Active GSM Cell-ID Tracking: "Where Did You Disappear?"

Kateřina Dufková⋆†, Michal Ficek⋆†, Lukáš Kencl⋆, Jakub Novák⋆‡,
Jan Kouba⋆†, Ivan Gregor⋆†, Jiří Danihelka⋆†

⋆R&D Centre for Mobile Applications
Czech Technical University
Prague, Czech Republic

†Faculty of Mathematics and Physics
Charles University
Prague, Czech Republic

‡Faculty of Science
Charles University
Prague, Czech Republic

{katerina.dufkova, michal.ficek, lukas.kencl, jakub.novak,
jan.kouba, ivan.gregor, jiri.danihelka}@rdc.cz

ABSTRACT

Location-based services are mobile network applications of growing importance and variability. The space of location technologies and applications has not yet been fully explored, perhaps omitting some important practical uses.

In this work we present the prototype SS7Tracker platform, an active, non-intrusive, GSM Cell-ID-based solution to network-based location tracking, and two novel applications of this technique: network diagnostics based on inroamer tracking and human activity research. We demonstrate the usability and performance limits of the platform on practical tests carried out in a live GSM network.

Categories and Subject Descriptors

C.2.3 [**Computer-Communication Networks**]: Network Operations—*Network management, Network monitoring*

General Terms

Experimentation, Measurement

Keywords

mobile entity localization, active tracking, network diagnostics, mobility, GSM, SS7, inroamer

1. INTRODUCTION

In the mobile communications industry the location-based applications are predicted to be a growing segment over the next years [1]. This opens research opportunities both in the localization platform design and among location data applications. Current localization techniques can be classified as network-based and terminal-based. Terminal-based techniques [8, 9] achieve good accuracy, but require special hardware or software on the side of the localized mobile phone. The best known representative of these techniques is GPS, which provides high accuracy but is not suitable for all applications because of its disputable availability. According to [9], GPS provides only 4.5% user-time coverage in tests with the device carried in users' pockets during a day. Network-based techniques possess the advantage that once implemented to the network, every subscriber can benefit from them. These techniques differ in the extent of network update needed, and face the trade-off between implementation costs and location accuracy.

In principle two tracking methods are used. Active tracking is based on periodic questioning of the network about the location of tracked devices. Conversely passive tracking methods use location information generated during communication between a mobile phone and the GSM network. The advantage of active tracking is that it can track passive subscribers who are not using the mobile phone at the moment, whereas the obvious disadvantage is the extra traffic.

Because of the nature of intended applications we focus on network-based localization and active tracking. We present the SS7Tracker platform - a feasible approach to mobile phone localization and tracking implemented within a live GSM network, and two novel applications that use the data collected using the platform.

For the mobile phone localization we use Cell-ID positioning based purely on signaling messages of the Mobile Application Part (MAP) [2] protocol from the standard SS7 protocol suite [3]. This determines the main features of the SS7Tracker platform: It is *non-intrusive* to the existing signaling network equipment in the sense that it does not demand any software or hardware changes neither in the network core elements nor in the localized mobile phones. The platform is able to localize *any subscriber* of the GSM network, no matter if his or her mobile phone is equipped with GPS or if the subscriber is passive. It provides *real-time* localization with only small delay caused by propagation of messages in the network, and the location accuracy depends on the size of network cells. The manageable load of the platform is limited mainly by the network signaling link capacity. The localization is ensured by queries hidden to the localized subscriber and does not require subscriber cooperation which brings privacy issues we discuss later.

The primary application of the SS7Tracker platform is directed towards GSM network signal coverage diagnostics, which is very attractive for the mobile operators. Our solution focuses on inroamers, which is a term for foreign roaming clients that subscribed to the studied network. Inroamers switch GSM networks freely, according to the mobile signal strength, unlike domestic clients that stay in one network constantly. Moreover inroamers are very important to mobile operators since globally 17 % of total mobile revenues come from roaming [4]. Roaming revenues depend on the level of market fragmentation and thus are unevenly geographically distributed. While in the United States roaming accounts for only 3 % of total mobile revenues [5], in Europe the roaming revenues are considered confidential and were so high that the European Union reacted with price regulation. Still, according to [4], even after the regulation, the most important region for roaming is Western Europe.

The idea behind the signal coverage diagnostics is that we can use the data from active tracking of inroamer location to find areas where the inroamers disappear to a rival network. The collected data can be statistically analyzed to identify areas of weak signal coverage or traffic anomalies.

These data are also valuable in wide range of other research areas. One such promising area is mobility and human activity research. When tracking city inhabitants and commuters, these data can help town-planners to choose optimal variant according to traffic density and movement pattern of the people between parts of the city during the day, week or even longer time segments. When tracking inroamers, these data can provide valuable information for travel industry about the typical behaviour of tourists.

While both active and passive tracking methods are used in mobility and human activity research, active tracking provides more accurate data because it can collect location information in arbitrary frequency and it localizes even passive subscribers. Passive tracking produces sparser location information whose quantity highly depends on the mobile phone usage pattern. Moreover the real-time nature of SS7Tracker platform allows utilization in real-time decision making processes like transportation management, organization of mass events or coordination of emergency situation.

A significant contribution of our research thus rests in opening further questions of interest to both the commercial and the research communities. In the area of GSM network diagnostics, we provide first indications as to where, why and how many inroamers do disappear from a particular mobile network. This naturally leads to the challenge of how may the network be optimized to prevent inroamers from switching to a rival? In the human activity research domain, we provide first accurate data for creating models of inroamer behavior. Questions such as "What places do tourists visit?" or "How long do tourists stay in a country or in certain regions of interest?" may now be answered with unprecedented accuracy, but also formal models of network subscriber migration may be developed more accurately.

This paper is organized as follows. Section 2 discusses related work. Section 3 describes architecture and performance limits of the SS7Tracker platform. Sections 4 and 5 present applications of the platform. Section 6 discusses possibilities of the platform and location tracking privacy issues. Finally Section 7 concludes the paper with a summary of our contribution and directions in which the platform may be extended.

2. RELATED WORK

Various papers have already dealt with the localization of mobile entities in GSM networks. Paper [6] summarizes main approaches to the localization, including the Cell-ID positioning technique we use. The advantages and disadvantages of using Cell-ID positioning are discussed in [7]. More possible localization techniques are presented in [8, 9, 10]. There have also been significant standardization efforts [11, 12] and corporate initiatives [13, 14] in this area.

Other approaches to tracking of mobile entities are presented in [15, 16]. A commercial implementation of passive tracking can be seen in [17].

GSM network signal coverage diagnostics falls into the frame of finding optimal antenna location problem that has been studied heavily in recent years, among others by [18, 19, 20]. In comparison, our approach is novel in using the inroamer location data to identify areas of weak signal coverage in a live GSM network.

Use of mobile phone location data in mobility and human activity research is still sporadic. Active tracking was tested in the investigation of daily activity and mobility patterns of city inhabitants and commuters in Tallinn [29]. The same team used passive tracking for the investigation of tourists spatial mobility [28]. Use of mobile phone location data in urban analyses on the example of Rome is described in [27].

How to secure the privacy of individuals and how to mitigate public fear of being tracked are important questions in the efforts to spread the use of location-based services. Methods to protect privacy in location-based application are presented in [21, 22, 23, 24, 26]. Legal aspects are discussed in [27] and the important role of public opinion is discussed in [28].

3. ARCHITECTURE AND ATTRIBUTES

The SS7Tracker platform implements active tracking: depending on the defined tracking scenario, the location of tracked subscribers is periodically requested and stored. The location is retrieved using a sequence of signaling messages that are sent from a single location within the studied network to network core elements and to the localized subscribers.

The architecture of the platform is client-server oriented. The server side is equipped with the Dialogic® SPCI4 [30] SS7 signaling board which acts as a GSM network signaling point. The server side is connected to a live signaling network in order to communicate with mobile network nodes to ensure the location retrieval. There are two cooperating server side modules - the QueryCellId module deals with network communication, the Tracker module coordinates the tracking process. Results of the tracking are visualized in a client side frontend application TrackerGUI.

The QueryCellId module deals with getting the location information from the GSM network. It uses a sequence of three messages of the MAP [2] protocol from the SS7 protocol suite [3] to obtain the Visitor Location Register number and Cell Global Identity (see Figure 1). The delay between the location request and the response from the network during localization of one single number is affected by SMS delivery time in the studied network, which can vary among operators.

The Tracker module coordinates processing of tracking tasks. The input of the Tracker module is a so-called job file that describes the tracking. At the beginning of tracking the location of all mobile subscriber numbers (MSISDNs) specified in the job file is requested. Depending on the results retrieved, the Tracker module evaluates for each single MSISDN the next tracking interval, defined as the time between the end of the last localization and the subsequent localization request. The evaluation takes into account the

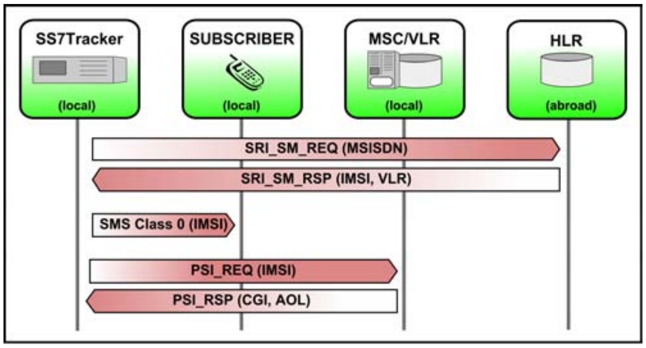


Figure 1: SS7 message flow for obtaining subscriber location
First we send SendRoutingInfo (SRI-SM) to subscriber's Home Location Register (HLR), for inroamers abroad. If the subscriber's mobile is off, the HLR responds with an error. Otherwise it sends subscriber's International Mobile Subscriber Identity (IMSI) and Visitor Location Register (VLR) number from which we obtain the mobile network the subscriber is in. Not to burden the rival network, we go on only if the subscriber is in the studied network. We send to the subscriber an invisible SMS Class 0 whose delivery leads to update of location information in local VLR, so the ProvideSubscriberInfo (PSI) response contains up-to-date Cell Global Identity and the Age Of Location (AOL).

last subscriber location, his or her movement and other criteria and it is determined by rules in the job file. These rules are linked together in conditions we call "rule chains". The processing of each rule chain leads to choosing an action for the MSISDN. Possible actions are - Query MSISDN after the evaluated time interval or Drop MSISDN, i.e., stop localizing it during the current tracking. The job file is in XML format and thus can be easily created, parsed and validated using common tools.

The TrackerGUI application is a Java interface for the SS7Tracker platform which allows to create jobs by selecting a representative set of subscribers to track and defining tracking rule chains for them. TrackerGUI also summarises and visualizes results of finished trackings and allows to export results to external mapping systems. The data are stored in a Microsoft® SQL Server 2000 database and accessed through stored procedures.

To limit the tracking overhead and load for the cooperating network nodes, the SS7Tracker platform provides the following configurable parameters: tracking interval, number of tracked subscribers, number of queries in a tracking burst, interval between the bursts and interval between sending SMS Class 0 and PSI message (see Figure 1). To understand the limits of deployment to mobile operator, we computed the dependence of signaling line utilization on these parameters (see Figure 2). The computation is based on a discrete simulation of messages sent through one 64kb signaling link.

4. SIGNAL COVERAGE DIAGNOSTICS

The question "How to prevent inroamers from disappearing from a mobile network?" goes hand in hand with "Where do they switch to a rival network?". For a GSM operator, the answer to these questions is key to improve the areas with weak signal coverage in terms of inroamers. In this section we provide a list of several kinds of necessary information about inroamer switches, explain their impact and we show how the SS7Tracker platform output, if properly interpreted, can give the operator the desired information.

To show the SS7Tracker platform usability we tracked 247 foreign inroamers in the Czech Republic in May 2008. The experiment took 7 hours, the tracking scenario was as follows: the tracking interval was set to 2 minutes in case of inroamer presence in any Czech network or in case of a mobile phone switch off, and to 1 hour in case of inroamer presence in a foreign network.

The most desired information, "where", can be obtained from the last inroamer position within the studied network, before the subscriber switches to a rival network. These weak points in the network are showed by the "Last cell before lost" graph (see Figure 5 (a)).

For the decision which network improvement to prefer, the knowledge of inroamer movement direction is necessary. Assuming that we have the information about last inroamer position within the studied network, then the way and direction the inroamer has been taking before his or her switch to a rival network gives us the right clues how to direct the BTS radio antenna or where to add another one. The results of the SS7Tracker platform can be visualized a 3rd party navigation software (see Figure 3).

The count of transitions between different cells can lead to discovery of overloaded or unused network segments. Also the count of inroamers that stay in a cell and the ratio between stay and switch to a rival network are suitable for diagnostics.

The distribution of inroamers among networks during the tracking period is shown in the "Sample inroamer group lifetime" graph (see Figure 4) that can provide global insight into inroamer behaviour: how long they stay in the studied network, to which network they switch and whether they return to the studied network.

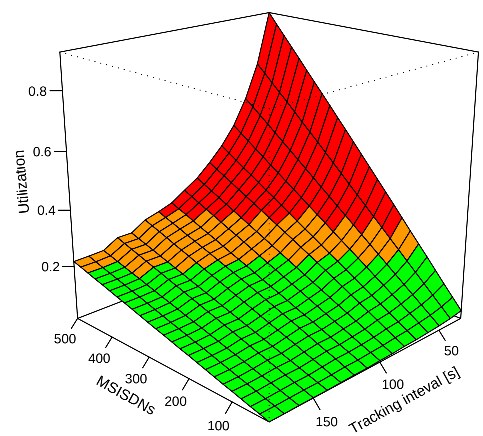


Figure 2: Signaling line utilization analysis
The graph presents average line utilization for various tracking intervals and numbers of tracked subscribers. The colors distinguish line utilization intervals prescribed by the mobile operator: permitted 0% - 20% are green, boundary 20%-30% are orange and forbidden 30%-100% are red. The values were computed with fixed following parameters of the SS7Tracker platform: The maximum number of location queries started in a burst is 10, the interval between the bursts is 1 second and the time between sending SMS Class 0 and PSI message (see Figure 1) is 10 seconds.

Because of the sophisticated tracking logic enabled by the tracking rules, the SS7Tracker platform provides high degree of freedom to measure special cases of network behavior as well as everyday inroamers' movement. However, correct data interpretation is tightly coupled with the tracking rules used. For example the tracking interval significantly increases the location accuracy, but also the overhead, because of higher request frequency. Thus great attention has to be paid on tuning the rules that determine it. The effect of tracking interval change is illustrated in Figure 5 (b).

5. MOBILITY AND HUMAN ACTIVITY RESEARCH

The SS7Tracker platform has the potential to be used as a unique survey tool in human behaviour research, urban planning and tourist survey. In comparison with the passive tracking approach, the unquestionable advantage of active tracking is the much better spatial accuracy and continuity of recorded personal location data. Basically there are two fundamental approaches how to utilize the collected location data - aggregate data statistic and individual tracks analyses. The first approach is focused on information about total numbers of people that visited particular cells. In general it characterizes how different places within a city or a region are used and how does the usage of places vary according to time of day. Specifically, in case of foreign visitors, represented by the tracked inroamers, the analyses of aggregated data can provide answers to these questions: Which places (cells) are visited by foreigners? How many foreigners do visit particular places (cells)? How long do they stay here? And finally how does the actual presence in particular places vary during a day, a week, or a season? Aggregate statistics help identify the most visited places and compare the visit rate of different tourist's attractions as well as cities and regions. Figure 6 illustrates the outputs of the aggregate statistics analysis.

The second approach processes tracks of individuals and offers unique opportunity to analyze individual spatial behaviour. In case of tourist research we can orient our inquiry to the questions concerning typical duration of stay in the Czech Republic, its organization and sequence of visited places. We can also distinguish whether the visit of the Czech Republic has a tourist or a business purpose.

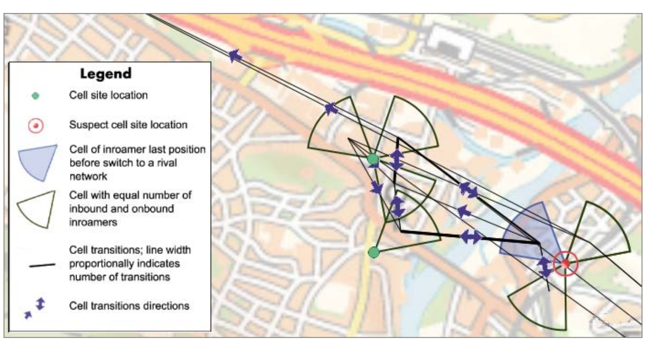


Figure 3: Map visualization example
Colored points and sectors enable quantitative analysis of inroamer movement. Points represent cell sites locations, each cell site contains several antennae which are drawn as sectors with the orientation corresponding to transmitting azimuth.

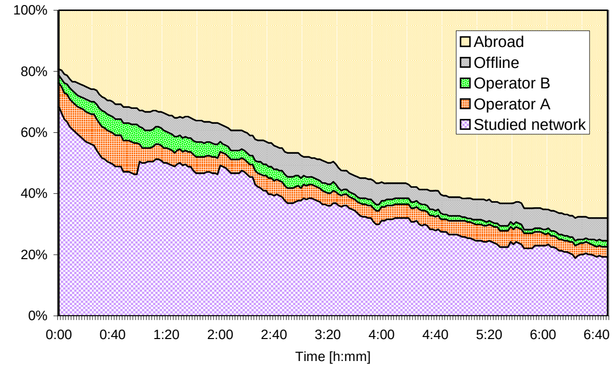


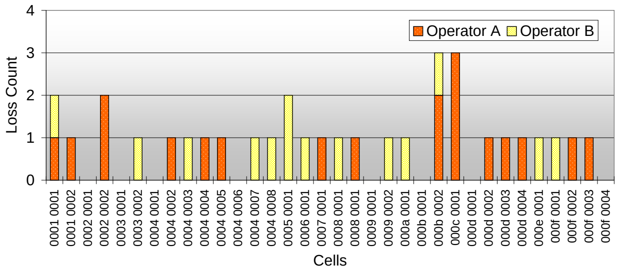
Figure 4: Sample inroamer group lifetime, Czech Republic
The graph allows to analyze how the inroamer fractions switch between the rival networks during the tracking time period. The sample consists of inroamers that were all previously present in the studied network. "Offline" means that the inroamer is unreachable, "Abroad" means inroamer's presence in foreign VLR.

Moreover we are able to identify various types of foreign tourists and their behaviour during their stay. Simultaneously similar set of questions can be explored in case of spatial mobility of ordinary city inhabitants. The accuracy of spatio-temporal data we obtain from the SS7Tracker platform is sufficient to investigate individual daily routines, action space and mobility behaviour. Recorded data adequately pictures daily mobility among the important personal activity nodes like home, work and leisure places.

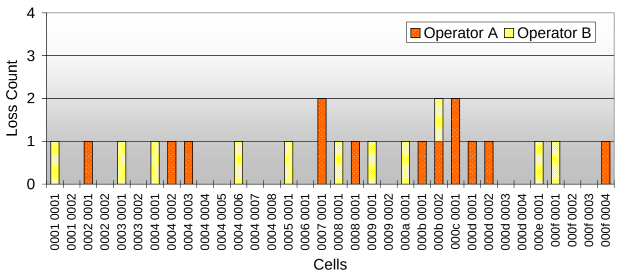
6. DISCUSSION

The Cell-ID positioning and its limits and benefits have already been described in [7]. As the study states, the main drawbacks of Cell-ID positioning are lower accuracy and the demand for cell planning knowledge. But none of these drawbacks limited us: the studied network operator provided us with the cell planning and we chose applications with lower accuracy requirements. GSM network diagnostics applications work only on the cell-level. Mobility research applications are focused on global insight into the area and a closer look is needed only in urban areas, where Cell-ID provides better accuracy because of higher cell density in big cities. Consequently Cell-ID positioning is a good choice for the applications, because it allows to collect data with a low cost and to design the SS7Tracker platform non-intrusively, without any software or hardware upgrade neither in the GSM network core elements (MSC, VLR, HLR, etc.) nor in the mobile phones.

The adopted active tracking approach has also some implications. In contrast with passive tracking that exploits location information generated during communication between a mobile phone and a GSM network, active tracking creates extra load. Generally, active tracking enables to collect data selectively at desired frequency and provides information even about passive subscribers that are imperceptible for passive tracking. However the possible impact of extra load on data accuracy must be considered and the tracking period needs to be tuned to minimize signaling overhead and possible impact on battery lifetime in the tracked mobile phone.



(a) Tracking interval 2 minutes



(b) Tracking interval 6 minutes

Figure 5: Last cell before lost graph and the effect of tracking interval change
The y-axis indicates the inroamer loss counts of cells figured as columns on the x-axis. The color corresponds to the rival operator that gained the inroamer. Only by a coincidence there is no cell with switches to more than one operator. The graphs correspond to the same set of inroamers, time period and tracking rules, only with different tracking interval. Longer interval can lead to incomplete or misleading results: We see less trouble cells in (b), because of unnoticed inroamer absences shorter than 6 minutes. According to (a) approximately the same number of inroamers switch to either rival network, while according to (b) switches to Operator A prevail. The reason is that the switches to Operator B are more often shorter than 6 minutes. Moreover some cells which appear to lose an inroamer in (b) have zero loss count in (a). This happens when the inroamer's motion is so fast that not all cell switches are noticed owing to the longer interval.

The focus on inroamers in the GSM network signal coverage diagnostics application allows to detect areas where the signal of studied network is weak while a rival network signal is stronger. To the contrary, tracking domestic clients would provide information about the studied network signal only, since domestic clients stay in the network constantly regardless of rival networks.

We are aware of the location information processing privacy risks, therefore the SS7Tracker platform employs the following security practices: the location data are stored in a secure database server and protected by SSPI authentication so that only the authorized staff can work with it. Except the individual track analyses, all produced reports are designed to provide only aggregate data with no relation to individuals.

Advanced anonymization techniques should be adopted within the SS7Tracker platform before its wider practical application in commercial or research areas. For location information and statistics the "hitchhiking approach" seems to be the most suitable [24]. In the case of individual track analyses the principle of k-anonymity and minimum reference area has to be applied [25, 26].

We consider it an advantage that our tracking method is not perceptible by the subscriber and does not require subscriber cooperation. Generally, the subscriber consensus with being localized is required, but the method can be used even in situations when the consensus cannot be obtained - e.g. in suspect tracking [31]. The use of location data is limited by the country legal system. In the Czech Republic it is based on a combination of national [33] and European Union legislation [34]. According to it, mobile operators are allowed to process and use operation and location data only in order to improve network functionality. In all other cases the data has to be provided and processed in anonymous form, otherwise each tracked person has to be informed about the purpose of tracking, the use of the data and asked for permission. Moreover there must be a simple way how to revoke the permission and stop the tracking.

7. CONCLUSION

We have presented the architecture of an existing GSM Cell-ID-based active tracking platform, and demonstrated two examples of its innovative use. However, much research work still remains to assess the potential of this platform comprehensively.

Mobile phone power consumption caused by additional communication should be analyzed to reveal possible impact on battery lifetime. Also the limits of network signaling overhead need to be properly understood. An optimal tracking interval may then be derived, taking into account tracking accuracy, network signaling overhead and mobile phone battery lifetime.

Cell-ID tracking accuracy may also be improved by further techniques, such as map-snapping, movement prediction, or combination with other technologies.

We intend to particularly focus on further applications that the location tracking platform may enable, such as location-based advertising and various user-oriented appli-

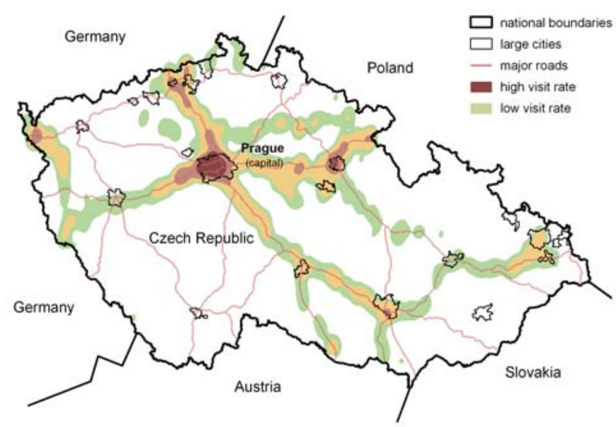


Figure 6: Places in the Czech Republic visited by the sample group of tourists
We employed the Kernel density function [32] to spatially interpolate numbers of tourist that visited each discrete cell. In the white areas the number of tourists is below a threshold limit value.

cations (e.g. context-based search). Also we plan to further explore location data-mining to derive aggregate real-time information for various applications, such as city traffic management, crowd control, advertising or crime prevention. The above will be coupled with further investigations into privacy-protection methods.

From the research perspective, the mobile network tracking platform enables to build and verify accurate models for user mobility within networks as well as among different geographic and commercial network segments, which ought to improve our understanding of real-time network dynamics and lead to novel methods of network management, dynamic self-optimization or business interaction modeling.

8. ACKNOWLEDGEMENTS

We wish to thank Vodafone Czech Republic a.s. for generous support of the project.

9. REFERENCES

[1] Ten Trends Influencing the European Mobile Phone Market 2007-2012. *In-Stat, Report No. IN0703687WMD, 2007.*

[2] 3GPP TS 29.002: Mobile Application Part (MAP).

[3] Q.700: Introduction to CCITT Signalling System No.7

[4] Mobile Roaming 2006-2011: Increasing Usage And Revenue To Counter Regulatory Burdens. *Bharat Book Bureau Report, 2006.*

[5] CTIA's Semi-Annual Wireless Industry Survey. *CTIA - The Wireless Association®, 2008.*

[6] K. Raja, W. J. Buchanan, J. Munoz: We Know Where You Are. *IET Communications Engineer, 2(3):34-39, 2004.*

[7] E. Trevisani, A. Vitaletti: Cell-ID Location Technique, Limits and Benefits: An Experimental Study. *Proceedings of IEEE WMCSA 2004.*

[8] A. Varshavsky, M. Y. Chen, E. de Lara, J. Froehlich, D. Haehnel, J. Hightower, A. LaMarca, F. Potter, T. Sohn, K. Tang, I. Smith: Are GSM Phones THE Solution for Localization? *Proceedings of IEEE WMCSA 2006.*

[9] A. LaMarca, Y. Chawathe, S. Consolvo, J. Hightower, I. Smith, J. Scott, T. Sohn, J. Howard, J. Hughes, F. Potter, J. Tabert, P. Powledge, G. Borriello, and B. Schilit: Place Lab: Device Positioning Using Radio Beacons in the Wild. *Proceedings of Pervasive 2005.*

[10] A. Quigley, B. Ward, C. Ottrey, D. Cutting, R. Kummerfeld: BlueStar, a privacy centric location aware system. *Proceedings of IEEE PLANS 2004.*

[11] 3GPP TS 03.71: Location Services (LCS).

[12] OMA Enabler Release Definition for Mobile Location Service (MLS), Candidate Version 1.1, 2006.

[13] Dialogic Corporation whitepaper: Adding Location-Based Services to Existing Architectures.

[14] Ericsson Mobile Positioning System. `www.ericsson.com/mobilityworld/sub/open/technologies/mobile_positioning/index.html`.

[15] Z. Naor: Tracking Mobile Users with Uncertain Parameters. *Proceedings of ACM MobiCom 2000.*

[16] C. M. Takenga, K. Kyamakya: Robust Positioning System based on Fingerprint Approach. *Proceedings of ACM MobiWac 2007.*

[17] Motorola Lifecycle Services - GSM Network Optimization. `www.motorola.com/mot/doc/1/1348_MotDoc.pdf`.

[18] A. J. Nebro, E. Alba, G. Molina, F. Chicano, F. Luna, J. J. Durillo: Optimal antenna placement using a new multi-objective chc algorithm. *Proceedings of ACM GECCO 2007.*

[19] E. Onur, H. Delic, C. Ersoy, M. U. Caglayan: Measurement- based replanning of cell capacities in GSM networks. *Elsevier Computer Networks, 39(6):749-767, Aug 2002.*

[20] L. Raisanen, R. M. Whitaker: Comparison and evaluation of multiple objective genetic algorithms for the antenna placement problem. *Springer Mobile Networks and Applications Journal, 10(1-2):79-88, Feb 2005.*

[21] M. Gruteser, J. Bredin, D. Grunwald: Path Privacy in Location-aware Computing. *Proceedings of ACM MobiSys 2004 Workshop on Context Awareness.*

[22] E. Snekkenes: Concepts for personal location privacy policies. *Proceedings of ACM EC 2001.*

[23] C. Y. Chow, M. F. Mokbel, T. He: TinyCasper: A Privacy Preserving Aggregate Location Monitoring System in Wireless Sensor Networks. *Proc. of ACM SIGMOD 2008.*

[24] K. P. Tang, P. Keyani, J. Fogarty, J. I. Hong: Putting people in their place: an anonymous and privacy-sensitive approach to collecting sensed data in location-based applications. *Proceedings of ACM CHI 2006.*

[25] M. F. Mokbel, Ch-Y. Chow, W. G. Aref: The New Casper: Query Processing for Location Services without Compromising Privacy. *Proceedings of VLDB 2006.*

[26] B. Gedik, L. Liu: A Customizable k-Anonymity Model for Protecting Location Privacy. *Proc. of IEEE ICDCS 2005.*

[27] C. Ratti, D. Frenchman, R. Pulselli, S. Williams: Mobile Landscapes: using location data from cell phones for urban analysis. *Environment and Planning B: Planning and Design 33, 2006.*

[28] R. Ahas, A. Aasa, A. Roose, Ü. Mark, S. Silm: Evaluating passive mobile positioning data for tourism surveys: An Estonian case study. *Elsevier Tourism Management, 29(3):469-486, June 2008.*

[29] R. Ahas, A. Aasa, S. Silm, R. Aunap, H. Kalle, Ü. Mark: Mobile Positioning in Space-Time Behaviour Studies: Social Positioning Method Experiments in Estonia. *Cartography and Geographic Information Science, 34(4):259-273, Oct 2007.*

[30] Dialogic® SPCI4 User Manual, 2006.

[31] P. Schmitz, A. K. Cooper: Using Mobile Phone Data Records to Determine Criminal Activity Space. *IQPC International GIS Crime Mapping Conference 2007.*

[32] B. W. Silverman: Density Estimation for Statistics and Data Analysis (Monographs on Statistics and Applied Probability). *New York, Chapman and Hall, 1986.*

[33] Protection of private information law, 101/2000 Sb., Czech Republic Collection of Law.

[34] Directive 2002/58/EC, EU Commission.