

Autonomous Cellular Road User Charging based on Unique Cell Point Identification

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Abstract

A new generation of Road User Charging (RUC) systems based on Wide Area Network (WAN) wireless communication and positioning is entering the market. The main advantages with these systems compared to DSRC-based systems are their flexibility in supporting different charging methods and tariffs and the reduced infrastructure cost. The standard approach to implement WAN tolling systems is to use a combination of Global Positioning System (GPS) and General Package Radio Service (GPRS) or Short Message Service (SMS). This paper introduces the novel Unique Cell Point Identification (UCPI) technology that uses GSM (Global System for Mobile communication) as a standalone technology to realize an autonomous cellular RUC system. By using an autonomous cellular RUC system, large cost savings can be achieved while maintaining integrity and charging flexibility.

Keywords

UCPI, UCP, RUC, GSM, GNSS, GPS, GPRS, EFC, ETS, Cellular Positioning

INTRODUCTION

During the last two decades, a large road traffic increase has led to congested road networks, severe environmental issues and high road wear. In many areas it is not possible, economically defendable, or even wanted, to increase the capacity. The developments within communication and sensor technologies have made it possible to use Road User Charging (RUC) as an excellent way of managing traffic flows on selected parts of the road network. RUC can be used for decreasing congestion levels, reducing environmental impacts, fairly distributing costs of road wear and funding of e.g., road works, environmental research, alternative transportation systems etc.

Early RUC systems interfered with the traffic flow due to the stop-and-pay layout. Both road capacity and user experienced travel times were affected negatively. Free flow systems were pioneered by Dedicated Short Range Communication (DSRC), which made it possible to deploy RUC without interrupting the traffic flow. Later also Automatic Number Plate Recognition (ANPR) systems have become a common technology. A large interest in road tolling, different requirements on tariffs and flexibility has motivated new RUC technologies. A new generation of free flow RUC systems is the Wide Area Network (WAN) based systems. The WAN systems are relying on existing infrastructure for positioning and communication over large geographic areas and they attract interest due to their low infrastructure cost and flexible tariffs. The system investment is no longer proportional to the number of tolling points or zones. By using WAN based tolling systems it is also feasible to realize distance based charging. WAN based RUC is discussed further in e.g., [1-2]. A comparison between different RUC systems can be found in [3].

This paper introduces the Unique Cell Point Identification (UCPI) technology that makes it possible to deploy a WAN based tolling system solely relying on a cellular network (e.g., GSM), without the need of a Global Navigation Satellite System (GNSS) module for positioning. This kind of system is from now on referred to as an autonomous cellular RUC system. In the following sections, the UCPI technology is explained together with possible applications within RUC and a comparison with other RUC systems. *Figure 1* illustrates the main concepts of the different free flow charging systems. In *Figure 1a*, the DSRC principle is illustrated, where a microwave camera is reading the tag information from the DSRC On-Board-Unit (OBU). *Figure 1b* shows an ANPR example, detecting and interpreting the vehicles number plate. *Figure 1c* illustrates a Satellite based system whereas *Figure 1d* shows a system solely based on GSM.

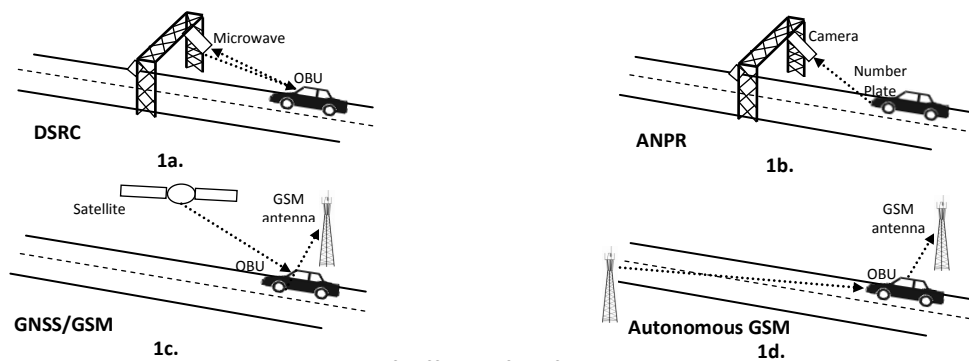


Figure 1. Concepts of different free flow RUC systems.

BACKGROUND

Current WAN-based systems typically use a GNSS module for positioning (typically Global Positioning System (GPS)) in combination with a cellular network device, e.g., a GPRS-module, for the communication with the central system. A cost-efficient alternative is to use the cellular network for both communication and positioning. A previous suggestion to an autonomous cellular based RUC system was made in [4]. However, this system has a large drawback in assuming that existing cellular traffic works as the input to the charging system. The existing cellular traffic will not generate location data that is detailed enough for most RUC scenarios and the user can easily affect the signalling data sent from the terminal. It is also likely that the RUC system will affect the mobile phone behaviour instead of the road traffic behaviour, which is an odd way to go. Apart from that, this has not been done so far due to the low accuracy of standard cellular positioning methods such as Cell Global Identity (CGI) + Timing Advance (TA), Time of Arrival (TOA), Angle of Arrival (AOA) and Enhanced-Observed Time Difference (E-OTD). These positioning methods are described in detail in e.g., [5-6]. The accuracy of these systems varies depending on cellular network structure, but the location error is typically too large to identify a vehicle route even with map matching.

By using the Database Correlation Method (DCM), a.k.a. fingerprinting, the accuracy of cellular positioning can be increased. This method exploits signal strength variation in the cellular network in order to determine the location. The signal strengths (fingerprints) of different locations are typically stored in a database and a sample fingerprint is matched to a location using correlation to the fingerprints in the database. Locating vehicles using signal strength is not a new topic, it was introduced in [7] already 1969. DCM positioning is further discussed in e.g., [8-9].

Even with fingerprinting the location accuracy is mostly too low to be used as input to a RUC system. However, as described in e.g., [10-11], tracking is a good way of increasing the accuracy of cellular location. In order to successfully use a cellular system to track a vehicle route for RUC purposes, a short location sampling time is needed. This is possible to achieve for terminals engaged in a telephone call or data transmission, since the cell phone reports the signal quality frequently to the network. This is utilised when vehicles are tracked in order to estimate travel times using cellular networks [12-13]. For a RUC application it is not scalable to have all tracked vehicles sending measurement reports with such high frequency, instead a mobile based technology can be deployed. A mobile based technology is characterised by the mobile making the measurements without the need of communicating with the cellular network. Following the terminology, UCPI is a mobile based, fingerprint tracking method that is optimised to identify travelled road sections for the purpose of RUC. The relation between the cellular location methods is shown in *Figure 2*.

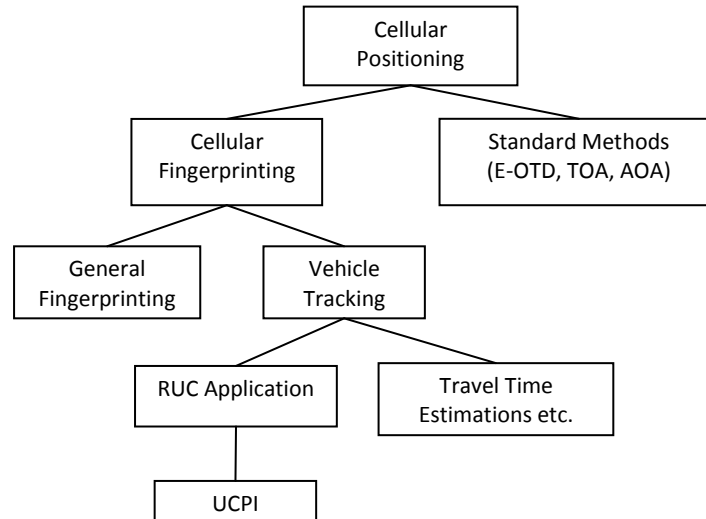


Figure 2. The UCPI technology in relation to other cellular positioning technologies.

UNIQUE CELL POINT IDENTIFICATION

Unique Cell Point Identification is a new way of thinking regarding vehicle positioning and RUC. UCPI is a tailor made RUC localization method. The method does not focus on achieving ubiquitous high location accuracy, instead it focuses on determining whether a specific route has been traversed or not. The UCPI technology is not based on E-OTD, TOA, AOA or similar methods. It uses road section fingerprints by using the CGI and the Received Signal Strength Indicator (RSSI) value, which is collected from test drives and stored into a database. During the detection phase incoming vehicle data is compared to the premeasured data in the database. The server side consists of a set of algorithms which determines the traversed sections of each vehicle.

To exploit cellular positioning in RUC, focusing on RUC objectives is crucial to make it work. Unlike other cellular mobile positioning methods, UCPI is optimized to determine vehicle routes based on previously collected measurements.

Definition of the UCPI method

- A Unique Cell Point is a finite area with a suitable size representing a geographic fingerprint with at least one detectable CGI, each with its corresponding RSSI value. The fingerprints are typically aggregated and filtered. Depending on available data, the UCP can be extended to include other variables.
- A set of UCPs are selected for each road section. The selection is made by using the most significant UCPs while minimizing ambiguity with neighbor UCPs in the system.
- Depending on where a UCP is located, the functionality will be different, e.g., when a UCP is placed on a side road (not to be charged), the UCP is referred to as a Clearing Point (CP).

The UCPI method – A RUC example

Data collection

Depending on which roads that should be charged, measurements of the charged roads and side roads are collected into a database. A vehicle equipped with a GSM and GPS unit can be used to collect fingerprints (CGI and RSSI values), together with a GPS coordinate on each sample, see *Figure 3*. When the whole network has been travelled, the collected data is transferred from the vehicle to a local database. Data might need to be collected more than once on each road.

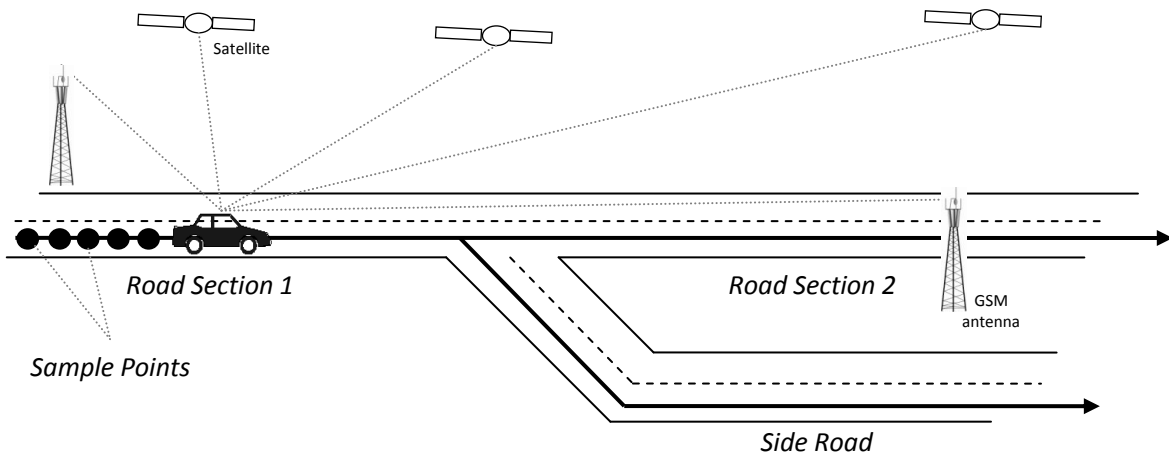


Figure 3. Data collection by sampling fingerprints.

Data Clustering

In the following step the samples from the data collection phase are aggregated to clusters, existing of a set of CGIs and their RSSI interval. The clustering can be done in two ways, by creating uniform or adaptive UCPs.

Uniform UCPs have the same finite sample size; see road section 1 and 2 in *Figure 4*. Uniform UCPs are easy to create but they are not as efficient as the adaptive UCPs. However, finding the best suited adaptive UCPs can be a quite complex procedure. Adaptive UCPs can be created automatically with constraints on how much nearby UCPs should be allowed to differ from each other. The side road in *Figure 4* exemplifies adaptive UCPs.

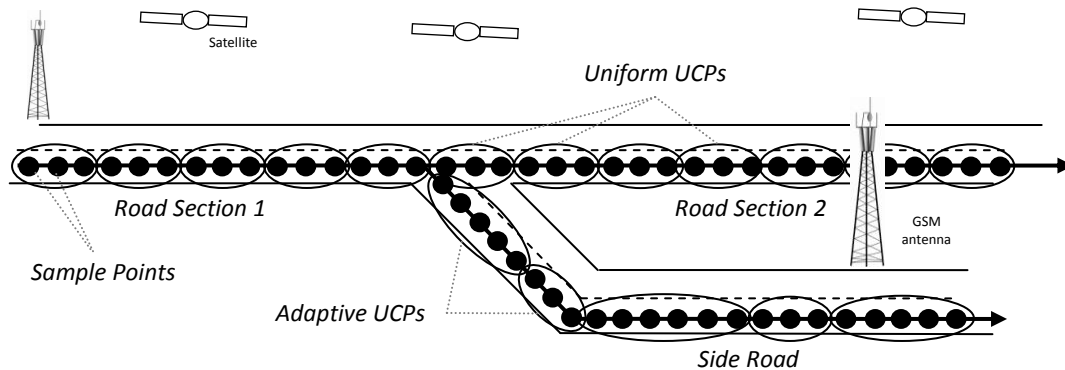


Figure 4. Data clustering for uniform and adaptive UCPs.

UCP Selections on Route Sections

Each UCP is defined by a finite set of CGIs where each CGI also has stored signal strength information, e.g., maximum and minimum RSSI value. The best suited points are then chosen to represent the fingerprints of a section or area. Having adjacent UCPs is not always necessary, which leads to a possible elimination phase. Dedicated algorithms decide when UCPs are similar enough and when to make eliminations. According to the best suited UCPs on a route, an internal ranking for each route is made possible by giving a weight to each UCP. The purpose of the weights is to get a dynamic metric of the UCP detection reliability.

Clearing points

A special type of UCP is referred to as Clearing Point. The purpose of the Clearing points is to clear out a possible incorrect detection of UCPs on the main road while travelling on the side road.

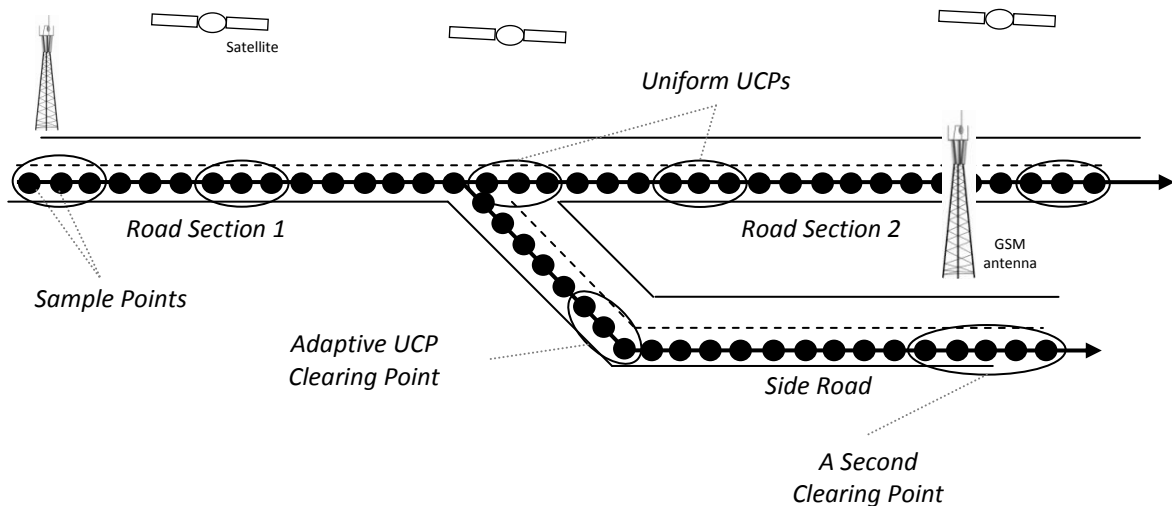


Figure 5. Example of using clearing points.

Detection Process

During the detection process, vehicles in the system travelling on the premeasured routes are sending data about their current visible CGIs and signal strengths to the server. The server matches that data to the best fitting UCPs stored in the database. When enough detections have been made on UCPs on a section, it is considered to have been traveled on. The difference compared to a GPS-based solution is that a whole section has to be traversed before a decision can be made.

New measurements can be used to update existing UCPs during the detection process. This is necessary when the radio signal pattern is changed due to modifications in the cellular network, the road network, nearby infrastructure etc.

Overall Functionality

The developed system has all the advantages that a WAN-based system has, i.e. flexible charging methods, flexible charging areas and flexible tariffs as well as little or no infrastructure cost. It has also inherent support for using the same OBU in different countries.

An important advantage is the easy installation of the OBU. Due to its small size and the option of different placements in the vehicle, the installation cost can be kept at a low level. This is increasingly important when the fleet size is very large. The lack of a GPS receiver also keeps the processing requirements of the unit and the power consumption at a minimum level.

An autonomous cellular RUC system does not have a problem with metallic wind screens or wind screens covered with snow and dirt. A cellular based system is also less susceptible to jamming signals.

Position coordinates are not sent from the OBU, which can be used to keep the communication cost down. Furthermore it is of importance due to the aspect of personal integrity, which is a topic of current interest, discussed in e.g., [integrity]. The system does not keep track on exact coordinates of the user, instead only the charging-related information is extracted, i.e., which charged area or road section the user has traversed.

Enforcement can be supported by allowing trusted parties to retrieve state information from the OBU. The system also has the flexibility to cooperate with other technologies, e.g., with a GPS/GPRS-based OBU.

UCPI APPLICATIONS

There are several application areas for UCPI, for instance RUC, Congestion Charging in Cities or Plaza Tolling. Also other road traffic parameters, such as average speed and density, can be derived from the location data.

Road Sections

Each section has to be determined in order to charge a whole route. In ideal cases one UCP per section is enough to determine a traversed section. *Figure 6* exemplifies two UCPs on a road section. By using distances between the sections in the server, an accumulation of driven routes will generate a distance defined trip. Time stamps can also be used to ensure consistency between a set of different driven routes. In *Figure 6*, it can be seen that the precision of detecting the section does not depend on the accuracy of each UCP on the section, but rather on whether a unique UCP is identified or not.

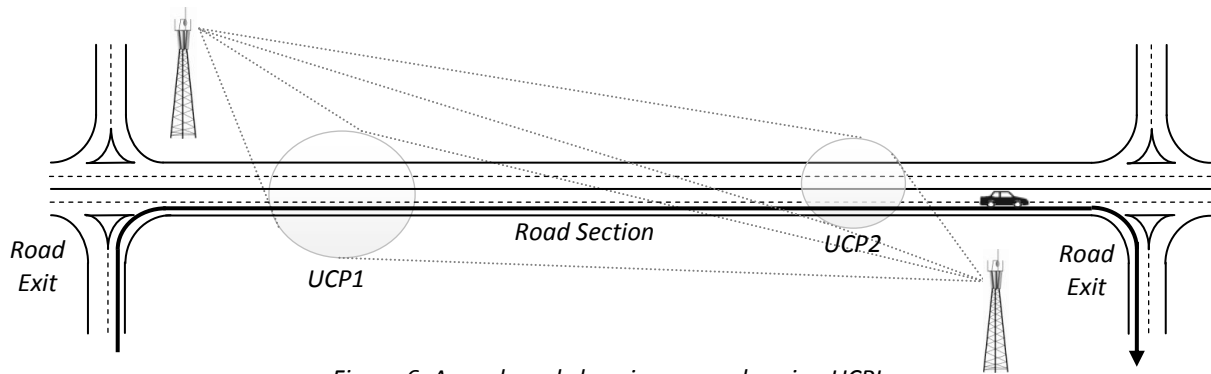


Figure 6. A rural road charging example using UCPI.

City Application

A fee can be connected to entering, leaving or staying within a specified area, e.g, a city. *Figure 7* illustrates how UCPI can be used for a City Application. By placing UCPs on the outside and inside of the boarder, a direction of the vehicle can be detected giving the option to have different pricing for entering or leaving the city. When driving inside the area, two different charging models are possible; distance-based and time-based. It is possible to use UCPI for both approaches, although the location resolution might be too low for some distance-based schemes.

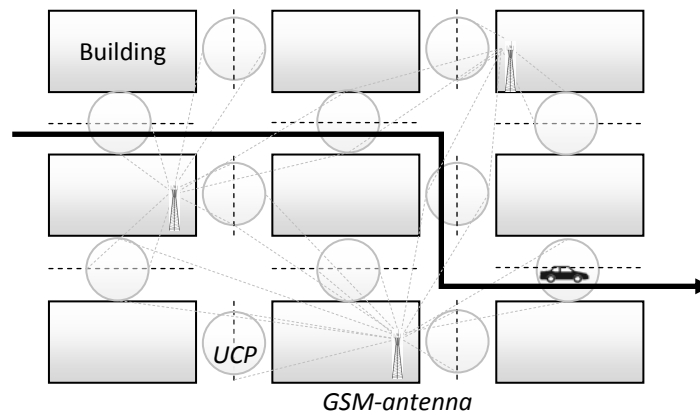


Figure 7. A city tolling application example using UCPI.

CONCLUSIONS

A new approach to Road User Charging, solely based on a GSM OBU, is presented. The UCPI technology focuses on determining traversed road sections instead of making single locations. By using geographic fingerprints, Unique Cell Points (UCPs) can be created and stored in a database. When a vehicle traverses a road section, it reports measurements to the server side, which compares the reported data with pre measured data of the section stored in the database. UCP detections are used to determine which sections a vehicle has traversed. UCPI is a promising technology, which is a very cost efficient alternative for charging of rural road networks as well as for city tolling.

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