driving speed, to implement smooth navigation according to our indoor parking garage experiments.

3.3 Application of the Results

The output of the OptiRef algorithm, thus the resulted reference point setup(s), in a given scenario can be considered as a good starting point for the real environment indoor positioning system design. The proposed method is technology neutral in the sense that it works with any wireless technology suitable for indoor positioning. Only the implementation of the signal propagation model and its parameters have to be changed in the simulation tool.

In our evaluations, the Wi-Fi [26] and ZigBee [4] technologies and their signal propagation model were used. As an example, Figure 4 shows a simulation output assuming ZigBee technology where the selected reference point locations and RSS values are illustrated in a 100 m x 100 m indoor area. The colors represent the highest RSS value at the given point of the territory that usually, but not necessarily, belongs to the closest reference sensor in the vicinity of the measurement.

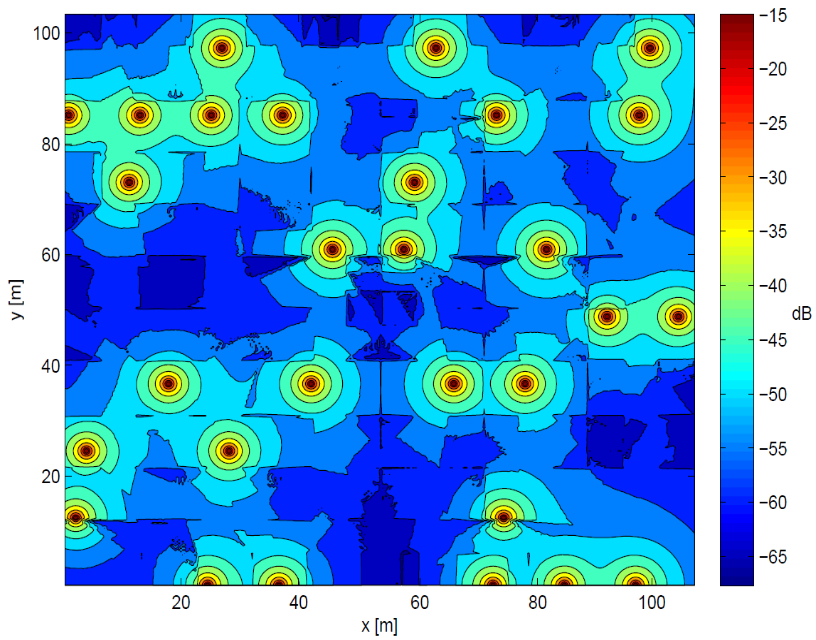


Figure 4: Resulted reference point locations and RSS values running OptiRef

The Wi-Fi signal fingerprint based indoor localization method has been developed and successfully applied in an institutional R&D project (iParking, 2011 – 2012). In this project, the goal was to develop and implement a prototype intelligent parking assistance system called iParking in a parking garage of a shopping mall (Allee, Budapest) for demonstration purposes. The iParking system is Wi-Fi based, it collects real-time parking slot occupancy data, and tracks and navigates vehicles entering the parking garage to a preselected, e.g., the closest to the favorite shop, free parking slot [5]. Figure 5 shows the level of the parking garage where the demo sector (highlighted area) was designated. Figure 6 depicts the physical setup of the prototype iParking system. Moreover, a short video is available about the implemented iParking prototype under the following homepage (institution introduction video, 2:34 min – 3:11 min): https://www.hit.bme.hu/.

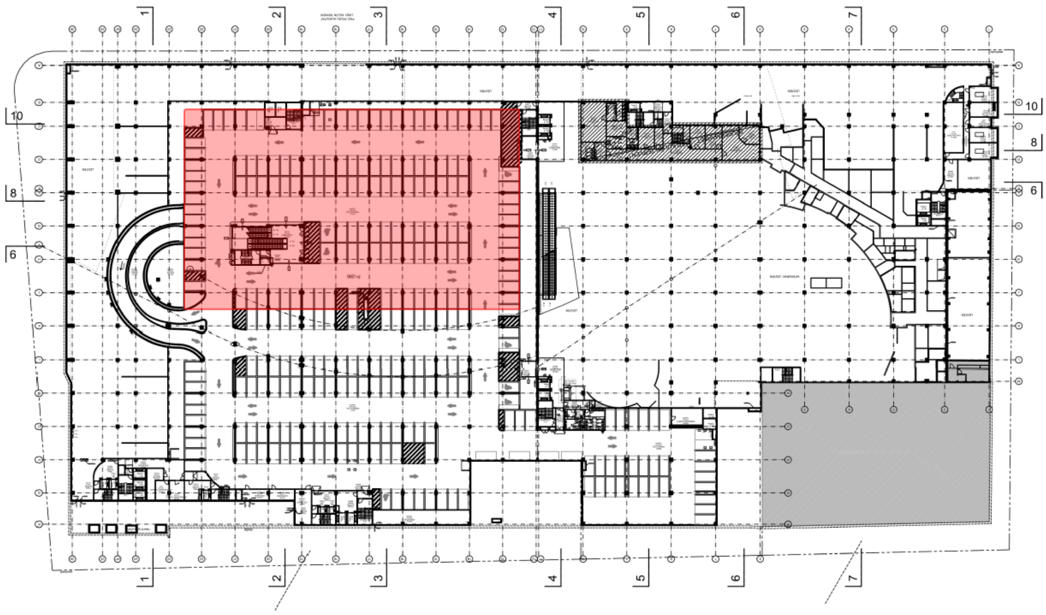


Figure 5: Level 1 of the parking garage with the demo sector

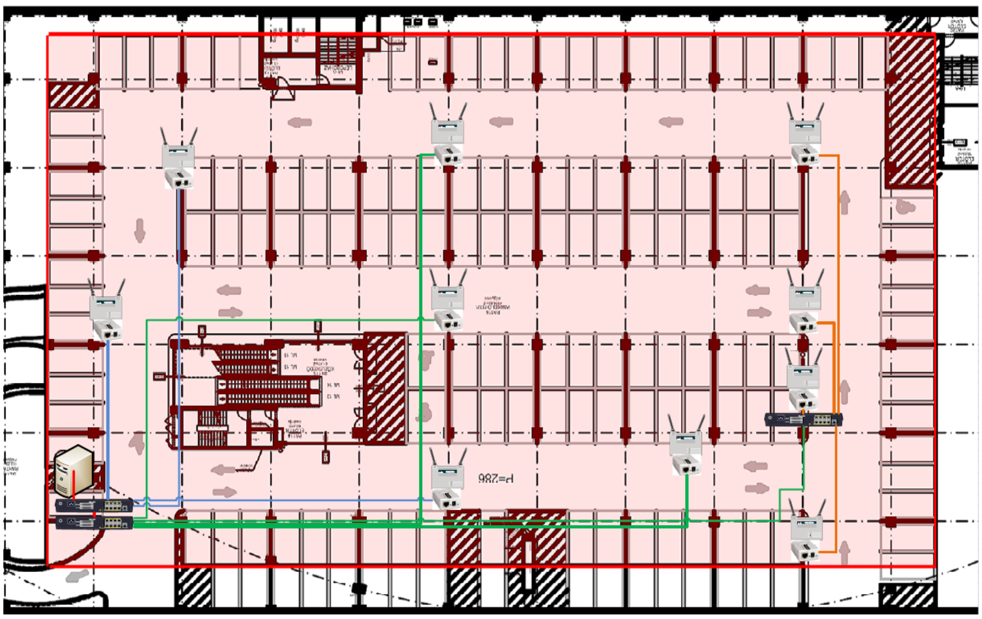


Figure 6: Physical setup of the prototype iParking system

Related to this topic, we have modeled the car parking process itself in a parking garage environment with various levels of assistance and investigated its performance in [27].

4 Crowdsensing Based Smart City Applications

4.1 Motivations and Goals

Smart cities offer services to their inhabitants, such as smart travel planner or smart parking, which make everyday life easier beyond providing a feedback channel to the city administration. Traditionally, the implementation of these smart city services requires the deployment of some costly sensing and tracking infrastructure. Alternatively, the crowd of inhabitants can be involved in data collection via their mobile devices because with the proliferation of smart-phones more and more computing and sensing power becomes available at the hands of urbanites. This emerging paradigm is called participatory sensing or mobile crowdsensing [28] that is a viable alternative if the community finds incentives (good services) for urbanites to participate in context sharing.

However, a typical crowdsensing application has two application specific components: i) one at the user's device and ii) another one in the cloud [28]. This results in many parallelism, unnecessary developments and slow application innovation cycle. A framework that separates the application logics from the core communication and data analytic functions fosters innovation via focusing on the application and presentation layers at the end systems. Introducing such a framework could boost developments similarly to innovation at the application front enabled by IP.

Talking about specific smart city applications and services, transportation is one of the domains where introducing intelligent solutions is inevitable in smart cities. For instance, maintaining and continuously improving public transportation are imperative in modern cities. However, the implementation of even a simple feature that extends the basic service functions can be costly. Let's consider just the replacement of static timetables with lively updated public transport information service. It requires the deployment of a vehicle tracking infrastructure consisting of among others GPS sensors, communication and back-end informatics systems and user interfaces, which can be an expensive investment. Or another issue is urban parking. It is really challenging if not impossible to find free parking spaces especially in the city center during rush hours. An intelligent parking assistance system could alleviate this problem by monitoring the occupancy of the parking slots and offering some aid to the drivers in selecting an available one and navigating to there. However, implementing such a system may demand huge investments, as well. It requires the deployment and maintenance of parking slot monitoring sensors, some communication and computation infrastructure, and user interfaces. In both cases, crowdsensing can be an alternative to collect tracking/monitoring data which may decrease the cost of introducing these smart city services.

With regard to this topic, our goals were treefold: i) develop a generic communication model and framework for crowdsensing based smart city applications to foster the development of such applications; ii) built on the developed communication framework design an appropriate architecture for crowdsensing based transit feed service which implements a live public transportation timetable; iii) develop a purpose-built simulation environment for analyzing and investigating the properties of crowdsensing based urban parking to facilitate the design of such a service.

4.2 New Results

4.2.1 Thesis 3.1: Communication Model and Framework for Crowdsensing Based Smart City Applications

A generic communication model and framework has been developed for crowdsensing based smart city applications. This communication model is based on the publish/subscribe interaction scheme which has been implemented by the framework via the Extensible Messaging and Presence Protocol (XMPP) protocol.

The corresponding results have been published in [6]. In the crowdsensing communication model, three roles has been defined, like *Producer*, *Consumer* and *Service Provider* (see Figure 7). These entities interact with each other via the core service, which consists of event based publish/subscribe (pub/sub) nodes [29], and have the following functions:

- *Producer:* The Producer acts as the original information source in the model producing raw data streams and plays a central role in data collection. He is the user who contributes his mobile's sensor data.
- *Consumer*: The Consumer is the beneficiary of the provided service(s). He enjoys the value of the collected, cleaned, analyzed, extended and disseminated information. The user is called as *Prosumer*, when he acts in the service as both Consumer and Producer at the same time.
- *Service Provider*: The Service Provider introduces added value to the raw data collected by the crowd. Thus, he intercepts and extends the information flow between Producers and Consumers. A Service Provider can play several roles at the same time, as he collects (Consumer role), stores and analyzes Producers' data to offer (Service Provider role) value added service. Moreover, multiple Service Providers can act concurrently and offer different value added services to different Consumers.

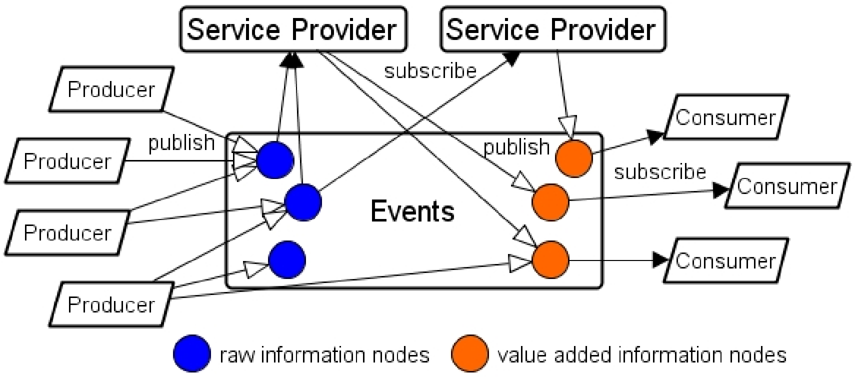


Figure 7: Crowdsensing communication model based on the publish/subscribe interaction scheme

In the model, depicted in Figure 7, Producers are the source of original data by sensing and monitoring their environment. They publish (marked by arrows with empty arrowhead) the collected information to event nodes (raw information nodes are marked by blue dots). On the other hand, Service Providers intercept the collected data by subscribing (marked by arrows with black arrowhead) to raw event nodes and receiving information in an asynchronous manner. They extend the crowdsensed data with their own information or extract cleaned-up information from the raw data to introduce added value to Consumers. Moreover, they publish their service to different content nodes. Consumers who are interested in the reception of the added value/service just subscribe to the appropriate content node(s) and collect the published information also in an asynchronous manner.

The framework implements this communication model via XMPP [30] and maps directly this model to the XMPP publish/subscribe service as follows (see Figure 8):

- Service Providers establish raw pub/sub data nodes, which gather Producers' data, for the services they offer.
- Consumers can freely publish their collected data to the corresponding nodes with appropriate node access rights, too. However, only the owner or other affiliated Consumers can retrieve this information.

- Producers can publish the collected data or their annotations to the raw data nodes at the XMPP server only if they have appropriate access rights.
- Service Providers collect the published data and introduce such a service structure for their added value via the pub/sub subscription service, which makes appropriate content filtering possible for their Consumers.
- Prosumers publish their sensor readings or annotations into and retrieve events from XMPP pub/sub nodes.
- Service Providers subscribed to raw pub/sub nodes collect, store, clean up and analyze data and extract/derive new information introducing added value. This new information is published into pub/sub nodes on the other side following a suitable structure.

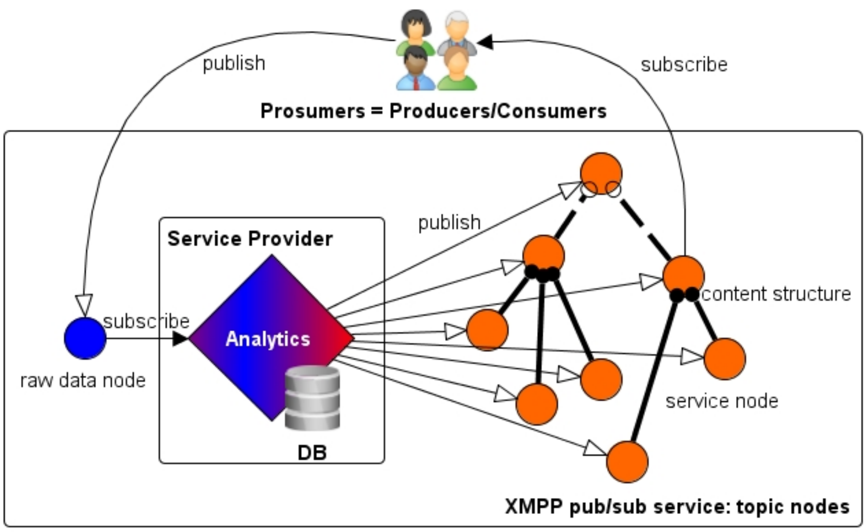


Figure 8: Crowdsensing framework implementing the communication model via XMPP

The pub/sub service node structure can benefit from the aggregation feature of XMPP via using collection nodes, where a collection node will see all the information received by its child nodes. However, the aggregation mechanism of an XMPP collection node is not appropriate to filter events. Hence, the Service Provider role has to be applied to implement scalable content aggregation. Figure 8 shows XMPP aggregations as dark circles at the container node while empty circles with dashed lines represent only logical containment where intelligent aggregation is implemented through the service logic.

4.2.2 Thesis 3.2: Architecture for Crowdsensing Based Transit Feed Service

An architecture for crowdsensing based transit feed service has been designed. This architecture is built on the developed crowdsensing communication framework. The service implements a public transportation timetable updated in real-time.

The corresponding results have been published in [7, 8]. The crowdsensing based transit feed service architecture has two main building blocks, such as the adapted communication framework described in Thesis 3.1 and the front-end application called TrafficInfo (see Figure 9). The adapted framework consists of two parts, such as a standard XMPP server and a General Transit Feed Specification (GTFS) [31] Emulator with an Analytics module.

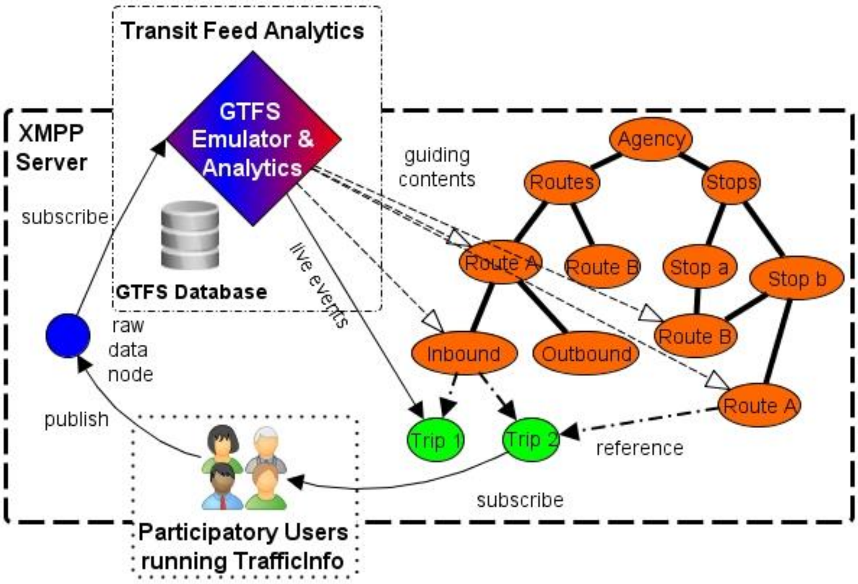


Figure 9: Crowdsensing based transit feed service architecture

The XMPP server maps the public transport lines, stored in GTFS format, to a hierarchical pub/sub channel structure. Thus, the GTFS database is turned into an XMPP pub/sub node hierarchy. This node structure facilitates searching and selecting transit feeds according to user interest. The pub/sub node model for content filtering in a transport information feed is depicted in Figure 10.

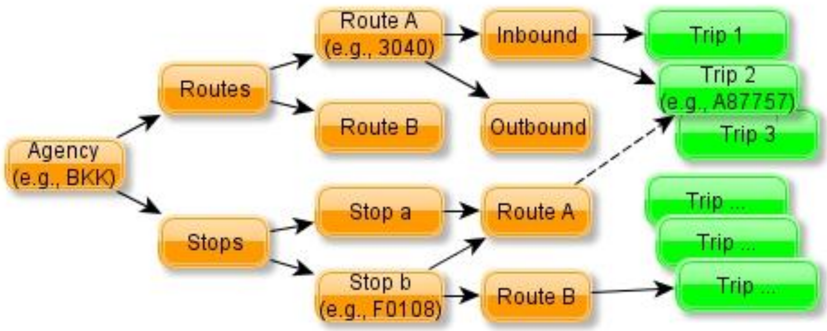


Figure 10: Publish/subscribe model for GTFS feeds

The root of the pub/sub tree is the *Agency* node referring to the public transport operator. Transit information and real-time event updates are handled in the *Trip* nodes at the leaf level. The inner nodes in the node hierarchy contain only persistent data and references relevant to the trips. The users can access the transit data via two ways, based on *Routes* or *Stops*. When the user wants to see a given trip (vehicle) related traffic information the route based filtering is applied. On the other hand, when the forthcoming arrivals at a given stop (location) are of interest, the stop based filtering is the appropriate access way. For instance, the leaf node with trip ID 'BKK-Routes-3040-Inbound-A87757' (cf. the bracketed labels in the nodes of Figure 10) handles transit feed and its real-time updates. It is related to Trip 2 in the inbound direction and belongs to Route A of Agency BKK (operator at Budapest, Hungary). On the other hand, node 'BKK-Routes-3040' stores persistent transit information with regard to Route A (e.g., route name, short name, stops, head-signs). References to all the currently active inbound trips are found in node 'BKK-Routes-3040-Inbound'. Similarly, node 'BKK-Stops-F0108' stores persistent data with regard to the given stop (e.g., stop name, GPS coordinates) and lists the routes this stop is part of. Furthermore, the trip ID of every active trip is listed in the route node.

The GTFS Emulator provides the static timetable information, if it is available, as the initial service. It basically uses the officially distributed GTFS database of the public transport operator of the given city. However, it also relies on another data source, which is OpenStreetMap (OSM) [32], a crowdsourcing based mapping service. In OSM maps, users have the possibility to define terminals, public transportation stops or even public transportation routes. Thus, the OSM based information is used to extend and clean the information coming from the GTFS source. The resulted data set reflects more accurately the actual situation in the given territory because the OSM data is updated more frequently than the GTFS data set. The Analytics module is in charge of the business logic offered by the service, e.g., deriving crowdedness information or estimating the time of arrivals at the stops from the data collected by the crowd. For this latter function some stop detection algorithms have been developed and implemented [7, 8, 33].

The front-end application, called TrafficInfo, handles the subscription to the pub/sub channels, collects sensor readings, publishes events to and receives updates from the XMPP server, and visualizes the received information.

4.2.3 Thesis 3.3: Purpose-built Simulation Environment for Investigating Crowdsensing Based Urban Parking

A purpose-built simulation environment, called UPark, has been developed for analyzing and investigating the properties of crowdsensing based urban parking. It has been implemented in Java using the MASON multi-agent simulation environment and the SUMO traffic simulation suite.

The corresponding results have been published in [9, 10]. The UPark simulation environment has been implemented in the Java programming language using the MASON multi-agent simulation environment [34] and the SUMO traffic simulation suite [35]. MASON has been used to generate the discrete actions undertaken by the drivers, i.e., to instantiate vehicles at the borders of the analyzed area, set their destinations and make decisions while cruising for parking, as well as to generate the parking related events (e.g., a parking spot taken). SUMO has been used to simulate and visualize the routes traveled by the drivers.

UPark models the driving behavior and crowdsensing in the following way. The driving behavior model supposes that the majority of the drivers drives through the urban area to be investigated, choosing the streets with the highest throughput. A smaller portion of the drivers choses a destination within the area and looks for suitable parking spots. The drive-through vehicles appear at one end of a street, travel straight with the maximum allowed speed, and disappear at the other end of the street. The rest of the vehicles traveling to a destination within the area might find suitable parking in the street segment they travel to and park. In case they do not find an appropriate parking spot, they start cruising around their destination. Such ‘cruisers’ are supposed to be driving slower than the maximum allowed speed, thereby affecting other vehicles, e.g., not allowing drive-through vehicles to leave the area with the maximum allowed speed. In extreme cases ‘cruisers’ do not find a free spot near their destination and leave the area via the shortest route.

With regard to modeling crowdsensing it is supposed that all vehicles traveling through the selected urban area might sense and share parking related events. Sensing might equivalently be performed by an app running on the drivers’ smart-phones, as well as by the vehicles themselves if equipped with necessary sensing hardware, software and communication capabilities. The following events are identified as being of interest for analyzing the operation of a crowdsensing based parking assistance application:

- *Parking spot freed* – immediately after parking out;
- *Parking spot taken* – immediately after parking in;
- *Free/taken on-street parking spot registered* – by a car driving by;

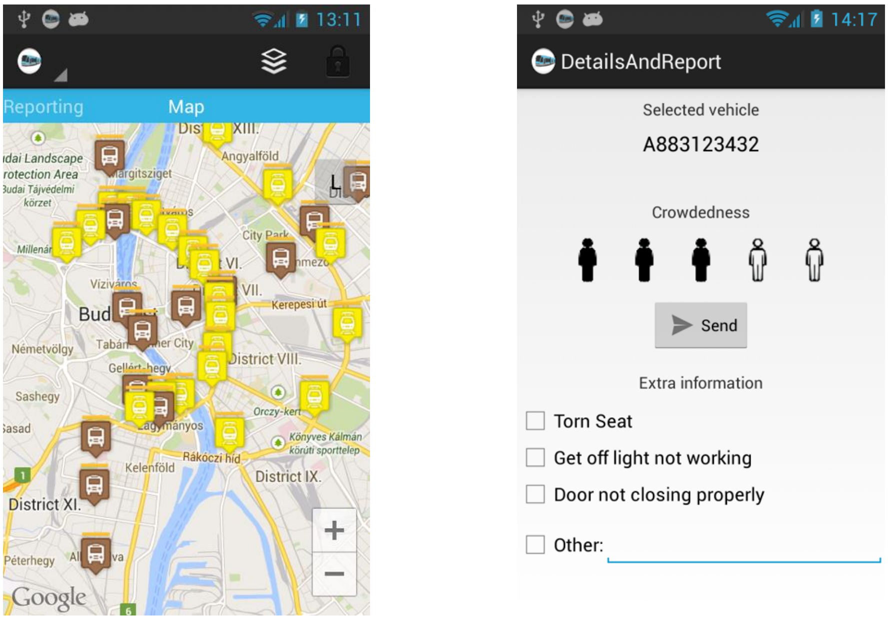
- *Parking failed* – created when a driver notices that a supposedly free spot is occupied, e.g., by a driver not taking part in the crowdsensing effort;
- *Cruising for parking* – when driving around the destination and looking for a parking spot.

Drivers looking for a parking spot within the investigated area might use the crowdsensed information on their mobile devices in order to find a parking spot, i.e., they might look for a quite new 'parking spot freed' event near their destination.

4.3 Application of the Results

The crowdsensing communication framework and the service architecture have been developed and successfully applied in several national and international R&D projects (TÁMOP: FIRST, 2012 – 2014; NFÜ: The EIT ICT Labs Hungarian National Associated Node Participation in the EIT KIC Association, 2013 – 2014; EIT ICT Labs: CityCrowdSource, 2013; COST: ENERGIC, 2012 – 2016). Built on the framework, beyond the live transit feed service two additional use-case smart city application scenarios, such as a soccer intelligence agency service and a smart campus application, have been implemented for demonstration purposes [6].

The proposed crowdsensing based transit feed service architecture together with the front-end TrafficInfo application and stop event detection algorithms has been implemented [7, 8, 33, 36, 37] and its performance was analyzed [38]. Figure 11 shows some TrafficInfo screenshots.



a) Vehicle vizualization b) User feedback form

Figure 11: TrafficInfo screenshots

The purpose-built simulation environment has been developed and applied in an international R&D project (COST: ENERGIC, 2012 – 2016). In this project, it was investigated among others, what could have made successful Google's OpenSpot [39], a crowdsensing based parking assistance application cancelled in 2012 [10]. We concluded that it is necessary to extend the sensing of parking spot availability by the drive-by sensing approach in order to achieve an appropriately high level system observability, which in turn allows the system to steer drivers to empty parking spots with a success rate higher than 80%. Moreover, the results showed that if the crowd collects information about free parking spots in urban environments of high traffic density and demand for parking spots, then the parking spots might be taken in as little as 10-15 seconds after they become unoccupied. Thus, the design of an appropriate aging algorithm of occupancy information is crucial for such a service.

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