An Enhanced Mobility Model

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Betsie Pérez Quiles

Universidad Politécnica de Valencia
Institut für Nachtichtentechnik und Hochfrequenztechnik

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Begutachter:
Univ. Prof. Dipl.-Ing. Dr. Ernst Bonek
Univ. Prof. Dipl.-Ing. Plamen Dintchev

To my parents, I specially dedicate this work

ABSTRACT

Mobile communications have been recently involved by a spectacular development. As the technological part as the popularity aspect. They are integrate in all sectors inside our society. In general, wireless communications have become very pervasive. The number of mobile phones and wireless Internet users has increased significantly in recent years. Therefore, it has been necessary to improve the design and the efficiency of the networks that provide these services. One of the most important key-points is the development of mobility models in order to determine the position of users in the system due to its influence in the load and the resources required. Mobility models are needed in the design of strategies for location updating and paging, QoS, radio resource management (e.g., dynamic channel allocation schemes), and technical network planning and design (e.g., cell and location area layout, network dimensioning).

A wide variety of studies can be found in literature about mobility modelling, from deterministic to statistical models, which determine the movement of different type of users. Moreover, they can be classified in function of different variables: geographical region, type of service, purpose (e.g. for location updating, for network planning), degree of randomness, and/or level of description (from macroscopic to microscopic models). On the other hand, the proposed modelling techniques also present a wide variety regards to the complexity, from more general models to others that determine the user movement in detail. This works begins by presenting a classification of mobility models that summarizes all this diversity.

The movement pattern of users plays an important role in performance analysis of mobile and wireless networks, and so, mobility modelling needs to be in continuous development and investigation. Nowadays, networks must support increasingly traffic loads and velocity connections. Therefore, network designs tend to reduce the cell size more and more and lead to picocellular structures in order to reduce the number of users per cell and increase the assigned resources for each one. These changes imply that complexity in spectrum distribution increases. But the enhancement does not affect only the access techniques, it is needed to know with higher precision the user allocation, the type of service required for each user in the cell, and the time the user will hold on the assigned resources. Therefore, the efficient dimensioning of the system requires a deep and detailed study. Thus, mobility models must be reviewed and improved. Because of this, I have presented an enhanced model based on the work [1] of P.I. Bratanov and E. Bonek about a statistical model that describes the movement of vehicular-borne terminals in an urban area. I have focused in the study of this model because it joins simplicity and accuracy.

This work presents a more realistic modelling of the user movement since it includes the possibility the user stops for certain period. The *stop-time* for a user within a cell has been analyzed, and the conclusions determine it is normal distributed in urban and suburban environments. To check its validity, two of most important parameters for allocation and updating techniques or radio resource management have been calculated by applying this model: cell dwell time and handover rate. Precisely, the handover is one of the fundamental reasons why this study is important for, especially in third-generation communications systems. In such networks, effects as soft/softer handover or power control cannot be fully investigated without the perfect knowledge of the mobile users' movement pattern.

Furthermore, due to the higher requirements on data rates, quality of service, and spectral efficiency, in conjunction with the smaller cell sizes in these networks, the accurate performance evaluation of these networks will become crucial. Particularly, for the analysis of heterogeneous networks, e.g. UMTS/WLAN, or ad hoc networks, it is imperative to use a mobility model that accurately represents the mobile terminals' movement. Results concerned different environments: urban, suburban and rural areas, by adjusting the parameters and they have been discussed and compared.

Finally, the work compares conclusions from other authors [3] about user's distributions. Exactly: User initialization and new user allocation. Studies showed that the most commonly used is the uniform distribution but if we consider the so-called border behaviour (i.e., what to do if users move out of the system plane) and investigate the impact of the mobility model on the spatial user distribution, we will conclude that by using the wrong model can lead to incorrect simulation results.

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Chapter I

Introduction

Mobility models are needed in the design of strategies for location updating and paging, radio resource management (e.g., dynamic channel allocation schemes), and technical network planning and design (e.g., cell and location area layout and network dimensioning). The purpose of mobility models is to describe typical terminal movement so that the analysis for these purposes can be made.

Thus, the movement pattern of users plays an important role in performance analysis of mobile and wireless networks, especially in third-generation mobile communications, since terminal mobility has a great influence in most UMTS communication aspects involving either performance or traffic generation as a result of handover. On the one hand, the use of hierarchical cell structures proposed for IMT2000 favours the handover between cells belonging to different layers. The overlaying of cell structures allows different rates of mobility to be serviced and handled by different cells. On the other hand, since the street-canyon propagation is recognized to be the dominant propagation mechanism in urban areas [29], soft or softer handover is very probable at crossroads.

Furthermore, due to the increasing requirements on data rates, quality of service, and spectral efficiency, in conjunction with the smaller cell sizes in these networks, the accurate performance evaluation of mobile communication systems will become crucial. Issues such as radio resource management, location management and QoS, as well as traffic handling capacity, are directly affected by mobility.

Regards to the relation between spectral efficiency and the cell size, we want to outline that once a channel allocation scheme has been adopted, more substantial improvement in network performance can be achieved by reducing the cell size. Covering crowded geographical areas with a larger number of smaller cells, among other benefits, it reduces the average number of users per cell. That is, it reduces the number of channel permanently or dynamically assigned to a cell. However, handover-events increase due to this cell size reduction. Handover-events are originated by a cell transition of a user with a call in progress; the user cannot use the same channel and the call must be handed over the neighbouring cell in order to provide service without interruption. As far as the users keep moving at their usual mobility, a cell size reduction corresponds directly to a rise of the hand-over rate. Thus, future cellular communication systems (picocellular) will experience high handover rate and wireless communication network design and modelling will be severely affected.

Therefore, the efficient dimensioning of the system requires a deep and detailed study. Because of this, we have presented an enhanced model based on a statistical model [1] that describes the movement of vehicular-borne terminals in an urban area. We have focused in the study of this model because it joins simplicity and accuracy and it makes the movement trace of mobile stations more realistic than common approaches for random mobility.

1.1. Evolution of Wireless Communications Networks

The terrestrial and satellite based mobile communications systems allow people to make and receive calls from any point on earth using the same multi-purpose handset whether at home, in the offices, or outside.

Nowadays, personal communication services are provided by a range of different generation networks and technologies. It is envisaged that the direction for new generations is bringing together all the attributes of existing personal communications into a single unified system. However, in order to see how this can be achieved it is necessary to consider a number of technical, economic, regulatory and market place issues.

Therefore, wireless communications have become very pervasive. The number of mobile phones and wireless Internet users has increased significantly in recent years. Traditionally, first-generation wireless networks were targeted primarily at voice and data communications occurring at low data rates. But, we have seen the evolution of second- and third-generation wireless systems that incorporate the features provided by broadband technologies. In addition to supporting mobility, broadband also aims to support multimedia traffic, with quality of service (QoS) assurance. We have also seen the presence of different air interface technologies, and the need for interoperability has increasingly been recognized by the research community.

The demand for change has been partly technological and partly vendor-side driven. The principal drivers of digital cellular technology are very similar across the world; however, the maturity of the market will influence the impact of these drivers. Factors affecting market maturity include pent-up demand for mobility due to changes in societies and working practices; competition; price reduction to the customer in handsets and tariffs; improved coverage and quality in cellular; broader distribution channels; and new and value added features like roaming (moving from one geographic area to another without losing the communications link), mobile information displays, e-mail, video-conferences or messaging. By seeking to liberalise mobile communications, governments and regulators encouraged demand for these new and value added features in telecommunications.

We will briefly summarize this evolution in mobile communications field. The first signs of the shift to ubiquitous personal communications are evident in the success around 1995 in Japan of the "Personal Handy Phone" (PHS): an inexpensive, light weight handset that operates as a cordless telephone in the home, and as a cellular phone elsewhere.

As a first step digital cellular systems were introduced in many countries because of the advantage they provide in terms of capacity and adaptability for new services. The principal goals for digital or second-generation technologies were to achieve more capability from the spectrum available, and to prepare for new (non-voice) features and facilities. Compared to first-generation systems, second-generation (2G) systems use multiple access technology, such as TDMA (time division multiple access) and CDMA (code division multiple access). Thus, Global System for Mobile Communications (GSM) uses TDMA technology to support multiple users.

Examples of second-generation systems are GSM, Cordless Telephone (CT2), Personal Access Communications Systems (PACS), and Digital European Cordless Telephone (DECT).

Second generation networks are in current use around the world. The protocols behind 2G networks support voice and some limited data communications, such as Fax and short messaging service (SMS), and most 2G protocols offer different levels of encryption, and security. While first-generation systems support primarily voice traffic, second-generation systems support voice, paging, data, and fax services.

Later, an enhancement over second generation arrived to the market. The move into the 2.5G world began with General Packet Radio Service (GPRS). GPRS is a radio technology for GSM networks that adds packet-switching protocols, shorter setup time for ISP connections, and the possibility to charge by the amount of data sent, rather than connection time. Packet switching is a technique whereby the information (voice or data) to be sent is broken up into packets, of at most a few Kbytes each, which are then routed by the network between different destinations based on addressing data within each packet. Use of network resources is optimized, as the resources are needed only during the handling of each packet.

GPRS supports flexible data transmission rates as well as continuous connection to the network and it is the most significant step towards 3G. Regards to second-generation systems for office communication we observe an evolution to integration of voice and data. However, for data transport through wireless Local Area Networks (LAN), much more bandwidth and transmission capacity is needed. Next generation systems would be able to deal sufficiently with these problems, facilitating broadband mobile applications such as wireless video.

A new generation of data services has been introduced into the market during last years. Third-generation mobile systems are facing several challenging technical issues, such as the provision of seamless services across both wired and wireless networks and universal mobility. There are three evolving networks under investigation: (a) UMTS (Universal Mobile Telecommunications Systems), (b) MBS (Mobile Broadband Systems), and (c) WLAN (Wireless Local Area Networks). Moreover, third generation and personal multimedia environments builds on GPRS and is known as Enhanced Data rate for GSM Evolution (EDGE). EDGE allows GSM operators to use existing GSM radio bands to offer wireless multimedia IP-based services and applications. EDGE let operators function without a 3G license and compete with 3G networks offering similar data services. Implementing EDGE is easy and cost-effective and requires relatively small changes to the network hardware and software as it uses the same TDMA (Time Division Multiple Access) frame structure, logic channel and 200 kHz carrier bandwidth as today's GSM networks. As EDGE progresses to coexistence with 3G WCDMA, data rates of up to ATM-like speeds of 2 Mbps could be achieved.

In conclusion, the world of mobile communications evolves rapidly and thus, networks that support these communications too. From first generation of mobile communications, the objective of terrestrial and satellite based mobile communications systems was to allow people to make and receive calls from any point on earth using the same multi-purpose handset whether at home, in the offices, or outside, to third generation mobile communication systems, that aim to integrate all the different services and technologies (cordless, PCS, cellular, satellite) and provide a competitive service (voice, data, video, multi-media) compatible with the technology developments taking place within the fixed telecommunications networks. Third generation mobile telecommunications systems aim to unify the present diverse systems into a seamless radio infrastructure capable of offering a wide range of services. Among them, second generation aimed to achieve more capability from the available spectrum, and prepare for non-voice features.

1.2. Consequences

The design of third generation mobile communication networks faces three major challenges: first, there is the tremendous increase in the demand for mobile communications services. Second, the main resource in wireless systems, i.e. the frequency spectrum, is extremely limited. And third, new access technologies (SDMA, CDMA) require new mobile network planning methods.

Since these challenges are strongly interconnected, they can only be addressed by an integrated user mobility and teletraffic concept, in order to obtain an efficient, economic and optimal mobile network configuration.

UMTS structure favours (soft/softer) handover. Figure 1 illustrates the basic architecture for a typical UMTS network. It is composed by three main units: user equipments, access network and core network. The UMTS access network comprises one or more Radio Network Subsystems (RNSs). Each RNS covers a group of UMTS cells, and it is responsible for the resource management in each cell. A RNS contains a controller device (RNC, Radio Network Controller) and a group of base stations, the so-called Nodes-B.

Two types of interfaces are defined in the radio network for third-generation communications systems. I_{ub} interface connects each Node-B with its controller (RNC) and I_{ur} interface connects different RNCs. This last interface, without equivalent in 2G networks, allows the direct communication among RNCs for the support of soft-handover between base stations (Nodes-B) that belong to different RNCs (Figure 1).

At the global level, the work carried out within ITU (International Telecommunication Union) has been instrumental in the definition of FPLMTS/IMT2000. The Universal Mobile Telecommunication Systems (UMTS) and Future Public Land Mobile Telecommunications Systems (FPLMTS/IMT2000) are third generation mobile telecommunications systems that aim to unify the present diverse systems into a seamless radio infrastructure capable of offering a wide range of services.

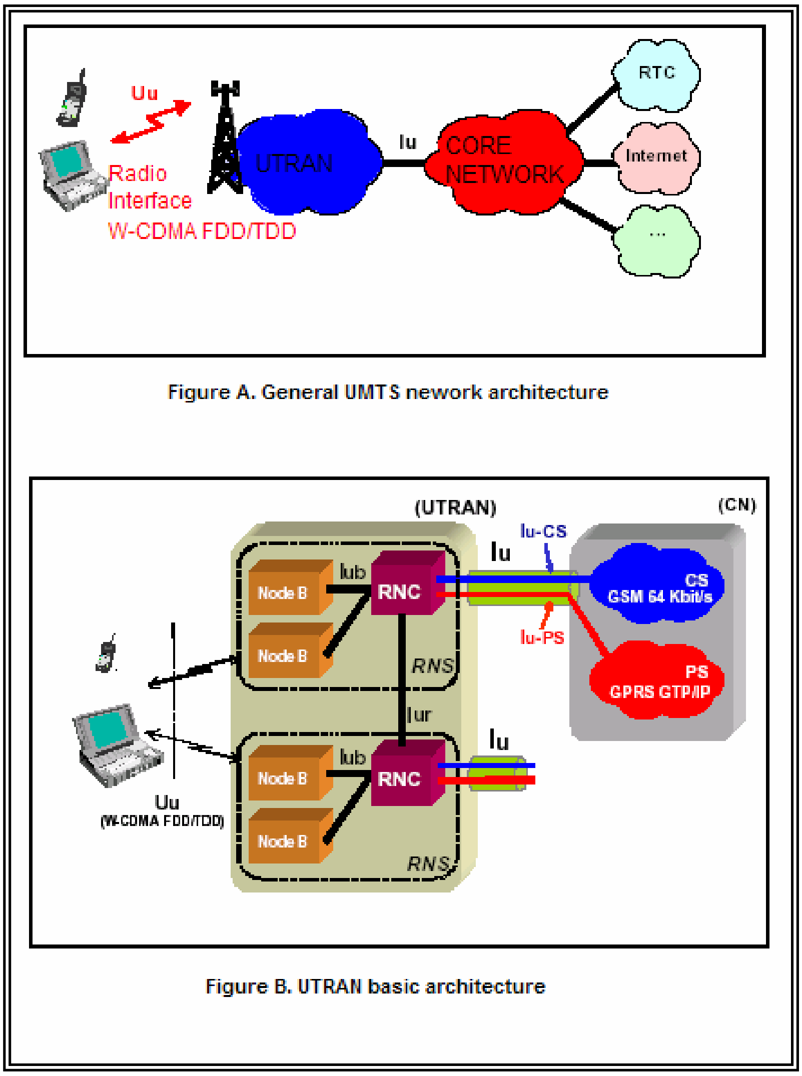


Figure A. General UMTS nework architecture

Figure B. UTRAN basic architecture

Figure 1. UMTS Architecture. A) General UMTS network architecture. B) UTRAN basic architecture

Regarding to the increased demand in number of services and users, new cell structures are proposed. The use of hierarchical cell structures is also proposed for IMT2000. The overlaying of cell structures allows different rates of mobility to be serviced and handled by different cells.

On other hand, advanced multiple access techniques are also being investigated, and two promising proposals have evolved, one based on wideband CDMA and another that uses a hybrid TDMA/CDMA/FDMA approach.

Another important consequence affects the cell sizes and the hand-over. Once a channel allocation scheme has been adopted, more substantial improvement in network performance can be achieved by reducing the cell size. Covering crowded geographical areas with a larger number of smaller cells, among other benefits, it reduces the average number of users per cell. That is, it reduces the number of channel permanently or dynamically assigned to a cell. However, handover-events are originated by a cell transition of a user with a call in progress; the user cannot use the same channel and the call must be handed over the neighbouring cell in order to provide service without interruption.

As far as the users keep moving at their usual mobility, a cell size reduction corresponds directly to a rise of the hand-over rate. Thus, future cellular communication systems picocellular will experience high handover rate and wireless communication network design and modelling will be severely affected.

Last but no least, we want to underline the influence of this evolution in mobility and call behaviour. UMTS needs to respond to the demand of consumers, who want to combine mobility with multimedia applications. The general trend foreseen for UMTS (dense cellular layout, variety of services and environments with several traffic and mobility levels) will increase the control capacity requirements. In this context it is important to model all the basic process, namely those related to the traffic management (e.g., call control) and those driving the mobility process. The latter can be further distinguished between "call related" (handover) and "call unrelated" (location updating). The overall behaviour of the mobile user must then be characterized through a suitable representation of its traffic (rate of calls and duration) and mobility (e.g., velocity, direction) attitude. In particular, it is important to model the rate of generation of the related signalling procedures.

Mobility models are needed in the design of strategies for location updating and paging, radio resource management (e.g., dynamic channel allocation schemes), and technical network planning and design (e.g., cell and location area layout, network dimensioning).

1.3. Importance of user’s mobility modelling

In recent mobile communication systems, the influence of the mobility on the network performance (e.g., handover rate) will be strengthened, mainly due to the huge number of mobile users in conjunction with the small cell size and the increasing data load (e.g. in UMTS). In particular, the accuracy of mobility models becomes essential for the evaluation of system design alternatives and network implementation cost issues.

For example, a user’s mobility behaviour directly affects the signalling traffic needed for handover and location management (location updates and paging) and for the network procedures related to initiate a communication with the terminal. The extra signalling messages over the air interface consume radio resources and increase the associated database query load. In addition, mobility has major effect on the channel holding time in circuit-switched services ([19], [18]). Moreover, the latter has in turn huge influence on the call blocking and dropping probability ([30], [23]).

It is important to study the user's mobility not only because of the performance of the location management procedures, but also for the prediction of handover statistics. They are related to the number of crossings from one cell to another, and therefore they depend on the cell size, call holding time, and mobility parameters.

There is another important case, where the user's mobility is needed - *dynamic simulations*. A *dynamic simulator* requires the feedback information (the signalling between the mobile station and the base station) to readjust some network-side parameters, e.g. the power control. The power control adjusts the base station's and the mobile station's transmit power, and it generally depends on the propagation path, thus, on the user's position and on its mobility. If the user is close to the base station, with the same propagation attenuation, the base will need less power to connect the mobile station (MS). In contrast, at the same distance, mobile stations affected by an strong attenuation will be served by the base station with higher power than mobile stations with best propagation conditions.

An application not directly connected with our field is the prediction of vehicle traffic characteristics. In literature ([32, 33, 34]), we can find some useful mobility models in order to describe cars' movement. For example, the location updates give information about the number of user's in a zone within the city, and the handovers give information about the user's direction movement.

1.4. Overview of this work

In the present Diploma Thesis an enhanced mobility model for the vehicle-borne subscriber units is introduced, based on a statistical model, and focusing on the traffic in a given cellular structure under realistic traffic conditions. The motion of the subscriber units is modelled by introducing distribution functions of street length, direction changes at crossroads and subscriber unit velocity (according to the mobility model described in Bratanov's Ph.D. thesis [1]), and the introduced improvement consists on the inclusion of the stop time distribution. In Chapter II, different mobility models are presented and discussed in order to understand the differences among them. Moreover some types of classification and the most representative models for each one are discussed. In Chapter III, the model taken as basis is described in detail. Therefore, the enhancement added is explained and the interest for introducing this variant is discussed. Moreover, the procedure for obtaining the stop time distribution is explained. In Chapter IV, the simulation tool we used in order to achieve the defined goals at the beginning is described. In Chapter V, the improved mobility model is used to characterize different mobility-related traffic parameters in cellular systems. These include the distribution of the dwell time in different geographical zones (corresponding to urban, suburban and rural areas) and the handover rate per user in these areas. Finally, main conclusions are pointed out and new directions for future work are mentioned.

Chapter II

Mobility modelling

2.1. Introduction

Research in mobility modelling is performed in two directions [2]. The first direction is to design new models in order to mimic the real world scenarios better. This was the primary research direction and it was followed until 2000 approximately. Afterwards, the direction changed to analyze these models: finding the statistical properties of mobility models, designing different mobility metrics and studying the influences of mobility models on routing protocol's performance.

2.2. Mobility and traffic behaviour of mobile users

The primary task of the mobile system planning is to locate and configure the facilities, i.e. the base stations or the switching centres, and to interconnect them in an optimal way. To achieve an efficient and economic system configuration, the design of a mobile network has to be based on the analysis of the distribution of the expected demand in complete service area. Therefore, the demand-based design of mobile communication systems requires a traffic estimation and characterization procedure, which has to be simple as well as accurate. For this purpose, the offered traffic is the main parameter required. The offered traffic in a region can be estimated by the geographical and demographical characteristics of the service area.

Taking into account the requirements relevant to mobile communications, two types of modelling techniques are defined:

- A *mobility model*, modelling the mobility behaviour of the users, in terms of for example user speed and typical density of users in a specific geographical area.
- A *call or teletraffic model*, modelling the possible call cases, where calls are divided into categories as mobile-to-fixed/mobile-to-mobile, business/residential etc. as these properties may have impact on the call arrival rate, call duration etc.

In this work, the first kind of modelling technique is studied and general parameters, as the mean call duration for the Poisson distribution of the call duration or a uniform distribution for initialization of new calls, are taken in order to design the call user behaviour.

2.3. Mobility models classification

There are many different mobility models in literature, and the classification can depend on

(1) the level of description [2] (microscopic, mesoscopic, and macroscopic),

(2) the purpose (for radio resource management aspects [4], for location management aspects [5] or for radio propagation aspects [20]),

(3) the defined user [22] (pedestrian or car user),

(4) the traffic type [11] (voice, data),

(5) the degree of randomness in user behaviour modelling [2, 12, 13, 14] (from a statistical way up to an analytical way).

We are not interested in every single mobility model, but we would like to present an overview of the main proposals in literature so that the difference between this work and earlier work can be appreciated. That is the reason why some different classification are considered here and afterwards, in Chapter III, after describing the model we used, the main advantages of our model in comparison to previous models will be emphasized.

2.3.1. Level of detail

If we consider the level of detail in mobility modelling, three levels of description are distinguished. They are defined as following.

2.3.1.1. Microscopic Models

A microscopic model describes the movement of a single vehicle by its space and speed coordinates at a given time *t*. The aim is obtaining a very detailed model, as for example the Street Unit Model [21] or the Street Pattern Tracing Model [23].

- Street Unit Model

In the first proposed model, the mobile is allowed to move on a rectangular (Manhattan) grid only. The grid models the street pattern of suburban or urban areas. Parameters are the distances d_X and d_Y between crossroads in *X*- and *Y*-direction respectively. The speed is chosen from a normal distribution and can be updated periodically or area dependent as well as in the previous models. Direction changes can occur at every crossroads, where the probabilities can be different for each of the four possible directions at every crossroads.

The Manhattan description is useful to represent many square grid cities. However, it is also has the flexibility to approximate any kind of path as a superimposed high-way or ring roads whose line out depart from the Manhattan outline. Using dummy streets, irregular paths can be denoted to the desired approximation degree but the computation effort and complexity increase rapidly with them.

Furthermore, other examples can be considered in this point due to their similar characteristics with Street Unit Model, such as high-way traffic models presented in [26]. These models are able to describe the mobility behaviour of mobile users with an accuracy of a few meters, and thus, they are useful for devising efficient and effective dynamic channel assignment algorithms.

- Street Pattern Tracing Model

In the second example, the Street Pattern Tracing Model, the mobile is allowed to move on a predefined stretch only, which models e.g. a highway or a main street where directions changes are very unlikely to occur. According to [23] and for the easy of simulation, those streets can be represented by a polygon set of consecutive straight lines. In this model just the speed v of the mobile is chosen randomly (from a uniform or normal distribution) whilst the direction is given by the position of the mobile within the street. Moreover, in [23] a model for estimating car and pedestrian crossing rates at the border of an area is developed. This model considers the mobility conditions near the border of an area. Using the same modelling approach it is possible to estimate the pedestrian crossing rate too. However, for implementation of this model is necessary to know a lot of input statistical parameters such the average distance between two cars moving in every lane of every street; the average car speed in every lane of every street, and so on. As conclusion, to develop such a model, a very detailed analysis of car/pedestrian motion and street type under any vehicular traffic conditions is needed.

2.3.1.2. Mesoscopic Models

At the mesoscopic (or kinetic) level, the homogenized movement behaviour of several vehicles (not only a single vehicle but a set of them) is reflected. These models achieve an accuracy of medium scale. The called group mobility models, where sets of users move as groups, are included in this category. In this case, the objective is, in general, to derive a distribution function of the number of vehicles at a certain location (x, y) or speed v in order to describe the movement of the group.

An example of group mobility model is the Reference Point Group Mobility Model (RPGM) [12]. Each user has a logical centre and the trajectory of the group as a whole is represented by the locus of the centre. Though each user has its own reference point, the group moves as a single entity because the reference points follow the group movement. It is a derivation of the Mobility Vector Model shown in next Chapter.

The above model represents the velocity of any user, the mobility vector $\vec{M}$, with a base vector $\vec{B}$ and a deviation vector $\vec{V}$ related by the acceleration α:

$$\vec{M} = \vec{B} + \alpha\vec{V}$$

If the base vector represents the movement of the whole group instead of representing the primary velocity component of a simple user and the deviation vector is used to represent the movement of individual users within the group, the RPGM is obtained.

2.3.1.3. Macroscopic Models

In contrast with the previous models, density, mean speed and speed variance, and traffic flow of vehicles are the points of interest in macroscopic models. We can enumerate here three families of these macroscopic models: the fluid flow models, the family of gravity models and the random walk models.

Fluid flow models [19], describes the mobility in terms of the mean number of users crossing the boundary of a given area. They derive from transportation theory and describe the movement of a group of users. The Reference Point Group Model [12] is also included in this family.

Gravity models are a second approach use for modelling the macroscopic movement behaviour. They also derived from transportation theory. Such models give an aggregated description of the movement of several users (as the fluid model).

Finally, random walk models are the most frequently used family as approach in cellular networks. They describe the movement of individual users from cell to cell. A state transition diagram basically defines the model: a cell is represented by a state and the users' movement is represented by transition probabilities between the states. Thus, the interest is focused in the cell where the user resides and not its exact location. At the same time, these models, also denoted as Markovian mobility models, have been applied for one dimensional scenarios, for two dimensions there are models which allow us to derive analytical measures for the crossing rates of cell and location area boundaries, and in recent enhancements, researchers have invented models for three-dimensional movement, including vertical movements within the buildings, in staircases or elevators [19, 22]. Some of these random walk models will be discussed in detail in Section 3.2.3.2.

On the other hand, this kind of classification, considering different levels of detail in mobility modelling, is especially studied in service provision to mobile users because it is mainly accomplished by:

- Location management procedures (location update, domain update, user registration, user location, etc.), used to keep track of the user/terminal location.
- The handover procedure, which allows for the continuity of ongoing calls. The performance of the above procedures is influenced by the user mobility behaviour.

Additionally, the handover procedure affects the offered traffic volume per cell as well as the quality of service (*QoS*) experienced by the mobile subscriber (e.g., call dropping). In wireless telecommunication systems, the estimation of the above parameters, which are critical for the network planning and system design (e.g., location and paging area planning, handover strategies, channel assignment schemes), urge for the development of "appropriate" mobility models. Due to the diversification of the above issues, different mobility detail levels are required. In this way, we can considerer a relation between the purpose and the level of description:

- Location Management Aspects - Location area planning, multiple-step paging strategies, data location strategies, and database query load. As consequence, location-management-related issues require the knowledge of the user location with an accuracy of a large-scale area (e.g. location or paging area).

- Radio Resource Management Aspects - Cell layout, channel allocation schemes (fixed/direct channel allocation, FCA/DCA), multiple access techniques (time-division/ frequency-division /code-division, TDMA/FDMA/CDMA), system capacity estimation, QoS related aspects, signalling and traffic load estimation, user-calling patterns. In this case, it is considered that radio-resource management-related aspects require medium-scale area accuracy (e.g. cell area).

- Radio Propagation Aspects - Signal strength variation, time dispersion, interference level (co-channel and adjacent channel interference), and handover decision algorithm (based in the signal strength variation). The level of description required for the study of this indicates that the analysis of radio propagation aspects needs accuracy of a small-scale area.

2.3.2. Degree of randomness

In [2] the degree of randomness is the criterion to classify models into three categories (from analytical to statistical, increasing the degree of randomness). This way of characterization and other categorization methods can be found in [6]. We also use this kind of classification because capacity of movement is supposed for users' patterns and their environments. Next sections present more detailed mobility models classified into three classes, according to the degree of randomness.

2.3.2.1. Trace based models

Everything is deterministic in these models because mobile users' movement is traced in their real scenarios. Researches in this area [7, 8] provide an interesting insight for actual local-area and cellular networks.

The main objection to the models based on traces is the actual situation: mobile ad hoc network is a new research area and no real working system is available yet. Moreover, although nowdays it is possible to study a real working system, it is a very complicated task to trace the mobility pattern of the users. As we can observe in [8], an analytical model of this type allows us to evaluate the effects on system performance of fixed channel allocation scheme, user load, mobility and distribution of users among cells, but assuming a finite population of users moving in a finite set of cells (thus, not a real scenario).

The only suitable field for these models could be the future picocellular system analysis. Besides, the main advantage of these kinds of models is that they allow the calculation of mathematical expressions with respect to system performance.

On the other hand, it has been already mentioned the complicated task of tracing the mobile users' movement. Because of this fact, analytical mobility models [19, 15, 9] are, in general, based on rather simple assumptions regarding the movement behaviour of users, and several authors have been able to derive important system performance parameters, such as channel holding time, user's cell residence time or handover and location update events.

2.3.2.2. Constrained Topology Models

Partial randomness is provided by these models, which simulate real scenarios where users' movement is constrained by obstacles or pathways; but speed and direction are still randomly chosen. Examples in this category include models that mimic freeway scenarios [9] and city block scenarios as the City Section Mobility Model [10] or the Street Unit Model [11] described in section 3.1.1 within the microscopic models group.

We briefly describe the more complicated constrained topology models:

- Mobility Vector Model [13]

The velocity of any user in this model is composed of a primary velocity component and a deviation from this vector. The deviation is useful in order to make movement smooth and therefore, in order to design more realistic scenarios due to the possibility of mimicking the deceleration of a user approaching its destination or the acceleration at the beginning of the movement. This model allows us to describe a large set of scenarios because it can be applied to other models (as the Random Waypoint model) so that the results will be more realistic: for instance, the user can be modelled with the capability of slowing down and stopping at the destination as in [3] it is presented.

This model represents the velocity of any user, the mobility vector $\vec{M}$, with a base vector $\vec{B}$ and a deviation vector $\vec{V}$ related by the acceleration α:

$$\vec{M} = \vec{B} + \alpha\vec{V}$$

The base vector represents the primary velocity component of a single user and the deviation vector, as its own name indicates, defines the deviation from the base vector. Many different mobility patterns can be produced by changing vector $\vec{B}$, $\vec{V}$ and α, such as the Reference Point Group Mobility Model [12]. It has been already mentioned as element of the mesoscopic group models. A group of users considered as a unique entity that move to perform some task. Each user has a logical centre and the trajectory of the group as a whole is represented by the locus of the centre. Though each user has its own reference point, the group moves as a single entity because the reference points follow the group movement. The randomly part is here introduced, because a random motion vector that denotes its offset from the reference point represents this movement. Therefore, the same equation for the mobility vector is employed here, but the base vector $\vec{B}$ represents the movement of the whole group and the deviation vector $\vec{V}$ is used to represent the movement of individual users within the group.

- Obstacle Mobility Model [14]

It is based on several real-life observations, taken as assumptions for modelling:

a. People move towards specific destinations rather than randomly choosing some destinations.
b. In real world there are obstacles, as buildings, parks or rivers for example. These obstacles block people's movements as well hinder signal-propagation.
c. It is not realistic to consider random trajectories for people's movement. They do not walk along random directions but along pathways and select shortest paths.

Common scenarios represented by this model are city centres or campuses. A user randomly chooses a building as its destination, moves towards it, then pauses there for a while and finally moves to another building. To reach a destination, the user can only move along pathways, although it may cross buildings through doorways. But, among all these pathways, which one selects the user? The answer is given by assumption third: the user selects the shortest. This model takes another assumption, in this case not too real, in order to simplify: the communication of a user with other users will be totally blocked by buildings if the transmission is out of Line-Of-Sight.

- City Area Model [11]

It describes user mobility and traffic behaviour within a city area environment (Figure 2). The need to analyze user mobility behaviour over large-scale geographical areas is raised by location-management-related aspects.

Figure 2. Typical city area environment

Source: City government of Vienna

According to transport theory, although each individual city area exhibits specific characteristics, some generic features can be observed and they are considered assumptions for modelling users' movement:

a. The population density gradually decreases while moving toward the city edges in suburban and rural area. In urban areas, typically, densely populated areas surround the city centre with high density of workplaces and shopping centres.

b. The street network supports two movement types: radial and peripheral.

c. The geographical area covers the whole city area, consisting of a set of zones connected via high capacity routes. A zone is assumed that corresponds to a network area (e.g. macro cell or local exchange area) and most frequently streets are considered as high capacity routes.

The randomly part corresponds to the user mobility behaviour (initial user's distribution, type of movement, criterion for selecting routes, etc.) and traffic behaviour (call arrival rates, available services, etc.).

This model provides the means to estimate the query load of a (distributed) database that covers the whole city area, and also, useful results for paging area dimensioning and location area planning schemes can be obtained. However, the assumptions taken are not valid for long time periods, but only for short periods, since mobility condition in a city area are quite dynamic.

2.3.2.3. Statistical Models

In this kind of models, users can move to any destination and their velocities and directions are chosen randomly. The movement of each user is described by some stochastic process. That reason explains these models are not too much realistic, because users are not able to move anywhere and moreover, in real world users don't move randomly without any destination. Nevertheless, in practice, tracing the actual mobility behaviour of users is a very complicated task and usually such information is hard to obtain from network providers. Thus, researches often use random models.

Moreover, there are some situations where no mobility pattern is known and no specific scenario is described. In fact, it is quite usual that the user's real mobility pattern was unknown and the scenario was undetermined. Examples of statistical models include Random Walk Model, Random Waypoint Model and Random Direction Model.

- Random Waypoint Model [2]

Probably this model is the most widely used and studied mobility model among all the models here presented. Basically, a user selects randomly a destination, so-called waypoint, in the system area and it moves towards it on a straight line with constant velocity. This velocity is also randomly chosen from a given range] $v_{min,}$ v_{max}] uniformly distributed. Then it pauses for a while before it again chooses a new destination. This is the base model but lots of extensions have been accomplished.

For instance, in [19] an enhanced random mobility model is presented, denoted as Smooth Random Mobility Model. The improvement pretends to make more realistic the simulated movement of users (cars and pedestrians) by introducing two new extensions that model typical mobility patterns: *stop and go behaviour* and *slowdown of turning users*.

Many researchers criticized that after arriving to the destination, the choice for a speed and a new direction is not correlated to previous values (such as in the random waypoint model). Physically, this fact may cause unrealistic movement behaviour with sudden speed changes and sharp turnings (Figure 3). Last model proposed, the Smooth Random Mobility Model includes both correlation features, and therefore, the speed is changed incrementally by the current acceleration of the mobile user, and the direction change is smooth. Once a station is intended to turn, the direction is changed in several time steps until the new target direction is achieved and so, velocity changes (v, v' and v'' in Figure 4) are related.

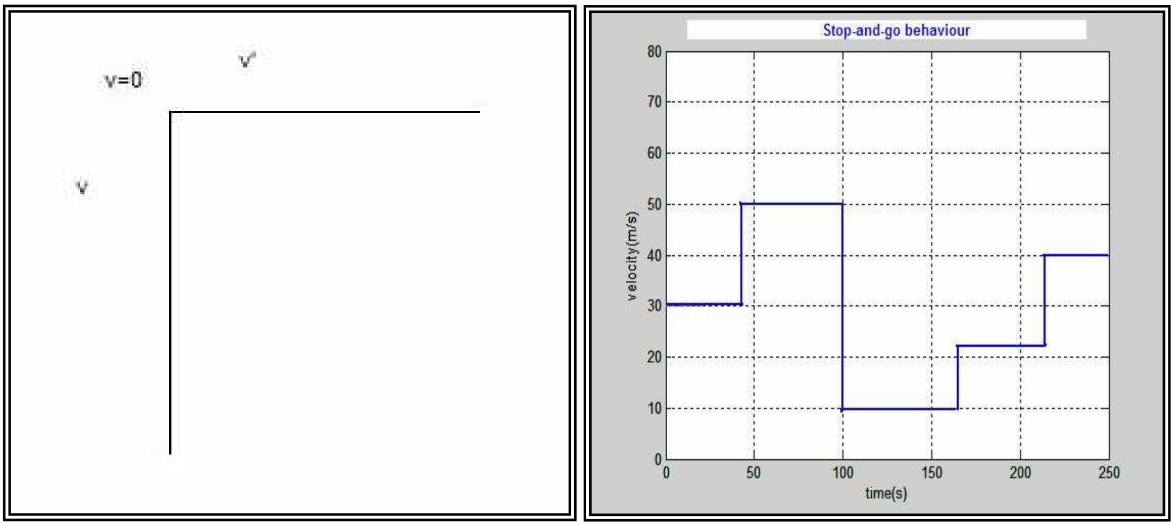


Figure 3. Stop-and-go behaviour

Moreover, we must taken into account that speed and direction change are not independent of each other: a speed change event (a stop event) triggers a direction change event, whilst a direction change event triggers a speed change (slow-down) event too.

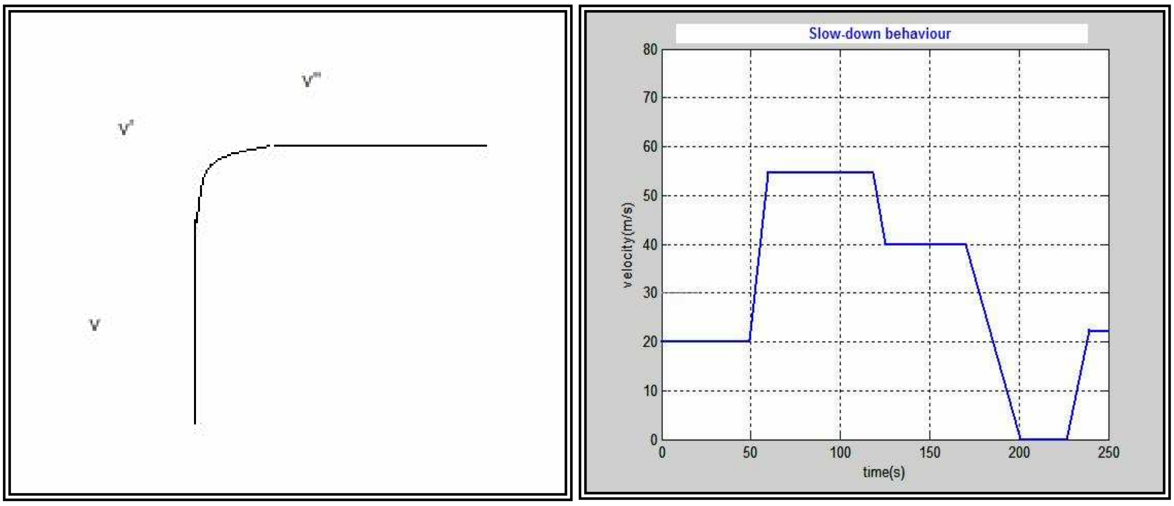


Figure 4. Slow-down behaviour

- Random Direction Model [24]

This model is quite similar to the Random Waypoint Model, but a user, instead of choosing a destination, randomly selects a direction from a given interval and moves in that direction.

After some random time, taken from an exponential distribution, the user either changes direction or changes speed. Users can move freely anywhere in the system area, the values for the user's direction are taken form a uniform distribution on the interval [0,2π [and the values for the speed follow a uniform distribution or a normal distribution [25], for example.

Since the stochastic processes for a direction and speed change are in general not correlated to each other [25], a user is completely described by its current space vector, its current speed and its current direction.

2.4. Teletraffic model

In Chapter II different mobility models have been described from the point of view of the mobility behaviour of the users, in terms of, for example, user speed or direction of the movement. Nevertheless, it has been also mentioned the importance of a *call or teletraffic model*, modelling the possible call cases, where calls are divided into categories as mobile-to-fixed/mobile-to-mobile, business/residential etc. since these properties may have impact on the call arrival rate, call duration etc.

In mobile communication networks mainly two traffic models that differ by their view of the network can describe the teletraffic originating from the service area of the system.

- The traffic source model, which is also often referred to as the mobility model, describes the system as seen by the mobile unit. The traffic scenario is represented as a population of individual traffic sources performing a random walk through the service area and randomly generating demand for resources, i.e. the radio channels. Due to their capability to describe the user behaviour in detail, traffic source models are usually applied for the characterization of the traffic in an individual cell of a mobile network. Using these models, local performance measures like new call blocking probability or handover blocking probability can be derived from the mobility pattern.

- In contrast, the network traffic model of a mobile communication system describes the traffic as observed from the non-moving network elements, e.g. base stations or switches. This model characterizes the spatial and time-dependent distribution of the teletraffic. The traffic intensity is in general measured in call attempts per time unit and space unit. Particularly, this model is of principal interest when determining the location of the main facilities in a mobile network, i.e. the base stations and the switching centres. These components should be located close to the expected traffic in order to increase the system efficiency.

Additionally, these models can be used to calculate the subjective quality-of-service (*QoS)* values for individual users.

In conclusion, apart from the mobility model, a call traffic model is needed. Each call traffic class should be characterized by its probability of occurrence, call arrival rate, mean call duration, and distribution. For this work, a traffic model that generates call arrivals (i.e., calls initiated) for different classes of traffic and models time-varying user behaviour has been chosen.

2.5. Environment

The choice of the scenario is not a random choice; it should represent an example of the set of test scenarios for system simulation of mobile communications systems [28], especially for UMTS, defined by the European Telecommunications Standards Institute (ETSI). Three basic environments are described: an indoor office, an outdoor pedestrian environment and a vehicular environment.

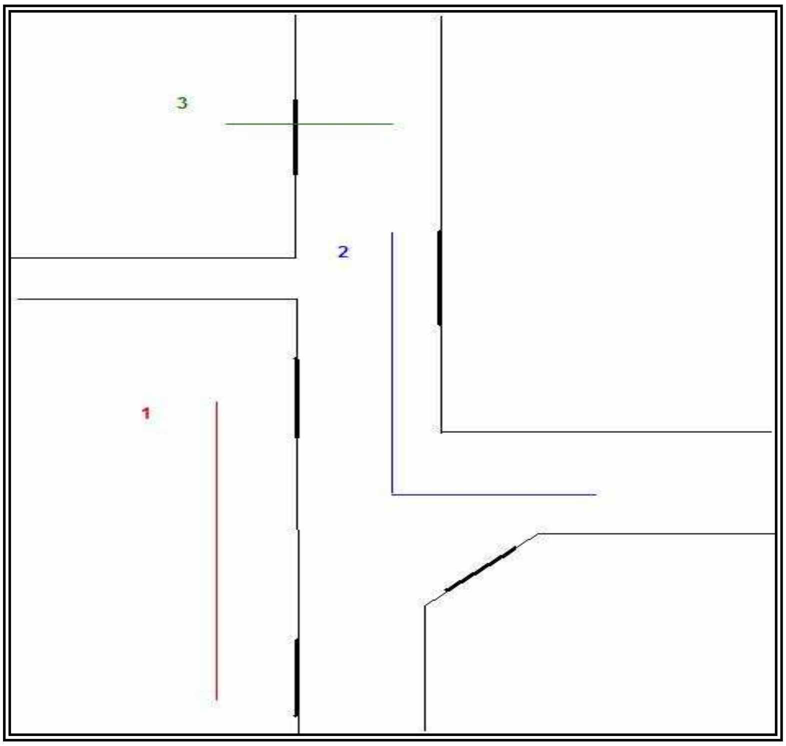


Figure 5 Indoor environment cases: 1) office-office; 2) corridor-corridor; 3) corridor-office.

Indoor environments are characterised by slow speeds (pedestrian or slow vehicular) and relatively well defined mobility paths, determined by architectural topology and activity patterns [35]. Each particular environment may however exhibit its own distinctive features.

Among others, the following environments can be enumerated:

- Home
- Office environments
- Airport and train stations
- Commercial zones
- Theatres / public diversion
- Parking zones

The particular case of office environments is characterised by a topology where office rooms are interconnected by corridors. Users will spend considerable time stationary at a desk and when in motion will move towards a particular destination using a given path. Destinations may be chosen randomly, using a uniform distribution. Two cases could be considered, concerning the nature of movements: In the first one, both source and destination are an office room, while, in the other, either source or destination is a corridor position (Figure 5).

The model for the outdoor pedestrian environment uses a Manhattan-like street structure (rectangular grid, Figure 6). Pedestrians walk along streets in a straight line and can change their direction at crossroads with a given probability. Moreover, after given intervals, pedestrians can modify their velocity.

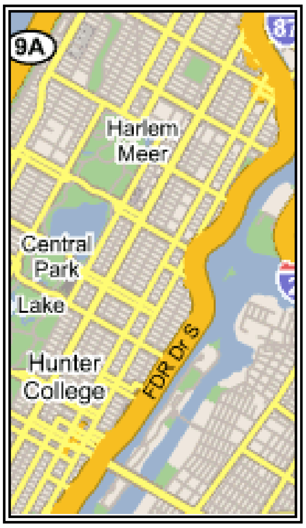


Figure 6 Typical Manhattan grid

The model for the vehicular environment is a random mobility model without a street structure defined. In the basic model cars are considered to move with constant speed (v=120 km/h) and they can change their direction every 20 minutes. The change probability turns around 20%. The model only considers as possible the changes of up to ±45º.

These basic environments can be modified, extended or more exactly detailed, and thus, they can originate a large set of scenarios.

Chapter III

Model description

3.1. Overview

The goal main objective of this work is modelling to model the user’s movement in an easy but accurate way. A simple but very powerful statistical model describing the mobility of vehicle-borne terminals is here presented.

In contrast, the studies presented beforein the previous Chapters, either impose limitations on the degrees of freedom in the direction of motion or assume some of the important parameters, like the velocities of mobiles, probability of turning, etc. as coincidental but without any explication, derivation or proof. For instance, microscopic/mesoscopic models [12, 21, 25] using rectangular or hexagonal radio cell bases do not take the actual road system into account, whilst models which are accurately based on the actual traffic system of a certain area require the collection and processing of extensive data [15]. On the other hand, by considering models in accordance with the randomness degree, most statistical models tend to be dependent on a great number of parameters and large databases [21], which frequently are not well suited for a general representation or are based on parameters that are not directly related to the users’ motion behaviour and street course [18].

Besides, application of the random movement tracing mobility models to a real geographical area is not straightforward. As such, a uniform spatial and temporal distribution of users underlying the call and mobility model is typically assumed for validation of resource allocation and location management procedures. This can lead to misleading conclusions about real networks [27]. This is my motivation for simulating such a real scenario that data from one of the leading Austrian operators have been used to derive the set of the simulation: server map, number of users, mean duration of the call, etc. Moreover, a new simulation tool over real city maps, which in Chapter IV will be presented, has been developed that uses real data (maps and distributions) and the distribution of users will be discussed in this Chapter, Section 3.3. This tool will be presented in Chapter IV. In the latter Section, I also will discuss the spatial distribution of the vehicle-borne users over the investigated area.

In the next section I present a comprehensive approach for mobility and teletraffic modelling in real networks. A primary contribution is the use of transportation studies results to model the subscriber distribution of the users and their behaviour for in a real service area. As regards the mobile user calling behaviour, it is expressed by the incoming/outgoing call arrival rate and the average call duration and it is the other important contribution on users’ mobility modelling which is detailed in this same Chapter III, Subsection 3.2.2.4.

3.2. A basic statistical mobility model

A model thatIn my further analysis I use as a base the model proposed by Bratanov [1] in his PhD thesis. brings together teletraffic theory and vehicular traffic theory is our base model. The mobility model proposed by Bratanov in his PhD thesis [1]is model is a statistical model one since it uses distributions functions of street length between crossroads, average velocity and relative change of the direction at crossroads in order to describe users' movement. However, and contrary to most statistical models, the parameters required for simulation are easily derived by observation and measurement. According to its level of description, the model can be included in the microscopic models group since it describes the movement of every single vehicle by its space and speed coordinates at a given time *t*.

In Chapter II, where a variety of classifications were introduced, the necessity of a distinction among users with different mobility behaviour was shown (pedestrians and vehicle's usersvehicle-borne users). Though this model can represent both type of users, it focus on vehicle-borne terminals in order to better characterize their movements in the system. The presented approach does not distinguish the user flows in the streets of the service area but models the user mobility in dependence of the different traffic paths of each mobile in the system.

3.2.1. Scenario

The model presented in Bratanov's PhD [1] considers a combination of the scenarios defined by the European Telecommunications Standards Institute (ETSI): an outdoor pedestrian environment and a vehicular environment. The required parameters were fitted to a typical European city for vehicle-borne terminals, and thus, vehicular motion is the behaviour mainly described. On the one hand, users drive along streets (in an imaginary street line) and can change their direction at crossroads with certain probability. Moreover, after given intervals users can modify their velocity. On the other hand, they can have a given direction change probabilitychange the direction according to a certain probability function and move without a predefined possible path.

As it has been already mentioned, an important factor parameter for the characterization of the user's' mobility pattern is the environment where it is measured where it moves. A typical European city has been taken as referenceconsidered: Vienna (Figure 7). Some conclusions can be obtained from observation of the city map and realistic traffic conditions:

- The mobile deviation from its current direction rarely exceeds 90°.
- The subscriber seems to follow more or less one certain direction.
- Though the heterogeneous street pattern of an urban setting provides subscribers with a lot of choices, they mostly use major roads. Urban traffic planners encourage this by a number of traffic regulations.

Figure 7. City map: general traffic conditions

3.2.2. Model parameters and estimations

In this section the user's mobility representation technique is described.In this section I describe the user mobility model proposed in the previous section. First of all, the method used to model the mobile user behaviour is presented, and afterwards, the mathematical functions and parameters required for the modelling are described.

Basically, the user's movement will be determined only with a vector positionby the user's current position, a his velocity and a direction of movement that will change every certain time interval. Plamen I. Bratanov [1] presented a model where the a user moves towards a crossroads and once there, he takes a new direction and moves till to the next crossroads with constant velocity. Thus, this model characterizes those factors introducing theby the following parameters – the probability distribution functions of the street lengths, direction changes at crossroads and terminal the velocity.

A mobile call can be initiated or received at any point within the cell. The user's position along the path within the cell can be represented by a vector $\vec{r}_n(x_{n,}y_n)$ as shown in Equation 1, where n is the number of direction changes occurred during the movement since the call was initiated in the cell.

The initial position is denoted as $\vec{r_0}(x_{0,}y_0)$ and the following relations provide the successive locations of the mobile user moving in random directions. In order to simplify the formulation a Cartesian co-ordinate system (x, y) is defined in addition to the polar coordinates (d, φ). Moreover, I assume that any point within the cell (Figure 8i) t iscan be considered as starting point for a new calls any point within the cell (Figure 8).

$$
\begin{aligned}
&\vec{r_1}(x_{1,}y_1) = \vec{r_0}(x_{0,}y_0) + \vec{d_0}(d_0, \varphi_0)\\
&\vec{r_2}(x_{2,}y_2) = \vec{r_1}(x_{1,}y_1) + \vec{d_1}(d_1, \varphi_1)\\
&\dots\\
&\vec{r_n}(x_{n,}y_n) = \overrightarrow{r_{n-1}}(x_{n-1,}y_{n-1}) + \overrightarrow{d_{n-1}}(d_{n-1}, \varphi_{n-1})
\end{aligned}
$$

Equation 1

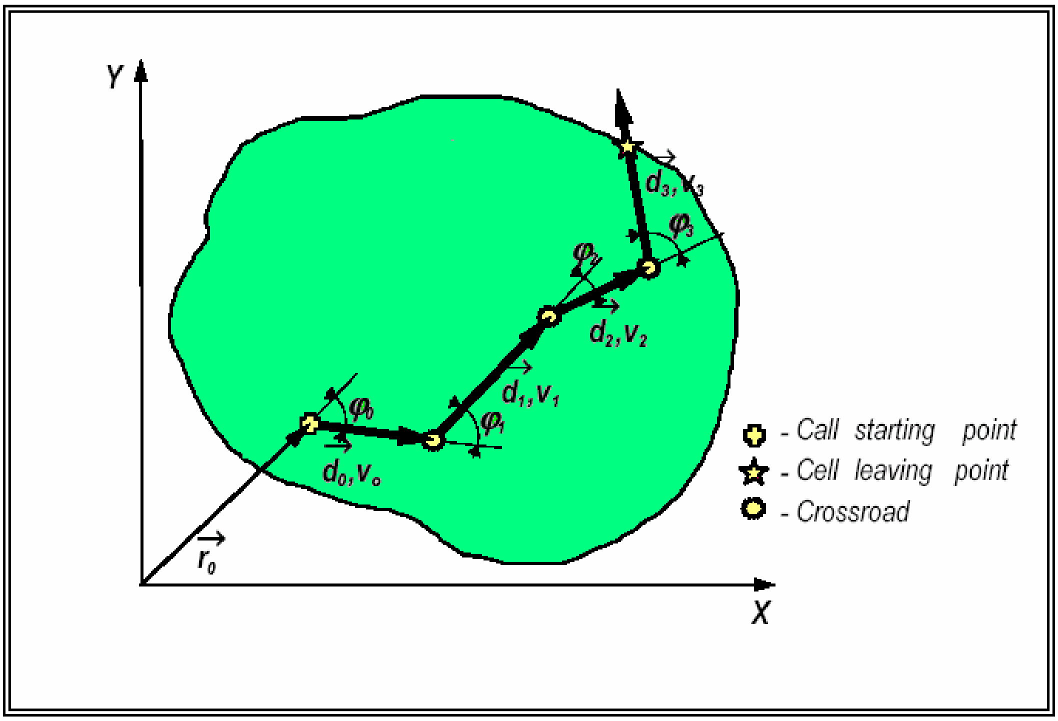


Figure 8. Tracing mobile figures

A suitable selection of input parameters allows modification of this to fit any particular required pattern.

3.2.2.1. Relative direction changes at each crossroads

Since the destination point of the mobiles can be any place in the coverage area, mobile users are allowed to move away from the starting point in any direction with equal probability. Depending on the structure of the cellular coverage area, a subscriber unit may move toward the destination point via different paths. However, in any case, the mobile direction should be biased towards the direction of its destination; the destination point should have influence on the mobile direction change. The amount of deviation of a mobile user from its current direction at successive intervals is referred to relative angle changes after each crossroads.

The probability distribution of the mobile direction change at crossroads is normally distributed according to [18]. Moreover, it was proved in [28] that in cells with handover calls the probability density function of direction for a boundary crossing mobile tends to the normal.

The changes in direction occur in time steps that are street-length and speed dependent but they don't depend on the last direction change. Plamen I. Bratanov explained in his work that the motivation for this choice is based on the fact that the time of the last change in direction hardly provides any information about the time of next change in direction (rapidly changes of mobile velocity after each crossroads are very unlikely).

However, let's consider the possibility the driver might realize suddenly a change of direction and/or velocity, for example, he might be looking for a parking place or a close-by address requiring multiple successive direction and/or velocity changes. Thus, these cases are taking into accountconsidered by introducing a continuous distribution for of the direction change with different probability parameters weights for each main direction change considered.

The model described in this Chapter considers the relative direction changes at each crossroads, φ_i , taking into account the fact that the changes in of the direction are street-length and speed dependent, as it has been already denoted. Therefore, the probability density function of φ_i (Equation 2) is built up from four random normally distributed variables weighted with certain change probabilities. These probabilities depend on traffic regulations and driver behaviour (e.g. drives tend to use major roads or they are more likely to turn right than left). Only the highestThe following four weights are considered - (-90º, 0º, 90º, and 180º.

The initial direction of a mobile is assumed to be uniformly distributed in the range of [-π, π) with respect to the current direction. Hence, the corresponding probability function is written as) have been considered in order to simplify the calculation:

$$p.d.f(\varphi_i) = p_{0^\circ}\frac{1}{\sigma_\varphi\sqrt{2\pi}}e^{-\frac{\varphi_i^2}{2\sigma_\varphi^2}} + p_{90^\circ}\frac{1}{\sigma_\varphi\sqrt{2\pi}}e^{-\frac{\left(\varphi_i-\frac{\pi}{2}\right)^2}{2\sigma_\varphi^2}} +$$

$$p_{-90^\circ}\frac{1}{\sigma_\varphi\sqrt{2\pi}}e^{-\frac{\left(\varphi_i+\frac{\pi}{2}\right)^2}{2\sigma_\varphi^2}} + p_{180^\circ}\frac{1}{\sigma_\varphi\sqrt{2\pi}}e^{-\frac{(\varphi_i-\pi)^2}{2\sigma_\varphi^2}}$$

Equation 2

where:

$p_{0^\circ}, p_{90^\circ}, p_{-90^\circ}, p_{180^\circ}$ are the direction change probabilities (and thus, they sum $p_{0^\circ} + p_{90^\circ} + p_{-90^\circ} + p_{180^\circ} = 1$).

σ_φ is the standard deviation of all four sub-distributionsdirection distributions, . It is assumed to be equal for all four distributions. This value depends on the road network pattern (the highest higher the irregularity of the street network, the highest higher the deviation value).

The required parameters required can be easilywere derived from observation and different measurements, and so, according to [1] for acarried out in European city as Vienna, Austria. theThe obtained values obtained weare: $p_{0^\circ} = 0.785$, $p_{90^\circ} = 0.085$, $p_{-90^\circ} = 0.125$, $p_{180^\circ} = 0.005$, and $\sigma_\varphi = 0.125\pi$ (parameters values for Figure 9).

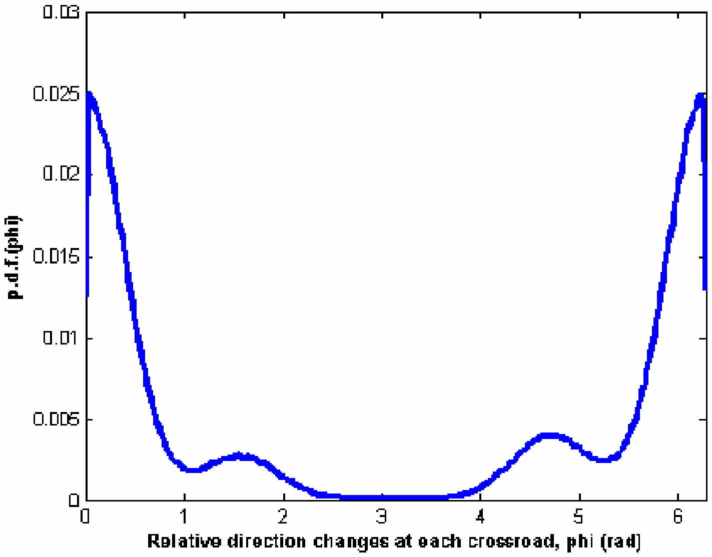


Figure 9. Probability density function of relative direction changes at crossroads

Two main conclusions can be derived from Figure 9. It proves that , the most probable direction taken by a user is going straight on ($\varphi_i = 0º$), in next step the user mostly continues the direction of last step movement. Moreover, the probability of turning right is higher than the probability of turning left due to the majority of the driving public obey the rules of the road and, as such, any hypothesized vehicle trajectory that appears to transgress a road rule is less likely to be the correct one. In order to prevent traffic jumps and crashes traffic trajectories are designed: Intersections are constructed such that all traffic is forced to turn a certain direction and U-turns or vehicle movements that invade the street usually are not allowed. Therefore, the lowest probability is coming back by the same way the user arrived at the crossroads: the lowest probability corresponds to make a U-turn, even though this is possible.

3.2.2.2. Street length between crossroads

Each user moves towards a crossroads and once there, he takes a new direction φ_i (an angle from the distribution above presented and respect to the actual direction) and moves till to next crossroads with constant velocity v_i.

$$p.d.f.(d_i) = \frac{d_i}{\sigma_d^2} e^{-\frac{d_i^2}{2\sigma_d^2}} \qquad for \quad d_i > 0$$

$$where \quad \sigma_d = \bar{d}\sqrt{\frac{2}{\pi}}$$

Equation 3

The covered distance covered may alsocan be also described by a random variable, the street length between crossroads, d_i, and for the easy of the representation, the projections in Cartesian axes are considered. Studies of the street patterns of severalin European cities showed that the projections $d_{x,i}$, $d_{y,i}$ of the street length between crossroads can be regarded as normally distributed random variables (Equation 3) in cities or areas with irregular street pattern whereas in more heterogeneous street pattern the probability density of d_i can be approximated by a Rice distribution (Equation 4), because urban traffic is regulated to guide drivers mostly by major roads.

$$p.d.f.(d_i) = \frac{d_i}{\sigma_d^2} e^{-\frac{d_i^2+\bar{d}^2}{2\sigma_d^2}} I_0\left(\frac{d_i\bar{d}}{\sigma_d^2}\right) \qquad for \quad d_i > 0$$

$$where \begin{cases} I_0(x) = \frac{1}{\pi}\int_0^{\pi} e^{x\cos\theta} d\theta \\ 0.75\bar{d}\sqrt{\frac{2}{\pi}} < \sigma_d < 1.5\bar{d}\sqrt{\frac{2}{\pi}} \end{cases}$$

Equation 4

In Equation 3, $\overline{d}$ represents the main mean street length within a regularly structured city (e.g. Manhattan grid type) and σ_d^2 the variance of the length of minor roads between two consecutive crossroads. However, in Equation 4 $\overline{d}$ is the average length of major roads between two crossroads, but σ_d^2 is, as in Equation 3, the variance of the length of minor roads between two consecutive crossroads, and I_0 is the modified Bessel function of first kind and order zero. The representation of this probability density function is shown in Figure 10 according to the parameters determined by analyzing the Vienna city map and by observing local traffic. The mean street length $\overline{d}$ may differ somewhat within the different parts of the city. Calculations for Vienna, Austria, shown that $\overline{d}$ = 80-110m in the city centre whereas it amounts to $\overline{d}$ = 110-170m in the outskirts.

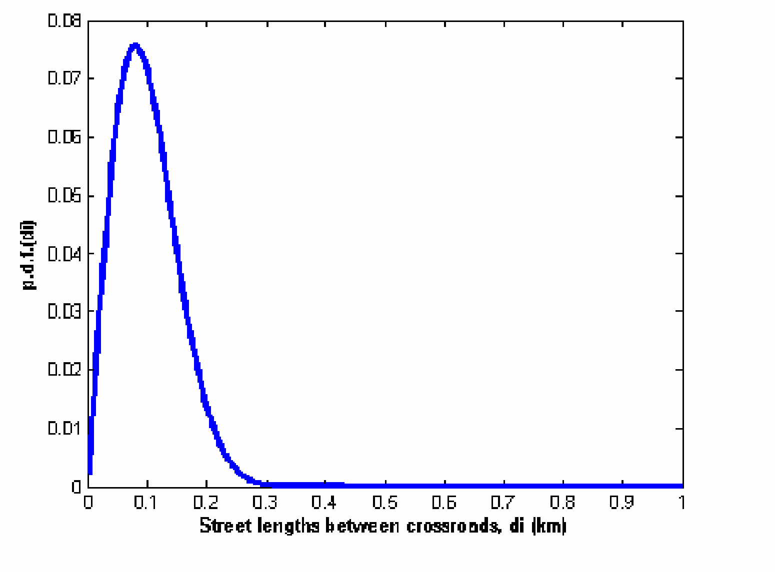


Figure 10. Distribution function of distance between crossroads

3.2.2.3. Average velocity

The speed of mobile unitsvelocity of the vehicle-borne users is chosen to be a realization of a random variable Rayleigh/Rice distributed, as have been proposed in Equation 5, in analogy with the calculation of street length statistic shown in last section. This variable, v_i, is the average velocity between crossroads.:

$$p.d.f.(v_i) = (1 - p_{mr}) \frac{v_i}{\sigma_v^2} e^{-\frac{v_i^2 + \overline{v}^2}{2\sigma_d^2}} I_0\left(\frac{v_i \overline{v}}{\sigma_v^2}\right) +$$

$$+ \quad p_{mr} \frac{1}{\sigma_v \sqrt{2\pi}} e^{-\frac{\left(v_i^2 - \overline{v_{mr}}\right)^2}{2\sigma_d^2}} \qquad for \quad v_i > 0$$

Equation 5

where,
p_{mr} is the fraction of the vehicles on a major road.
$\bar{v}$ is the mean velocity in the city area,
$\bar{v}_{mr}$ is the mean velocity on major roads within the city area,
σ_v is the velocity deviation.

As it has been already mentioned before, the traffic is bundled on major roads where the average speed might be higher than in the urban streets. This effect is modelled by adding the second term in Equation 5. The user is supposed to move with constant speed till the next crossroads and a new velocity, v_i , is chosen at each crossroads according to this distribution function (Figure 11). The chose of such a modelling way, that combines a Rayleigh with a Rice distribution, seems reasonable since the more extreme the speed value, the less likelihood of its occurrence. The above consideration is illustrated in Fiigure 11. In this case the validity of the parameter were proven by a chi-square goodness-of-fit test in [Bratanov's PhD]. The values of the parameters for the city centre of Vienna are:

P_{mr} = 0.56 $\bar{v}$ = 10 km/h $\bar{v}_{mr}$ = 40 km/h σ_v = 10 km/h

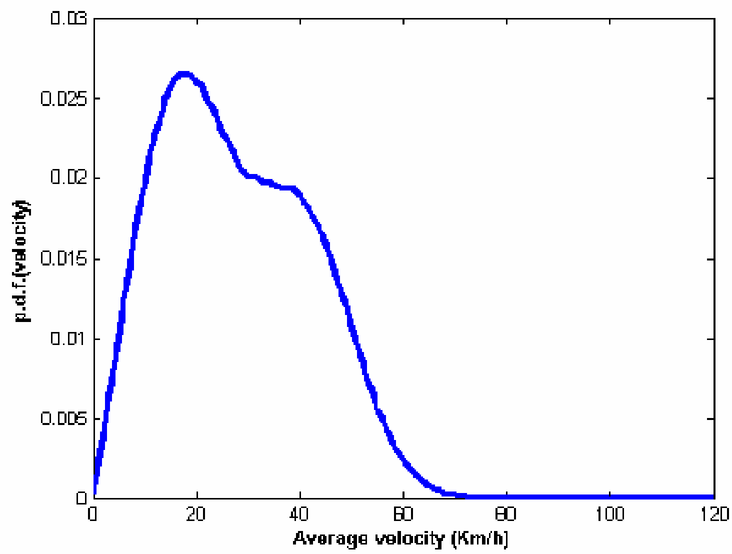


Figure 11. Probability distribution function of average velocity between crossroads

The average velocity is the most critical parameter for this model and, in fact, it will be discussed in detail in next sections. In this model, the velocity is averaged over the *stop-times* at crossroads or traffic lights, which are common for urban and suburban areas. Thus, the velocity v_i can be also taken as zero when the user arrives at a crossroads, as well as another velocity value. So, if the v_i is supposed to change when the user arrives at the next crossroads, it will never modify its velocity since it will never reach the crossroads because it really doesn't move (v_i = 0 km/h). A stop-and–go behaviour is included in next Chapter for extending this model.

This completes the presentation of the method used as basis to represent the mobility behaviour.This model proved to be a very good trade-off between robustness and complexity [31].

3.2.2.4. Teletraffic model

In first Chapter, the importance of the call traffic model was underlined. As mentioned, teletraffic models can be used to calculate the subjective quality-of-service (*QoS)* values for individual users. It is possible to define different call traffic classes for the same mobility model. Each call traffic class should be characterized by its probability of occurrence, call arrival rate, mean call duration, and distribution.

For this work, a traffic model that generates call arrivals uniformly distributed has been chosen. The mean call duration is 90 seconds and the call duration for a user is determined from an exponential distribution.

3.3. An enhanced mobility model

The average velocity has been denoted as the most critical parameter for the model proposed in Bratanov's PhD thesis [1]. Not only it is difficult to model the velocity distribution but also its parameters are the most complicated to estimate in comparison with the other two distributions. A sum of circumstances determines the speed of a vehicle within the city, which makes it very difficult to estimate and model. Estimation for of the average velocity is obtained in the previous model proposed in [1], which was described and it has been shown in Ssection 3.2, but. tThere is another important characteristic of the mobile user's movement pattern it that should be considered, especially for in urban and suburban areas: the stop-and-go behaviour of the vehicle-borne terminals. The average velocity value is deeply influenced (decreased) by considering for its calculation the time the user is stopped at a crossroads.

Here a another approach is presented which considers two possible states of the users: moving and non-moving. It is a typical modelling for the traffic. This new approach can better describe the users' behaviour in urban and suburban areas. In this model, Tthe vehicle is either moving or is in a stopped state (may bee.g. because it is waiting for the green ligth of the traffic lights, it is looking at the next streets at the crossroads or it is waiting for a pedestrian that crosses the street). Therefore, regards to the allowed movement for a vehicle, we can distinguish three types of crossroads (Figure 12): those with traffic ligths, those without traffic lights nor traffic signalling and finally, those that difference streets with lower priority (last case may include or not traffic signalling).

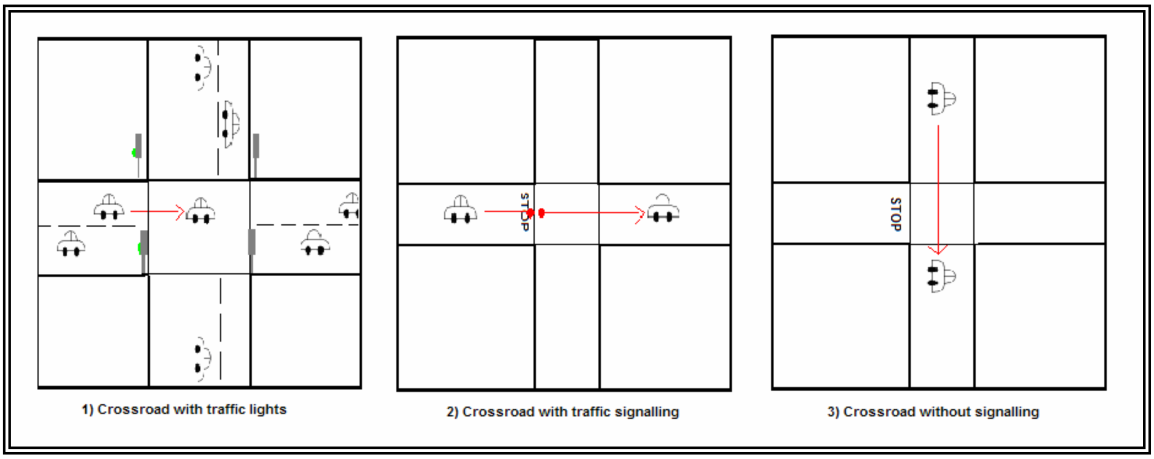


Figure 12. Different types of crossroads

We will study the movement of the vehicle-borne users through these crossroads. The improvement of our model consists on the inclusion of a *stopped state*. It allows to model in a better way the user's movement. , what The latter is very important especially in the case of the soft/softer handover case, as it will be further discussed.

3.3.1. Relevance of modelling the stop-and-go behaviour

The motivation for modelling the car stop at a crossroads lies in the propagation phenomena at crossroads and the effect of these phenomena on the soft/softer handover.

There are two major mechanisms for the wave propagation in urban and suburban areas: diffraction over the rooftops and street-guided propagations along the street-canyons. The last one is of special interest for this work because according to [29] the street guided propagation dominates in urban areas. Whereas the signal components coming over the rooftops are weak and contribute with 3-13% of the total received power to the signal strength, the street-canon effect generates about 78-93% from the total received power. Moreover, it was proved that at crossroads there are a large number of paths with comparable strength. Besides, in [30] authors show that the last two phenomena lead to severe interferences between cells at crossroads.

These considerations allow us to conclude that in areas close to crossroads the probability for hard or soft/softer handover is very high, and thus, crossroads play an important role for the cellular network planning and optimizing in urban and suburban areas. Fig. 13 illustrates an example of soft/softer handover area at a crossroads.

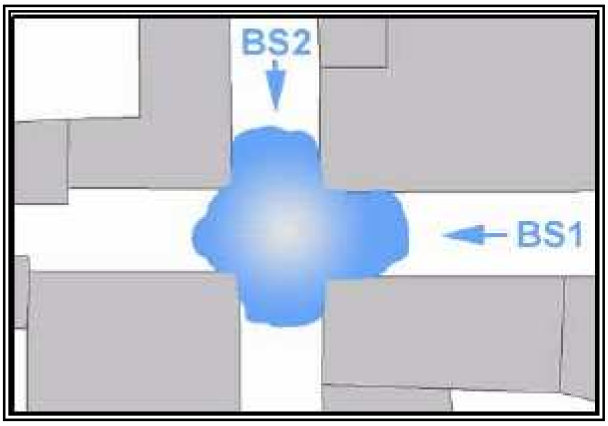


Figure 13. Handover area at a crossroads

Crossroads require special attention in UMTS due to the soft-handover. On the one hand, UMTS applications are characterized by high data rate requirements (e.g. Table 1 in [35] shows applications with data rates up to 2 Mb/s in both directions). On the other hand, when the user is inside the overlapping cell coverage area, communications between mobile station and base station take place currently via two air interface channels from each base station separately (Figure 13). Thus, double load and resources are required.

The importance of crossroads for the network performance evaluation requires a detailed study of the user movement at a crossroads. The original model presented does not pay special attention to this situation, in which severe conditions for the wave propagation creates high interference and very high probability for handover [30]. In this base model, a user covers certain distance with constant velocity and when the mobile user passes through the crossroads, a new velocity is chosen from the relevant distribution. Thus, the movement is continuous with stepwise change of the velocity, but it does not consider the stop-times. So, the velocity is averaged over the *stop-time*.

Here another approach is presented which considers two possible states of the users: moving and non-moving. The vehicle is either moving or is stopped (may be it is waiting for the traffic lights, it is looking at the next streets at the crossroads or waiting for a pedestrian crossing the street).. In order to consider the vehicle movement near the crossroads, an additional parameter is included: the *stop-time*, the time the user is not moving. This parameter models the probability that a car stops at crossroads or/and traffic lights during its drive. With this improvement, it is considered that vehicles stay for many tens of seconds in a soft/softer handover area at a crossroads, instead of driving through this area in just a few seconds. If we imagine that there are several vehicle-borne terminals at a crossroads waiting for the green phase of the traffic lights, all of them in soft/softer handover mode, then we can appreciate estimate the impact that such a scenario can have on the network performance.

3.3.2. Improvement: Stop time distribution

As well as we have considered the distribution function of street length between crossroads, average velocity and relative direction change regards to [1], we looked for a distribution function of stop-time in urban and suburban areas. It is also assumed that users change neither its velocity nor its direction between two crossroads. However, until now the average velocity was calculated including not only the time the user was moving but also the time the user was stopped (the *stop-time*) [1]. We wanted to separate these effects and we tried to find an accurate distribution function of the *stop-time*. Moreover, the parameters were also fitted for a typical European city: - Vienna, Austria.

In order to obtain the distribution of the stop-time we had to take into account two types of crossroads, those with traffic lights and those without traffic lights.

3.3.2.1. Measurements

During a measurement campaign in Vienna, Austria, we measured the green and the red phases at several traffic lights in the 4th district of that city (a typical city centre). In order to average over all possible cases we did the measurements at different types of crossroads (black points on Figure 14) and on several different days. We measured in on several major and minor roads but also we measured in low-priority and high-priority streets, in order to represent a real scenario.

In order to generate a representative measurementRegards to the moment of measurement, w, we measured during the week, at the weekend and during vacancy periods. Moreover, we considered three times a day and we measured in the morning, at noon and in the evening. The values obtained are showed in Appendix A.

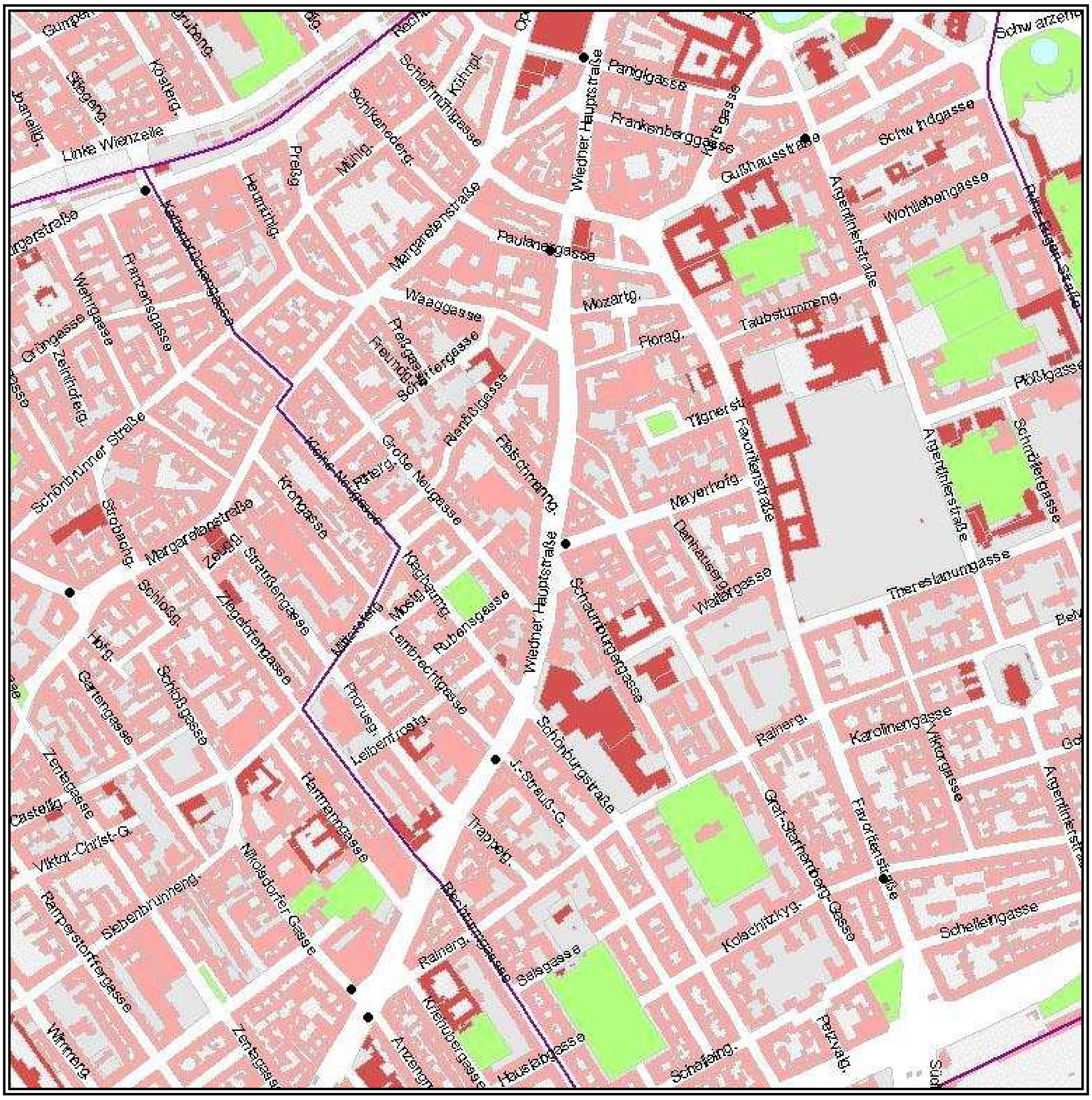


Figure 14. Measurement points

3.3.2.2. Crossroads with traffic lights effect

Figure 15 shows the measurement results in crossroads for urban and suburban areas in Vienna. After trying to fit many different distributions, Wwe found out that the empirical values obtained, the blue stars in the plot, can be well approximated with a normal distribution, red stars in the figure.

The approximation is even better if we take into account the assumption from base model: the users mostly drive on major roads.

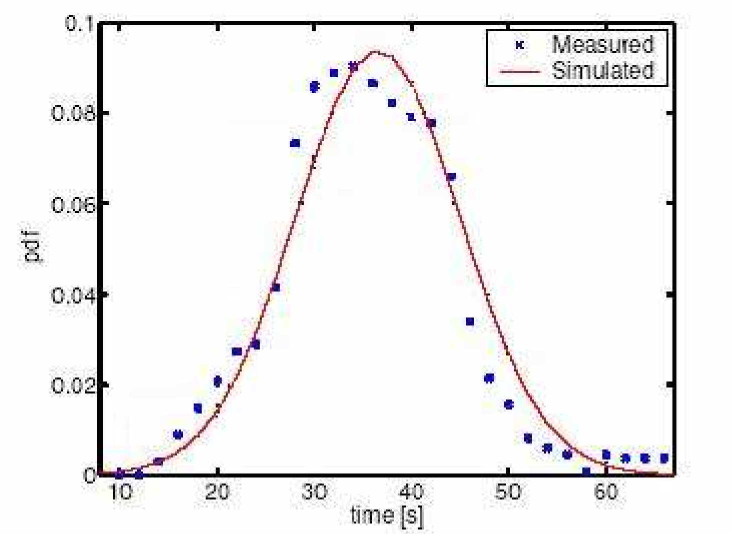


Figure 15. Probability density function of stop time at crossroads with traffic lights

This distribution has been obtained by comparison. In Figure 16, different weighted distributions are presented to fit the distribution obtained from measurements (in blue stars).

We can appreciate as the normal distribution is the best fitted.

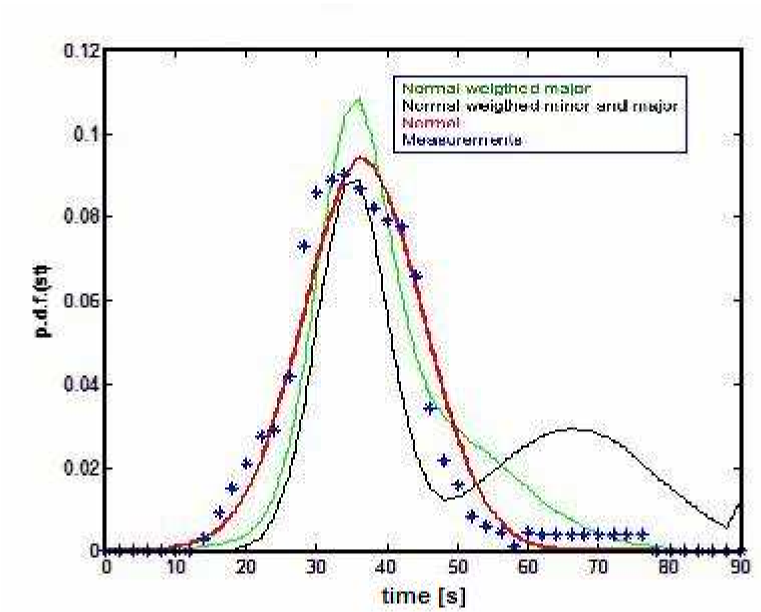


Figure 16 Different functions for the stop time disribution

3.3.2.3. Inclusion of crossroads without traffic lights effect

Besides the study of crossroads with traffic lights we also investigated the case that there are crossroads without traffic lights where users may also stop. We have found out that the probability that a crossroads is regulated with traffic lights is about 40-50% in urban areas (measured in Vienna). Moreover, we considered the probability that a vehicle stops at a crossroads without traffic lights. In these crossroads the user stops to look at both sides and make sure anyone is coming towards the crossroads, or maybe the vehicle must wait for a pedestrian who crosses the street. This probability is modelled as one-sided normal distributed with deviation σ_{wtl}.

This kind of stop lasts a few seconds; generally it takes less time than a stop at a crossroads with traffic lights. Otherwise, the user finds more frequently a crossroads without traffic lights than a crossroads with traffic lights in a rural or a suburban area.

Figure 17 illustrates the probability that a vehicle stops at crossroads, by joining both probability density functions (p.d.f.): the p.d.f. of the stop-time at crossroads with traffic lights and the p.d.f. of the stop-time at crossroads without traffic lights. Since these distributions are not equally probable, each one has a weight in such a way that the resulting expression is Equation 6.

$$f(s_i) = p_{tl} \frac{1}{\sqrt{2\pi}\sigma_{tl}} e^{-\frac{(s_i-\mu_{tl})^2}{2\sigma_{tl}^2}} + (1-p_{tl}) \frac{1}{\sqrt{2\pi}\sigma_{wtl}} e^{-\frac{s_i^2}{2\sigma_{wtl}^2}} \qquad for \quad s_i > 0$$

Equation 6

where,

p_{tl} is the probability that there are no traffic lights at crossroads,

μ_{tl} is the mean stop-time at a crossroads with traffic lights,

σ_{tl} is the deviation of the stop-time at a crossroads with traffic lights,

σ_{wtl} is the deviation of the stop-time at a crossroads without traffic lights.

Finally, I calculated this the probability density function with according to the measurements in the city centre of Vienna (Figure 17). It was modelled with the values presented in table Table 1.

σ_{wtl}	p_{tl}	μ_{tl}	σ_{tl}
5	0.5	36.5	8.5

Table 1. Stop time distribution parameters

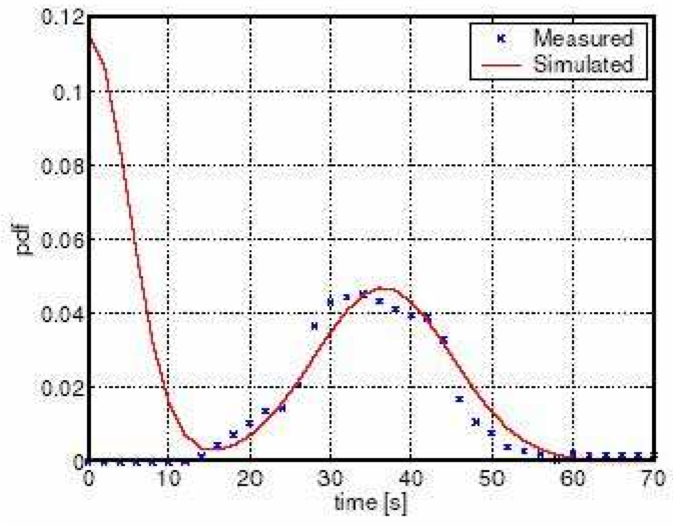


Figure 17 Probability density function of stop time at a crossroads

Thus, in our model when the user arrives at the crossroads the velocity, the direction and the distance to cover change but also we consider the possibility of a stop at the crossroads. The time the stop lasts is a random variable choice from the above distribution (as well as we did with the other parameters)modelled after proposed model. After having waiteding the indicated time, the user continues its movement with the values obtained from the other distributions (for the velocity, the direction and the distance between crossroads).

3.3.3. Vehicle traffic measurements

Apart from the stop-time we measured the number of cars that passed under the traffic lightsI have also measured the traffic flow at certain streets' cross sections. As wellIn the same manner as I as we did with the stop-time measurements, we chose different types of crossroads, different days and we measured three times a day: in the morning, at noon and in the evening. The same map already shown in Figure 14 indicates the points where the measurements were placed. Numeric results are also shown in Appendix A. The results are illustrated in Figure 18. In blue spots measurements are plotted and the distribution we used to fit them is drawn in red.

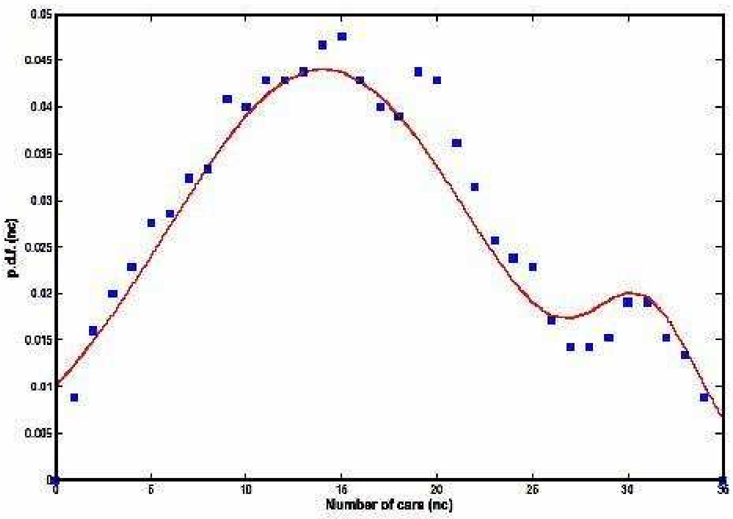


Figure 18 Probability density function of the number of cars at a crossroads

On the one hand, it can beI would like also to discussed the choice of the initial distribution of the users. The first step for the simulation is the initialization of the users in the area. We can use different distributions. The easiest possible distribution is the uniform distribution but it is not the best one for allevery situations. By modelling about the car density in the urban area we obtained a more accurate, more realistic distribution function of users who move in a vehicle (the focus of our work). However, we want to underline that the simplest mode simple the distribution function (e.g. uniform distribution), the easierest the simulation. Thus, the choice depends on the goal of the simulation.

On the other hand, most authors use a uniform distribution for the location of new users in the simulations according to their proposal mobility models. Nevertheless, C. Betsstetter [19] proved that it is not always the best choice. According to [19], if we use a uniform distribution for random placement of users, we obtain a higher user density in the middle of the area and a lower density at the area edges. The main problem is the process followed. At the beginning of a simulation, we place a given number of users on the system area using a uniform distribution in both dimensions. Most studies that use a random mobility model do so. Moreover, users are allowed to leave the area. In literature three basic principles define what to do with the leaving user (Figure 19):

1. The leaving user is bounced back to the system area, according to a certain rule.

2. The leaving user is "deleted", and a new user is initialized according to the node initialization distribution, or

3. The leaving user is wrapped around to the other side of the simulation plane.

The most common rule used for *user border behaviour*: we delete the user that leaves the area and generate a new user. Thus, the so-called *border effect* appears. The resulting spatial distribution for random placement of leaving users has a higher density in the middle of the area and a lower density at the area edges. This *border effect* is detailed in [19]. It can create generate a non-uniform users distribution and this can lead to unwanted effects in studies of networking algorithms. These problems do not occur if we use a wrap-around border behaviour or the boundary strategy, which generate a uniform user distribution.

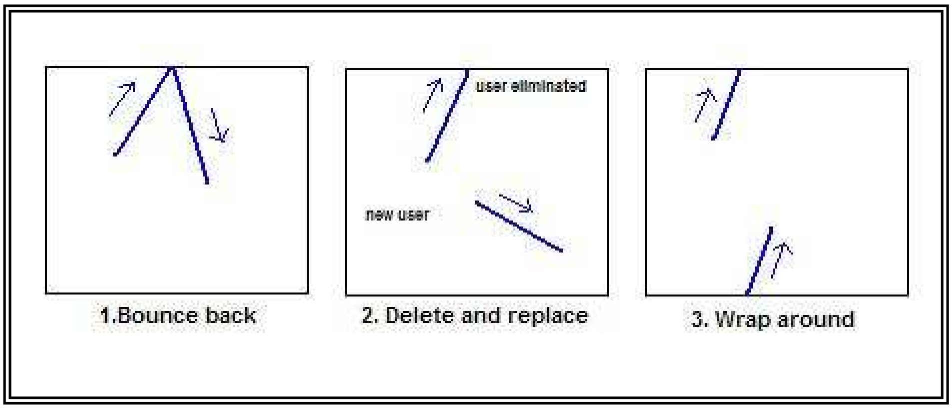


Figure 19. Border strategies

Chapter IV

Simulation

In order to model various scenarios of user mobility and teletraffic I propose here a procedure using the previous teletraffic and mobility model (Chapter III).

Computer simulations aim to obtain statistical estimates of the mobile boundary crossings and other related parameters in an environment where the mobiles are allowed to move and stop freely with randomly varying velocities and directions within realistic environments.

At first the simulation framework is defined. The objective of the simulation is to generate sufficient data to examine different parameters as the boundary crossing probabilities or the dwell time, as a function of cell size and shape, mobile user behaviour and geographical environment. I also have to define relevant network performance parameters to be able to compare the design alternatives.

According to previous studies, the simulation must incorporate a sufficiently large mobile population or otherwise, sufficiently long simulation time. This will minimize the influence of initial conditions and the variation of the stochastic processes. In this simulation, a mobile population of 10,000 mobile users drives the statistics of the boundary crossing phenomena to reach the steady state condition. Initially, a uniform distribution is assumed for spatial location of the users [18]. This assumption is valid, since in a cellular network the relative orientation of streets in cells varies randomly, giving on the average an approximately uniform distribution of possible directions. However, as it has been already discussed, other distributions may result more accurate (though also more complex) and a suitable selection of input parameters allows modification of this to fit any particular required pattern. Since the destination point of the mobiles can be any place in the coverage area, mobile users are allowed to move away from the starting point in any direction with probability given by the distribution of the relative direction changes (Equation 2). And its velocity will be determined randomly from Equation 3.

4.1. Simulation tool

In order to apply the model to a real scenario I used a simulation tool implemented in Matlab by Plamen Dintchev[1]. Basically, the tool allows drawing cells over a real city map. The sizes and shapes can be different for each cell, that is, it is possible to draw coverage cells with arbitrary shapes and variety of sizes. Moreover the accuracy of the representation is determined by the minimum resolution that can be also arbitrary selected. In Figure 20 the simulation tool is illustrated, which allows introducing any grid value (the smashed lines) for the cells representation. The smallest coverage area in a cell is the square limited by the smashed lines.

On the other hand it is also possible to select a part of the map, in order to represent with more detail the cells, and so, different scale and zoom can be applied to the area map shown on the right corner (View Window).

[1] Plamen Dintchev,
Technische Universität Wien, Gusshausstrasse 25/389, 1040 Vienna, Austria
Email: plamen.dintchev@nt.tuwien.ac.at,

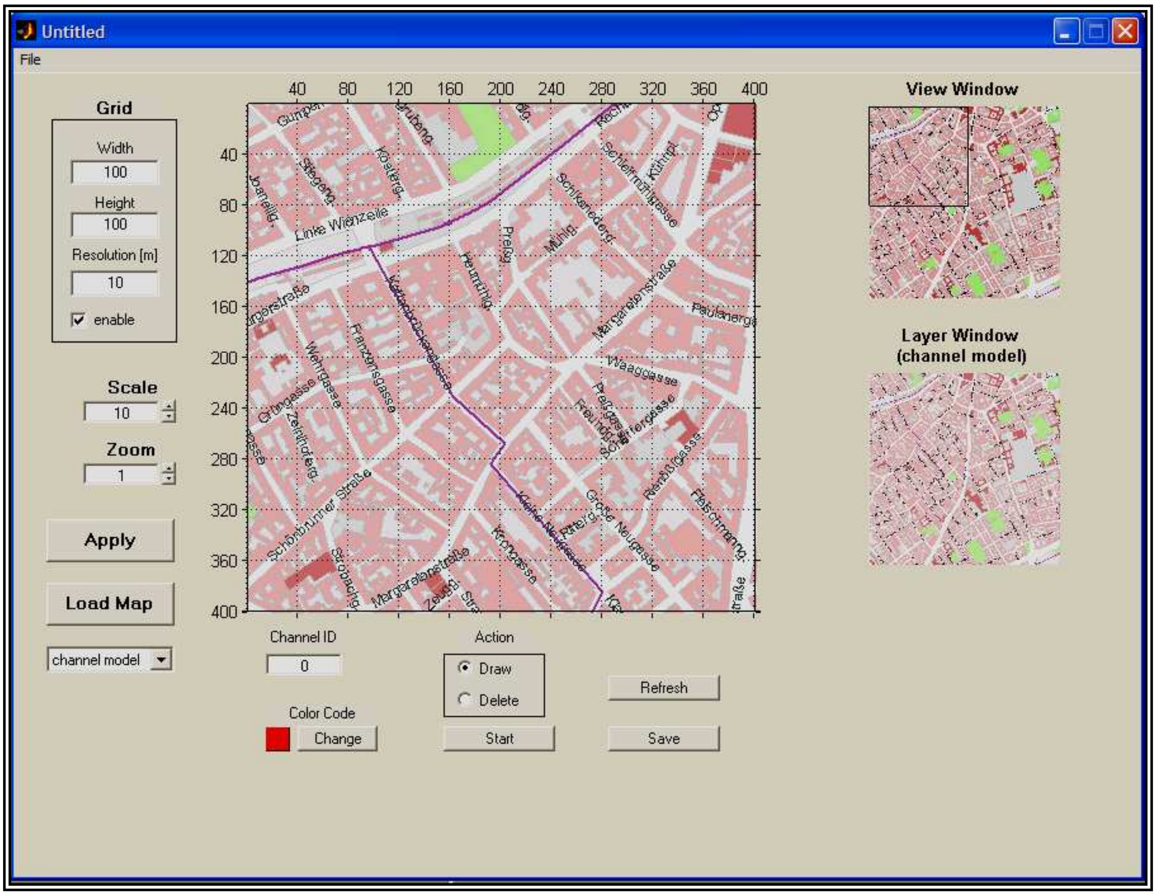


Figure 20. Simulation tool

Another important characteristic of this tool is the possibility of applying different layers to the simulation. The simulation tool was implemented in such a way that, for example, it is possible to map a best server map[2] to a geographical map, and then separate this area into several different subareas (urban, suburban, rural, etc). Thus, it is possible to apply the model with different parameters according to the street patterns for each area, or even define the most suitable mobility model for each region according to the street pattern in the same geographical area instead of using the same set of parameters for the whole area or the same model for different regions.

The concept of *hierarchical* or *multilayer* cellular systems appears to be a logical extension of the cellular system. Figure 21 presents an example of these layer cellular systems. Hot spots are covered by microcells (in blue) while the macrocells provide a continuous coverage of the service area (in red).

In very dense areas a continuous coverage with both microcells and macrocells may be achieved and also the inclusion of hot spots (in black) may be necessary.

[2] NB : The best server map presented here does not exactly correspond to the operator's best server map, nor the exact geographical position - only the approximate cell sizes and shapes are considered.

Figure 21. Scenario divided by layers: macrocells, microcells and picocells

The mobility and teletraffic aspects of wireless networks commonly require different architectures and strategies to offer this continuous coverage of the service area.

Propagation conditions in microcells are highly dependent on the environment: width of the street, moving obstacles, and so on. Users may experience a dramatic decrease of the signal strength when they turn a street corner. Such rapid variations of the received level may cause communication interruptions for high-speed terminals because the network does not have enough time to hand over the communication when the terminal leaves a cell. Furthermore, such high-speed terminals may generate a lot of handover and hence cause a signalling increase in the network [1].

Once the frequencies are allocated on micro and macro layers, terminals may be served by two cells in large areas. The question that rises is to known which policy provides the best efficiency. The admission strategies must be optimized in areas where both layers are deployed.

In general, macrocells must accommodate high-speed terminals while microcells are more adapted for low-speed terminals. In order to maximize the system efficiency, all low-mobility users have to use preferably the lowest layer (i.e., micro cell). Upper layers are used for high-mobility terminals and act as overflow recipients for low layers.

When a user sets up a call, the system does not generally know its speeds. It is always possible to direct the call toward the correct layer. The system may set up all calls on the micro cell layer. Strategies to sort terminals based on the dwell time of mobiles in cell before the handover are proposed [38, 39]. According to its speed the system will situate the user on the adequate layer cell. Though this is not the goal of my work, I propose as possible direction for future work, the employment of this simulation tool with the proposal model in order to compare the results for the handover rate and the cell dwell time between layers with other models and with real values. Figure 22 illustrates an example of scenario with different mobility layers which the tool can simulate. On right side appears the representation by layers for the whole map (Layer Window).

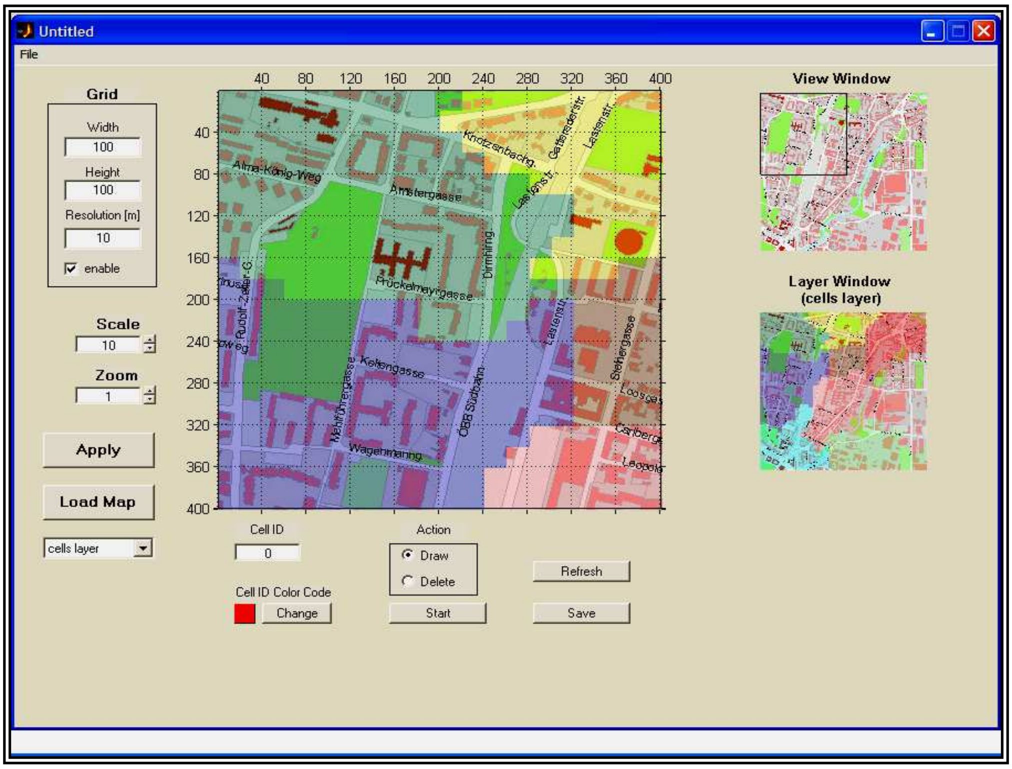


Figure 22. Simulation tool: Scenario divided by layers

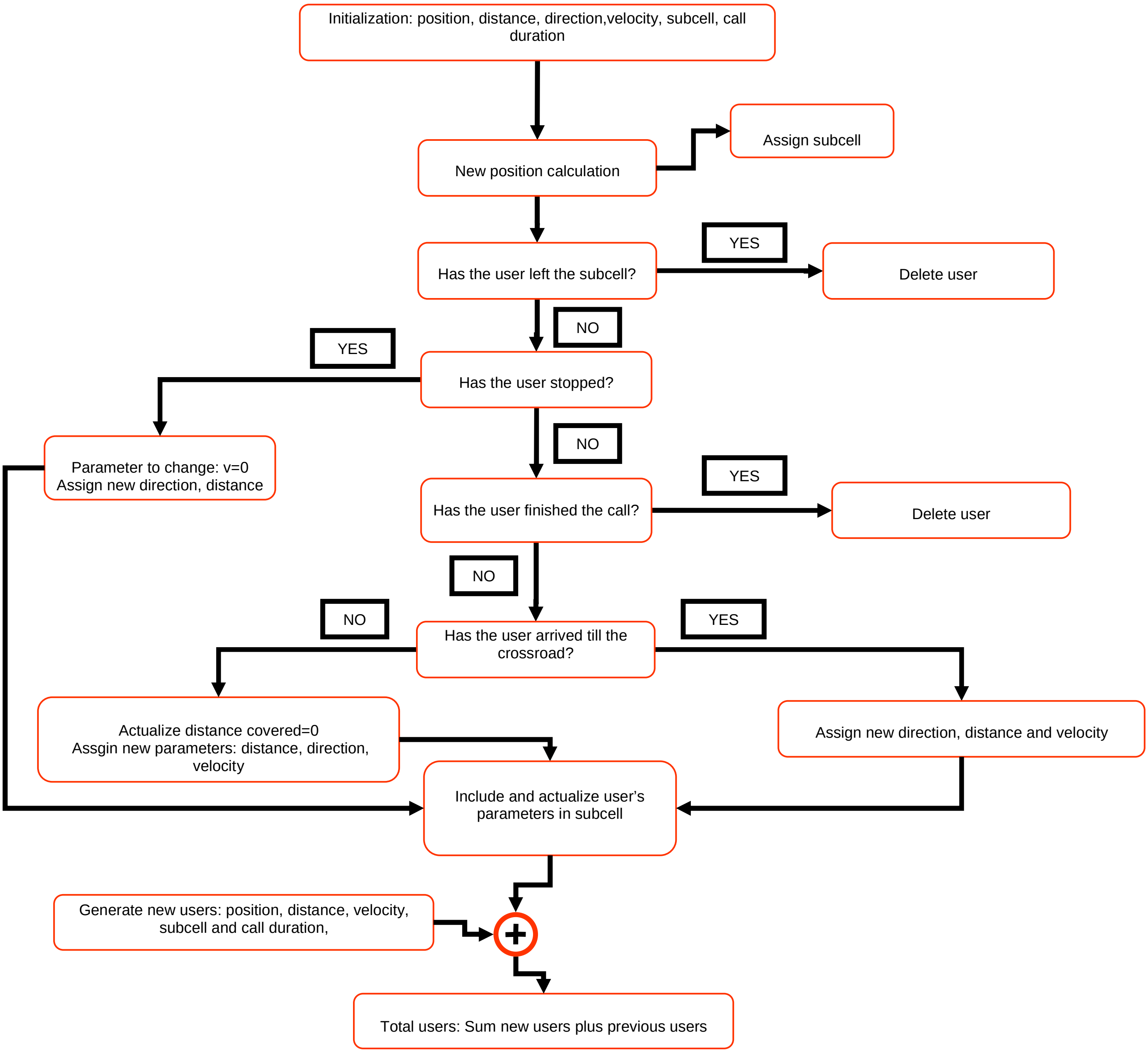
In conclusion, thanks to this tool we know the cell that serves each user at each moment and/or the mobility layer where the mobile user is registered. For each vehicle-borne terminal we know its starting point and its ending point by applying the mobility model. Thus, by using this tool we know the cell where the user is placed every moment. I will use this information to determine the dwell time or the boundary crossing probabilities.

4.2. Simulation description

Regards to the study realized by I. Bratanov, I obtained the values for the simulation from one of the leading Austrian operators to derive the set of the simulation’s parameters, such as the simulation’s best server map, the number of users, the mean duration of a call, etc.

Flowchart 1 shows how I simulate the users’ movement according to the mobility model proposed. It synthesizes the cadence of steps for each instant. In order to reduce the computational load and simplify the simulation I chose a time step of 2 seconds.

This flowchart represents the sequence of actions or decisions taken for every single user. The complete simulation evolves a group of users, initially uniformly distributed in the covered area (the cell). Moreover it is important to denote that these users are not considered as just only people but as people who initiate a call. Every time step, the sequence is repeated for each user.



Flowchart 1. Simulation process

Chapter V

Results

The lack of statistical information or its non-adaptation for cellular network planning is an important problem in the modelling of user mobility in cellular networks. On the one hand, may be difficult to find the required parameters for the simulation in some random models, e.g. the destination point in the random waypoint model[3]. On the other hand, the assumptions present in order to simplify and characterize statistically a zone can be too unreal. For example, the model presented by Hong and Rappaport [17] considers that once the values of speed and direction are chosen for each user, they remain constant until the user crosses the boundary of the cell.

The traffic flow is a mobility parameter of prime interest to derive the amount of signalling of mobility procedures such as handover and location updating. Car passengers may more or less maintain their average speed but a pedestrian is likely to stand still or look for a private location to handle the call. In fact, shopping areas are main centres of destination for pedestrian users. But we do not pay attention to this kind of users, because of their low velocities and the difficulty of predicting their movement. Moreover, the measurements of the pedestrian traffic in the cities are rare in the sense that in most cases only vehicular traffic is subject to measurements.

The present study is made on the example of the city of Vienna (Austria). In Figure 23, a density distribution graph of vehicular traffic over the whole city area is shown. There are seven levels organized from low traffic density (1) to high traffic density (7).

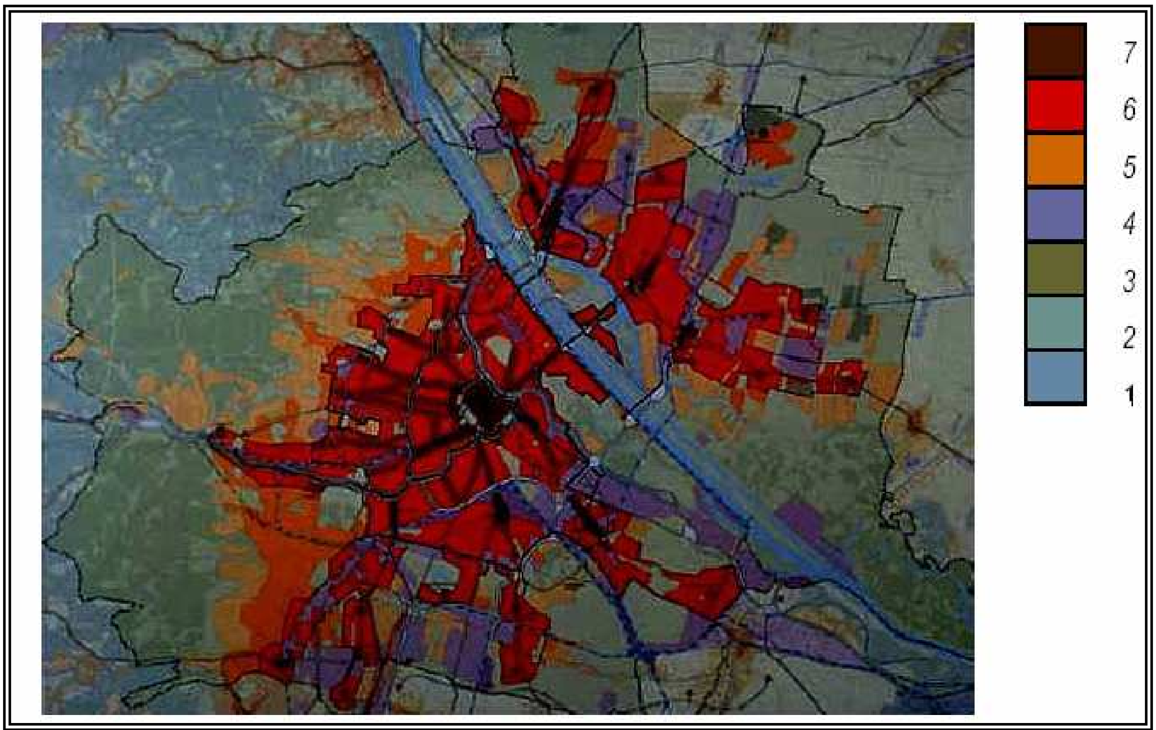


Figure 23. Traffic density on the streets of Vienna (source: City government of Vienna, Municipal authority 18: Town Development and Town Planning)

[3] The random waypoint model is very similar to a generalized random direction model though not the direction is chosen but the destination point. A user's movement is determined by its current space vector, its current speed and its current destination point.

As mentioned before, the different user flows are deduced from statistical data on the vehicular traffic in the studied area.

The mobile network operators can, by means of different measurements, verify the dimensioning of the user flows in an existing system and extrapolate and adjust the input parameters for the studies on new systems or for the case of modification in existing networks. For example, in GSM systems, the operator can measure the number of arriving and leaving inter-cellular handovers in each cell and thus it can estimate the street bounded user flow at border between cells.

The proposed mobility model may be applied as a wide powerful aid in cellular networks design and optimization. Consequently the basic verification has to be related to these topics. The most important signalling and teletraffic related parameters such as dwell time and handover rate will be determinate with respect to this model in the next sections.

The model taken as basis was compared with the known theoretical and empirical relations and measurement data. Only through this means would be possible to reach a validated assertion about how good and accurate is the description of the actual subscribers' behaviour made by the proposed mobility model. A deeper and more detailed description is presented in [1]. It is also possible to find various simulation results and implementations. The same line will be followed for the validation of the enhanced model.

It has been already pointed out that the mobility model must be integrated with a call model to describe the real subscriber behaviour and its influence over the whole mobile communication system. The assumptions made for the teletraffic statistics are classical. In the simulation, the call behaviour was modelled with a Poisson process for the arrival of new calls and an exponential distribution for the total call duration, with mean call duration of 90 seconds.

I also assumed that the total service time [4] and the terminal motion are independent, what it is not exact but the approximation is quite good for the purpose of this simulation. For example, it is ignored the possibility that people blocked in traffic jams might have longer communications than the typical customer, or the fact that the kind of terminal (handy, integrated in the car, etc.) affects the call initiation and duration. I take this assumption in favour of the simplicity of the simulation.

The performance parameters to be able to compare the design alternatives are presented in table 2. II district of Vienna has been chosen (Prätersten) as urban area, IV and V district as suburban area (Sudbanhof Station) and outskirts of Vienna as rural area[5]. With the simulation tool described above, it is possible to set up more precisely the parameter for each subarea, instead of using one parameter set for the whole area. Thus, the accuracy of results can be improved.

[4] The total service time considers as beginning the sending of a call establishment request and as ending the disconnection that implies the liberation of call-required resources.

[5] This zone does not exactly correspond to a typical rural area but the mobility model taken as basis is best suited for urban areas, so it is called rural areas to zones far away from the city centre.

	Urban	Suburban	Rural
$\overline{d}$	100m	170m	1000m
$\overline{v}$	30km/h	50km/h	80km/h
$\overline{v_{mr}}$	50km/h	80km/h	130km/h
p_{mr}	0.56	0.3	0.8

Table 2. Simulation parameters

I considered two aspects of network performance during the simulations: the dwell time and the handover rate. Moreover, I have compared the previously described base model and the enhanced model by studying their velocities.

5.1. Velocity comparison

It has been already mentioned that the most critical parameter for Bratanov's model is the average velocity. In order to compare the base model with this enhanced model and thus, appreciate the differences between them, a representation of the velocity for a single user is presented here. Its velocity at each step time is simulated during a period of 500 seconds for an urban environment. The parameters for the probability density function of the average velocity have been chosen from measurements in Vienna (and they have been presented in Table 2).

Figure 24.b shows the average velocity v_i in an urban area at each step (step-time = 2s) with the base model. The same parameters are used in the second simulation but with the inclusion of the stop-time characteristic (Figure 24.a).

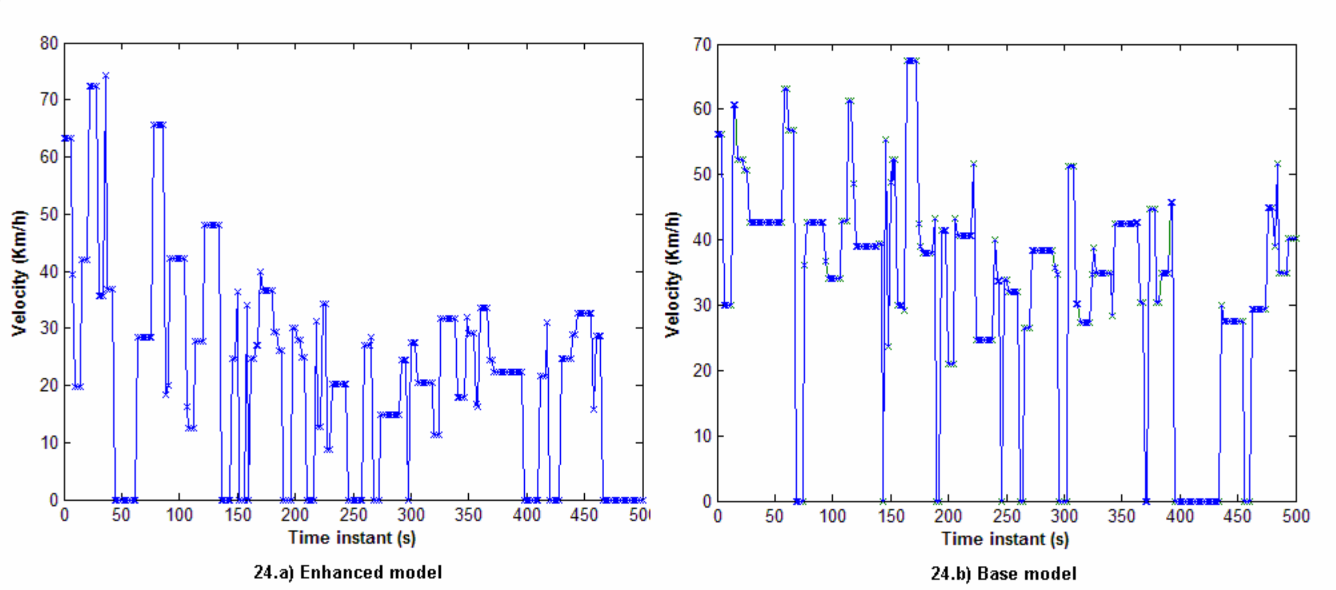


Figure 24. Velocity for a single user: a) Enhanced Model, b) Base model

We can observe the vehicle stops for a while several times in Figure 24.a. Not only it has the possibility of driving with v=0 km/h as in Figure 24.b but also in Figure 24.a this velocity keeps for a few seconds (it represents a stop).

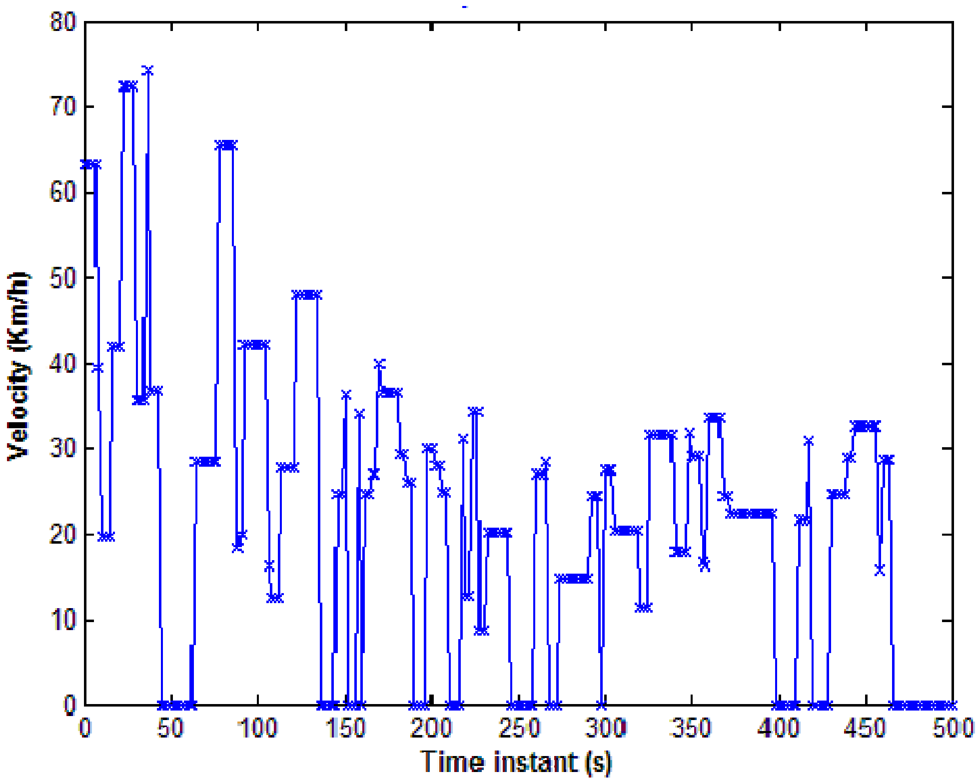


Figure 25. Velocity of a user in an urban area

Moreover, Figures 25, 26 and 27 compare the velocity of a single user moving in different areas: urban, suburban and rural according to the results obtained with the enhanced model.

From Figure 25 we can observe that the user has velocity zero in some instants or in some long periods of time, but user does not stop for short periods. However, in Figure 27 we can see as the user stops for a while several times, due to the random velocity assignment from the probability density function of the stop time distribution obtained in Chapter III, Section 3.3.2.3.

Figure 26 illustrates an example of a user that leaves the cell where it starts the movement before the end of the simulation time. The representation considers only the cell where the user starts the movement. As the user leaves the cell before the end time (500 seconds), the user disappears from simulation after its leaving. The main differences among the velocity in a rural, a suburban or an urban area are the frequency of the stop, that increases from a rural to an urban area, and the margin of variation of the velocity, higher in rural than in either suburban or urban areas. It is a logical conclusion we could also have derived from the observation of a real situation.

In rural areas exist less density of population than in urban areas, cities are far away and roads are longer and wider, so it is allowed to drive with higher velocity.

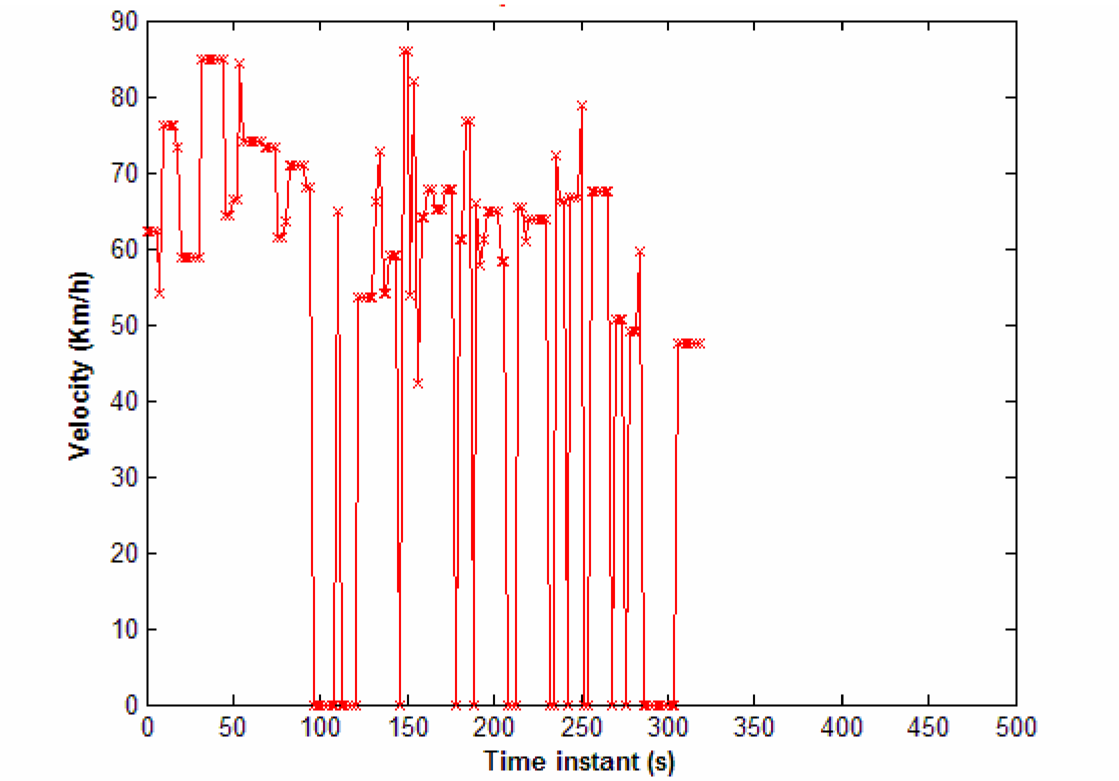


Figure 26 Velocity of a user in a suburban area

On the other hand, in urban and suburban areas the number of crossroads and traffic lights are higher than in rural areas, and thus, for the simulation the number of crossroads and traffic lights per cell should be higher.

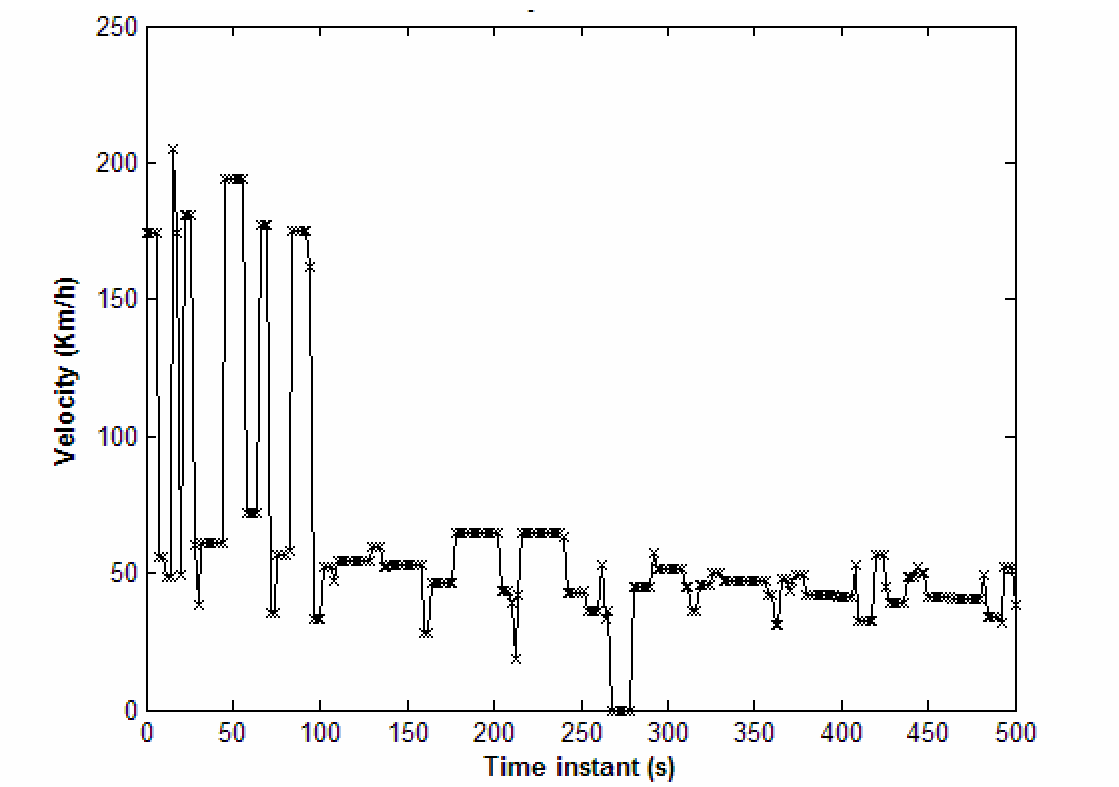


Figure 27. Velocity of a user in a rural area

This fact proves a vehicle must stop more times during a call with the same duration in an urban area than in a rural area (as Figure 27 shows).

5.2. Dwell time comparison

The dwell time is defined as the time the user stays in a cell, not from the physical point of view but from the system point of view, it is the time a mobile terminal dwells in a cell. It is also known as cell sojourn time or cell residence time (Figure 28). A considerable amount of research effort (see [17], [18] and references therein) has been devoted to the characterization of the time spent in a cell by terminals.

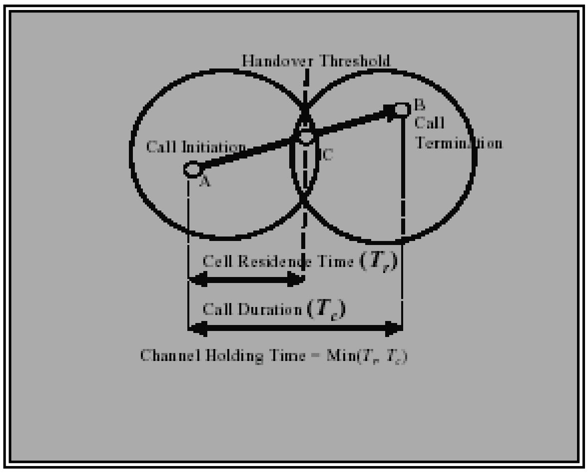


Figure 28. Dwell time/ Cell residence time concept

A plot of the dwell time for the three cases mentioned before: urban area, suburban area and rural area is shown in Figure 29.

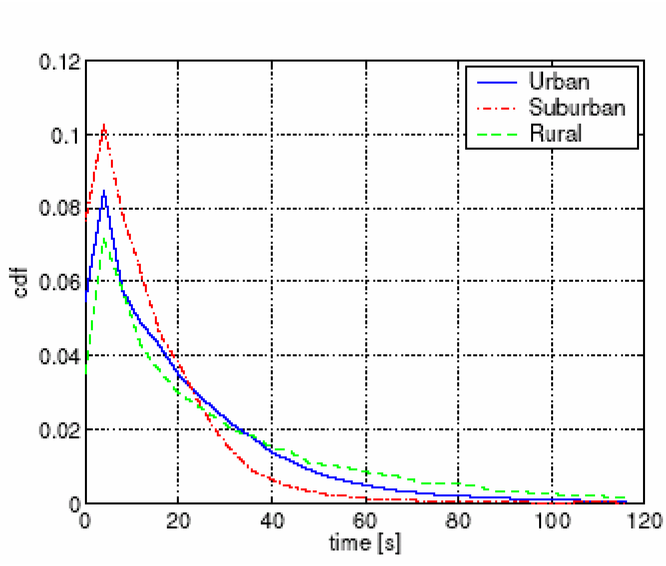


Figure 29. Handover comparison

At first we can see as most users stay for a short period within the cell. The actual network planning techniques lead to designs of smaller and smaller cells according to data from different operators [37]. In this way it is a logical conclusion the fact that small values of mean dwell time are obtained. If we compare the curves of the urban and suburban area, we can see that the higher velocities compensate the effect of the smaller cell sizes in the urban area allowed in the suburban areas. Another influent factor is the probability of major roads in suburban areas and the probability of crossings with traffic lights. Both are higher in urban areas, because suburban areas have in general more irregular street patterns and residential population, whilst city centres concentrates a huge number of offices, shopping centres and public buildings, frequently areas with high number of pedestrians and vehicles. Therefore, they present a huge need of traffic regulations.

Thus, the probability for small dwell times in suburban area is higher than the one in the urban case. However, the situation changes by increasing the dwell time. The explanation for this change is the volume of calls generated by the kind of users in an urban area, that hardly move from their position during the call due to the low speed of vehicular users in this area, the low number of crossings with traffic lights per cell and the shorter mean distance between crossroads in the city centres. All these factors generate an inverse tendency in urban areas with the increasing dwell time, and the curve for urban areas overcomes the values for the dwell time in suburban areas.

The curve of the rural area case is the flattest one. In fact, this was expected because of the very large cell sizes on the one hand, and the high velocity allowed on the kind of typical roads for these areas: highways and big roads between cities.

These results are suitable for network planning requirements not only for performance evaluations of second-generation mobile networks but also for third-generation.

5.3. Handover rate comparison

Typical functions of mobile communications systems are to monitor the channel quality and try to allocate a new channel (handover function) when the one in use no longer meets the minimum quality requirements. It is called handover threshold the point at which the power received from the base station of a neighbouring cell has started to exceed the power received from the current base station by a certain amount and /or a certain time. On the other hand, the receiver threshold is the point at which the power received from the current base station is at the minimum acceptable level. Handovers are focus of special interest in third-generation wireless networks because when the user is in the overlapping area between two cells, communications between the mobile station and the base station take place via two air interface channels from each base station separately (Figure 30). In general, in cellular systems using CDMA as encoding technology for the air interface multiple access schemes; the mobile station can be simultaneously connected to more than one base station. Therefore, the load and the resources required are doubled.

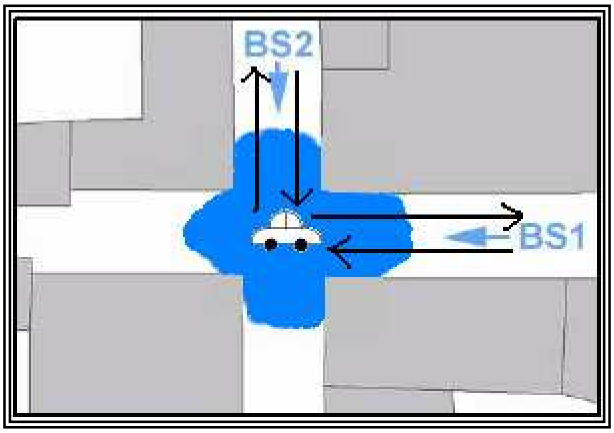


Figure 30. Softhandover example: double use of air interface channels

Allocating a new channel calls for almost immediate availability of radio resources and raises teletraffic problems, which range from service prioritization to admission control. The channel quality is assessed by considering a range of metrics and depends on the service type. The "quality" of the connection- dependent on the channel quality and perceived by the end user, or as relevant to the particular service- is then of paramount importance in order to initiate the handover procedures.

A mobile user can move through several cells while being involved in a call. This implies that when a subscriber moves from one cell to another, the call in progress has to be handed over from one base station to another to ensure continuity of service. The number of times a mobile crosses different boundaries during a call is a random variable dependent on the cell size, call holding time, and mobility parameters: the handover. Each handover requires network resources to reroute the call through a new base station. It is preferred to have as few handovers as possible in order to alleviate the switching load and to decrease the processing required in the system. The number of handovers has a lower bound, which is equal to the number of boundary crossings a mobile undergoes. I will use this limit to estimate the mean number of handovers per call, the so- called handover rate.

A great advantage of mobility modelling is that it allows a simple statistical computation of the number of handovers occurring during a call. The main emphasis of the simulation is to reflect, as far as possible, the real case. Figure 31 compares the handover rate of the vehicle-borne terminals in the three studied cases, in urban areas, in suburban areas and in rural areas. Note that the cumulative density function (c.d.f.) does not begin from zero, because not all users experience handover during their calls. As we have seen in the previous representation of the dwell time, some users stay in the same cell, even at the same position for the whole duration of the call. Results for the urban and the suburban areas are quite similar. However, the rural case significantly differs from the other two cases. It is obvious that the very big cell sizes cannot be compensated by the higher speeds, and most of the users do not have handover at all. The probability of staying in the same cell for a user in a rural area is higher than in urban or suburban areas.

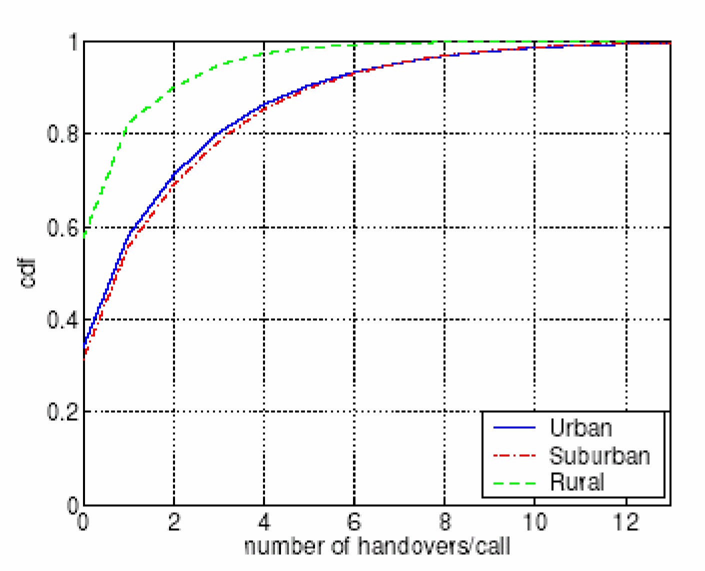


Figure 31. Handover rate for urban, suburban and rural areas.

But this is not the only difference. The lowest the number of handovers per call, the greatest the difference between rural environment and urban or suburban environments (related to their number of handovers per call). The maximum difference among three curves is around two handovers per call (for the parameters of our simulation); and from this point starts to get closer all the curves. Despite the model described here is best suited for urban and suburban areas, results are very realistic and suitable for the design of the network performance.

Only approximately 40% of the users experienced handover during their calls in rural areas, whilst in the urban and the suburban this percentage is 66% and 68%, respectively. The explanation of this effect is that the cell sizes in the rural area turns around 10 times higher than in rural area and the ratio of the corresponding velocities only overcomes in 2.6 times. Regards to this, it is important to outline that in case of large cell size the possibility of multiple handovers is normally neglected and so little care is given to the consequences, in terms of quality of service of the exceptional single handover which might occur during the conversation. In fact, the higher handover probability, the higher the probability for forced termination of the call due to a blocking of the handover. From the point of view of a mobile user, the forced termination of a call is less desirable than an initial blocking of a new call.

Chapter VI

Conclusions

The movement pattern of the vehicle-borne mobile users plays an important role in the performance analysis of mobile and wireless networks, especially in third-generation mobile communications due to the great influence of terminal mobility in most UMTS communication aspects involving either performance or traffic generation as a result of handover.

An enhanced mobility model for vehicle-borne mobile terminals has been presented here. We can find a wide variety of mobility models in literature, the differences depend on the complexity, the type of service, the size of cells, the geographical area, the environment, etc. A classification of mobility models that are used in wireless network research has been presented, and their main characteristics have been described in order to establish a global framework where it was possible to include this work. This enhanced model can be classified as statistical regards to its degree of randomness, macroscopic regards to its level of detail and vehicular regards to the type of user described.

The mobility model proposed in [1] is the basis for this work. It is a simple but very powerful statistical model since a real scenario can be described with a few parameters related to the relative direction change at crossroads, the distance between two crossroads and the velocity in this street section. An enhancement has been introduced to this model: the inclusion of the possibility that a vehicle stops at crossroads. The probability for such event is an input parameter. Thanks to this new study, I found out the time a user stops at a crossroads is normally distributed. And this allows to difference when the mobile users stop at crossroads for several tens of seconds while having soft handover connection, and when they just drove through these areas. The inclusion of *the stop behaviour* is very interesting due to the problematic of soft handover at crossroads. This is the major advantage of the improvement introduced.

The goal of this enhanced model was to reach a compromise between simple models, such a basic random way-point model, and very realistic mobility models, such as models from transportation research or movement traces. The latter are usually very complicated to implement and/or need a huge database (in particular for long simulations). The first are too general and cannot determine the position and the movement with accuracy. Contrary, this model makes the movement trace of mobile users more realistic than common approaches for random mobility but describes the movement with very few parameters, and thus, it joins simplicity and accuracy. It accounts for arbitrary street patterns and realistic terminal movements by a limited number of parameters that can be easily measured or derived from a city map or a vehicular traffic analysis. Thus, while the movement behaviour of users becomes more realistic, the implementation and computation effort is still low. Because of this change, it is possible to model in a better way the network performance of second and especially third-generation mobile networks.

Furthermore, simulations with this model are best fitted to a real scenario due to the use of arbitrary cell shapes and the possibility of defining different mobility regions or layers with the simulation tool that has been used. So, it has set a framework for realistic mobility simulations where three different scenarios have been analyzed: urban, suburban and rural areas. By adjusting parameters to each case, it was possible to compare some parameters like the dwell time and the handover rate in these different environments. Regards to the dwell time calculations, the probability for small values in suburban area is higher than the one in the urban case.

However, the situation changes with increasing dwell time. The curve of the rural area case is the flattest one. In fact, this was expected because of the very large cell sizes on the one hand, and the high velocity allowed on the kind of typical roads for these areas: high-ways and big roads between cities.

Regards to the handover rate, similar results are obtained for urban and suburban cases due to differences between cells sizes are compensated by differences between velocities. However, rural areas present, in general, higher handover rate per call than the other areas. Despite of the increase in terminal velocity and cell sizes in these areas, both terms are not proportional and velocity increases more rapidly than cell sizes.

Last but not least, the initialization of users within a cell has been discussed. The problem of using a uniform distribution and the impact of the border behaviour on the spatial mobile users' distribution has been described. This impact is produced by the unwanted effects in studies of networking algorithms the spatial mobile users' distribution might lead and it has been also presented by other authors [3]. I have proposed a distribution based on density car and the application of the "wrap-around border behaviour" technique in order to obtain a spatial distribution as uniform as possible.

Results regards to the cell dwell time and the handover rate per call have showed a notable accuracy improvement in comparison with other models but much further work remains in validating the model and simulating scenarios with different layers overlapped.

Chapter VII

Future work

I would like to underline here the different lines of investigation that have been opened with this work. On the one hand, much further work remains in validating the model with real values obtained from operators for the parameters described here or for other that can be interesting for radio-resource management. In this sense, a comparison among urban areas of different cities of diverse countries or different operators can be made.

Another important approach which has not developed in this work is the consideration of layered scenarios. The simulation tool presented before (Chapter IV) is capable to define different layers for the same geographical area. Simulating scenarios with different layers overlapped is one task of high interest due to the real network design, as in case of second generation of mobile communications as in case of third generation. Moreover, it is also possible to use this tool not only in order to define different layers of a cellular system but also to apply different mobility patterns on users located in the same area (different mobility models or the same model with different parameters).

The last direction, I would like to suggest, leads to the discussion presented in Chapter II about the *stop-and-go* behaviour and the *slowdown* behaviour. From this point of view, it could be interesting to analyze the impact of a sudden change of direction and velocity. As mentioned before, many researchers criticized that after arriving to the destination, the choice for a speed and a new direction is not correlated to previous values. The base model taken as basis considerers this fact by introducing a continuous distribution weighted with probabilities for the main four directions (0º, 90º, 180º or -90º) in order to determine the direction change at crossroads: user takes a new direction relative to its previous direction according to these probabilities. However velocity user behaviour does not correspond to a *slowdown behaviour*. This model does not consider the correlation in velocity. The speed is not changed incrementally by the current acceleration of the mobile user, and the direction change is not smooth. Therefore, the present work could be extended by including a *slowdown behaviour* for users in such a way that once a user is intended to turn, the direction is changed in several time steps until the new target direction is achieved and so, velocity changes are related. Moreover, it should be compared the added computational effort (especially in time simulation) versus the improvement in accuracy that is achieved in order to evaluate its viability.

APPENDIX Table of measurements

Wiedner Haupstraße/ Planiglgasse

Redstart	Redend/ Greenstart	Greenend	Red Phase	Green Phase	Ncars
9:11:33	9:12:08	9:13:12	00:35	01:04	32
9:13:12	9:13:48	9:14:51	00:36	01:03	33
9:14:51	9:15:28	9:16:32	00:37	01:04	28
9:16:32	9:17:09	9:18:10	00:37	01:01	31
9:18:10	9:18:47	9:19:49	00:37	01:02	31
13:14:51	13:15:27	13:16:31	00:36	01:04	20
13:16:31	13:17:08	13:18:11	00:37	01:03	28
13:18:11	13:18:48	13:19:52	00:37	01:04	14
13:19:52	13:20:27	13:21:32	00:35	01:05	22
13:21:32	13:22:07	13:23:14	00:35	01:07	15
18:16:34	18:17:09	18:18:13	00:35	01:04	25
18:18:13	18:18:48	18:19:53	00:35	01:05	29
18:19:53	18:20:28	18:21:33	00:35	01:05	31
18:21:33	18:22:09	18:23:13	00:36	01:04	29
18:23:13	18:23:49	18:24:53	00:36	01:04	28
		AVERAGE	00:35,9	01:03,9	26,40
		STDEV	00:00,9	00:01,4	6,01

Favoritenstraße/Mayerhofgasse

Redstart	Redend/ Greenstart	Greenend	Red Phase	Green Phase	
9:34:48	9:35:26	9:36:28	00:38	01:02	23
9:36:28	9:37:06	9:38:07	00:38	01:01	16
9:38:07	9:38:45	9:39:51	00:38	01:06	19
9:39:51	9:40:24	9:41:28	00:33	01:04	22
9:41:28	9:42:04	9:43:10	00:36	01:06	24
12:36:28	12:37:05	12:38:05	00:37	01:00	16
12:38:05	12:38:43	12:39:46	00:38	01:03	22
12:39:46	12:40:24	12:41:26	00:38	01:02	17
12:41:26	12:42:04	12:43:06	00:38	01:02	17
12:43:06	12:43:44	12:44:46	00:38	01:02	17
17:56:37	17:57:15	17:58:17	00:38	01:02	23
17:58:17	17:58:55	17:59:57	00:38	01:02	23
17:59:57	18:00:36	18:01:37	00:39	01:01	14
18:01:37	18:02:18	18:03:17	00:41	00:59	15
18:03:17	18:03:55	18:04:55	00:38	01:00	21
		AVERAGE	00:37,7	01:02,1	19,27
		STDEV	00:01,5	00:01,8	3,18

Gußhausstraße/Argentinierstraße

Redstart	Redend/ Greenstart	Greenend	Red Phase	Green Phase	Ncars
8:51:46	8:52:14	8:52:48	00:28	00:34	8
8:52:48	8:53:15	8:53:47	00:27	00:32	14
8:53:47	8:54:15	8:54:48	00:28	00:33	6
8:54:48	8:55:14	8:55:46	00:26	00:32	5
8:55:46	8:56:14	8:56:46	00:28	00:32	8
12:52:44	12:53:13	12:53:44	00:29	00:31	5
12:53:44	12:54:14	12:54:44	00:30	00:30	3
12:54:44	12:55:14	12:55:44	00:30	00:30	11
12:55:44	12:56:14	12:56:45	00:30	00:31	8
12:56:45	12:57:14	12:57:44	00:29	00:30	12
18:21:49	18:22:16	18:22:48	00:27	00:32	3
18:22:48	18:23:16	18:23:45	00:28	00:29	6
18:23:45	18:24:16	18:24:46	00:31	00:30	6
18:24:46	18:25:16	18:25:46	00:30	00:30	11
18:25:46	18:26:16	18:26:46	00:30	00:30	6
		AVERAGE	00:28,7	00:31,1	7,47
		STDEV	00:01,3	00:01,4	3,48

Wiedner Haupstrasße/ Schönburgstraße

Redstart	Redend/ Greenstart	Greenend	Red Phase	Green Phase	Ncars
8:36:53	8:37:29	8:38:08	0:00:36	0:00:39	15
8:38:08	8:38:45	8:39:23	0:00:37	0:00:38	17
8:39:23	8:39:59	8:40:39	0:00:36	0:00:40	22
8:40:39	8:41:13	8:41:53	0:00:34	0:00:40	18
8:41:53	8:42:29	8:43:09	0:00:36	0:00:40	17
12:44:22	12:44:57	12:45:37	0:00:35	0:00:40	18
12:45:37	12:46:13	12:46:53	0:00:36	0:00:40	12
12:46:53	12:47:27	12:48:06	0:00:34	0:00:39	17
12:48:06	12:48:40	12:49:22	0:00:34	0:00:42	21
12:49:22	12:49:56	12:50:38	0:00:34	0:00:42	16
17:43:39	17:44:19	17:45:19	0:00:40	0:01:00	21
17:45:19	17:46:00	17:46:59	0:00:41	0:00:59	32
17:46:59	17:47:39	17:48:39	0:00:40	0:01:00	19
17:48:39	17:49:23	17:50:19	0:00:44	0:00:56	16
17:50:19	17:50:59	17:51:59	0:00:40	0:01:00	29
		AVERAGE	00:37,1	00:46,3	19,33
		STDEV	00:02,3	00:07,7	4,99

Paulanergasse/Wiedner Haupstraße

Redstart	Redend/ Greenstart	Greenend	Red Phase	Green Phase	Ncars
9:24:03	9:24:45	9:25:18	0:00:42	0:00:33	12
9:25:18	9:26:00	9:26:33	0:00:42	0:00:33	12
9:26:33	9:27:15	9:27:50	0:00:42	0:00:35	5
9:27:50	9:28:29	9:29:04	0:00:39	0:00:35	11
9:29:04	9:29:45	9:30:18	0:00:41	0:00:33	11
13:01:33	13:02:15	13:02:46	0:00:42	0:00:31	10
13:02:46	13:03:29	13:04:01	0:00:43	0:00:32	12
13:04:01	13:04:45	13:05:17	0:00:44	0:00:32	9
13:05:17	13:06:00	13:06:35	0:00:43	0:00:35	4
13:06:35	13:07:13	13:07:46	0:00:38	0:00:33	11
17:33:06	17:33:32	17:33:55	0:00:26	0:00:23	4
17:33:55	17:34:23	17:34:44	0:00:28	0:00:21	6
17:34:44	17:35:14	17:35:39	0:00:30	0:00:25	12
17:35:39	17:36:06	17:36:28	0:00:27	0:00:22	8
17:36:28	17:36:57	17:37:19	0:00:29	0:00:22	10
		AVERAGE	00:37,1	00:29,7	9,13
		STDEV	00:05,9	00:04,6	3,23

Rechte Wienzeite/Kettenbrückengasse

Redstart	Redend/ Greenstart	Greenend	Red Phase	Green Phase	Ncars
9:04:07	9:04:30	9:05:20	0:00:23	0:00:50	20
9:05:20	9:05:45	9:06:37	0:00:25	0:00:52	18
9:06:37	9:07:00	9:07:50	0:00:23	0:00:50	22
9:07:50	9:08:14	9:09:06	0:00:24	0:00:52	14
9:09:06	9:09:30	9:10:12	0:00:24	0:00:42	12
12:37:52	12:38:15	12:39:05	0:00:23	0:00:50	28
12:39:05	12:39:32	12:40:19	0:00:27	0:00:47	12
12:40:19	12:40:45	12:41:37	0:00:26	0:00:52	30
12:41:37	12:41:59	12:42:49	0:00:22	0:00:50	18
12:42:49	12:43:15	12:44:02	0:00:26	0:00:47	19
18:20:19	18:20:43	18:21:35	0:00:24	0:00:52	14
18:21:35	18:21:59	18:22:50	0:00:24	0:00:51	15
18:22:50	18:23:14	18:24:05	0:00:24	0:00:51	17
18:24:05	18:24:30	18:25:20	0:00:25	0:00:50	19
18:25:20	18:25:45	18:26:35	0:00:25	0:00:50	21
		AVERAGE	00:24,3	00:49,7	18,60
		STDEV	00:01,5	00:03,0	5,84

Margaretenstraße/Pilgramgasse

Redstart	Redend/ Greenstart	Greenend	Red Phase	Green Phase	Ncars
9:21:10	9:21:44	9:22:21	00:34	00:37	19
9:22:21	9:22:59	9:23:37	00:38	00:38	14
9:23:37	9:24:13	9:24:53	00:36	00:40	10
9:24:53	9:25:30	9:26:09	00:37	00:39	15
9:26:09	9:26:44	9:27:22	00:35	00:38	18
12:57:27	12:57:57	12:58:39	00:30	00:42	9
12:58:39	12:59:12	12:59:51	00:33	00:39	8
12:59:51	13:00:27	13:01:09	00:36	00:42	18
13:01:09	13:01:40	13:02:23	00:31	00:43	22
13:02:23	13:02:57	13:03:34	00:34	00:37	17
18:02:22	18:02:57	18:03:36	00:35	00:39	13
18:03:36	18:04:13	18:04:51	00:37	00:38	12
18:04:51	18:05:27	18:06:06	00:36	00:39	12
18:06:06	18:06:42	18:07:21	00:36	00:39	15
18:07:21	18:07:58	18:08:38	00:37	00:40	13
		AVERAGE	00:35,0	00:39,3	14,33
		STDEV	00:02,4	00:02,0	4,36

Nikolsdorferstraße/Wiedner Haupstraße

Redstart	Redend/ Greenstart	Greenend	Red Phase	Green Phase	Ncars
9:06:50	9:07:37	9:08:10	00:47	00:33	4
9:08:10	9:08:51	9:09:18	00:41	00:27	2
9:09:18	9:10:06	9:10:33	00:48	00:27	2
9:10:33	9:11:26	9:11:50	00:53	00:24	9
9:11:50	9:12:36	9:13:04	00:46	00:28	7
13:20:35	13:21:20	13:21:44	00:45	00:24	2
13:21:44	13:22:33	13:23:00	00:49	00:27	1
13:23:00	13:23:48	13:24:16	00:48	00:28	4
13:24:16	13:25:05	13:25:32	00:49	00:27	3
13:25:32	13:26:20	13:26:46	00:48	00:26	7
17:54:15	17:55:24	17:55:55	01:09	00:31	4
17:55:55	17:57:04	17:57:36	01:09	00:32	8
17:57:36	17:58:45	17:59:16	01:09	00:31	7
17:59:16	18:00:24	18:00:56	01:08	00:32	10
18:00:56	18:02:04	18:02:36	01:08	00:32	6
		AVERAGE	00:54,5	00:28,6	5,07
		STDEV	00:08,9	00:02,9	2,68

Favoritenstraße/Kolschitzkygasse

Redstart	Redend/ Greenstart	Greenend	Red Phase	Green Phase	Ncars
9:11:50	9:12:27	9:13:30	00:37	01:03	17
9:13:30	9:14:07	9:15:10	00:37	01:03	9
9:15:10	9:15:47	9:16:50	00:37	01:03	10
9:16:50	9:17:27	9:18:30	00:37	01:03	24
9:18:30	9:19:07	9:20:10	00:37	01:03	21
13:13:29	13:14:05	13:15:09	00:36	01:04	10
13:15:09	13:15:45	13:16:49	00:36	01:04	22
13:16:49	13:17:26	13:18:29	00:37	01:03	11
13:18:29	13:19:05	13:20:09	00:36	01:04	13
13:20:09	13:20:45	13:21:49	00:36	01:04	13
18:14:20	18:14:58	18:16:02	00:38	01:04	25
18:16:02	18:16:38	18:17:41	00:36	01:03	22
18:17:41	18:18:19	18:19:21	00:38	01:02	13
18:19:21	18:19:58	18:21:02	00:37	01:04	16
18:21:02	18:21:38	18:22:41	00:36	01:03	12
		AVERAGE	00:36,7	01:03,3	15,87
		STDEV	00:00,7	00:00,5	6,07

Wiedner Haupstraße/Anzengrubergasse

Redstart	Redend/ Greenstart	Greenend	Red Phase	Green Phase	Ncars
8:57:33	8:58:08	8:58:46	00:35	00:38	29
8:58:46	8:59:23	9:00:01	00:37	00:38	22
9:00:01	9:00:38	9:01:16	00:37	00:38	19
9:01:16	9:01:53	9:02:31	00:37	00:38	22
9:02:31	9:03:08	9:03:46	00:37	00:38	23
12:28:50	12:29:24	12:29:59	00:34	00:35	10
12:29:59	12:30:35	12:31:15	00:36	00:40	24
12:31:15	12:31:51	12:32:30	00:36	00:39	22
12:32:30	12:33:06	12:33:45	00:36	00:39	17
12:33:45	12:34:23	12:34:59	00:38	00:36	18
17:45:19	17:46:01	17:46:59	00:42	00:58	33
17:46:59	17:47:41	17:48:39	00:42	00:58	33
17:48:39	17:49:20	17:50:19	00:41	00:59	32
17:50:19	17:51:01	17:51:59	00:42	00:58	29
17:51:59	17:52:41	17:53:39	00:42	00:58	33
		AVERAGE	00:38,1	00:44,7	24,40
		STDEV	00:02,5	00:07,9	6,64

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