Mobility Model of Vehicle-Borne Terminals in Urban Cellular Systems

Plamen I. Bratanov and Ernst Bonek, *Senior Member, IEEE*

***Abstract*— This paper presents a new model describing the mobility of vehicle-borne terminals under realistic urban traffic conditions. The model accounts for arbitrary urban street patterns and realistic terminal movements by a limited number of parameters that can be easily measured or derived from a city map. It introduces distribution functions of street length, direction changes at crossroads, and terminal velocity to find an analytical formulation. For validation, we show by simulation that the model yields cell sojourn time and remaining sojourn time distributions in agreement with previous results. Further independent validation by measurements and by a street pattern tracing software tool prove the model's accuracy.**

***Index Terms*— Cellular mobile networks, mobility model, user behavior, sojourn time.**

I. Introduction

MOBLIY analysis gives a deep insight on the impact of the terminal mobility on the cellular system performance. In third-generation mobile communication Systems, the influence of mobility on the network performance will be strengthened, mainly due to the huge number of mobile users in conjunction with the small cell size. In particular, the accuracy of mobility modeling becomes essential for the evaluation of system design alternatives and network implementation cost issues.

The determination of the time spent by a terminal in the coverage area of a cell, "cell sojourn time", is an important parameter for service quality evaluation, and improvement [1], [2]. This is particularly true for overlay-underlay network configurations [3], [4]. Therefore, a suitable model to analyze and estimate movements of subscriber units is of major interest [5], [6], [7]. Known mobility models either tend to be dependent on a great number of parameters and large databases [8] and thus are not well suited for a general representation, or are based on parameters that are not directly related to the users´ motion behavior and street course [9]. A link between real street maps and rate of location updates was given in [12].

For mobility modeling under realistic traffic and environmental conditions, our work introduces a novel representation technique, which uses the distribution functions of street length, direction changes at crossroads, and terminal velocity. The parameters required, e.g. mean and variance of street length, user velocity, and direction changes distributions, can be *easily* derived by observation and measurement. Other important factors influenced by user mobility concern the mobile user calling behavior expressed by the incoming/outgoing call arrival rate and average call duration. This work thus brings together teletraffic theory and vehicular traffic theory.

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Plamen I. Bratanov was with the Institut für Nachrichtentechnik und Hochfrequenztechnik, Technische Universität, Gußhausstraße 25/389, A-1040 Wien, Austria. He is now with Information and Communication Networks, Siemens AG Österreich, Erdberger Lände 26, A-1031 Vienna, Austria. (phone: +43-5-1707-39315, e-mail: plamen.bratanov@siemens.at).

Ernst Bonek is with the Institut für Nachrichtentechnik und Hochfrequenz-technik, Technische Universität, Gußhausstraße 25/389, A-1040 Vienna, Austria. (phone: +43-1-58801-38936, e-mail: ernst.bonek@tuwien.ac.at)

II. Mobility Model

Concerning the arrival of a call, mobile radio network cells can be classified as "call-initiated cells", when the call is newly placed within the cell; or as "handover-call cells", when the call has been handed over from neighboring cells. A mobile call can be initiated or received at any point within the call-initiated cell along the path of the vehicle, Fig. la. The traveling terminal will exit the call-initiated cell after having used up the remaining sojourn time t_{rs}. Figure la shows an arbitrary traffic path, which includes all crossroads a subscriber unit would pass in this cell. The vectors $\vec{d}_i$, represent both the street-length value between crossroads, and the direction of movement. If $\vec{r}_0(x_0, y_0)$ denotes the initial position, the following relations provide the successive locations of the mobile user moving in random directions:

$$\vec{r}_1(x_1, y_1) = \vec{r}_0 + \vec{d}_0(d_0, \varphi_0),$$
$$\vec{r}_2(x_2, y_2) = \vec{r}_1 + \vec{d}_1(d_1, \varphi_1), \quad (1)$$
$$\cdots,$$

where φ_i is the change in direction with respect to the previously direction at last crossroad. In order to simplify the formulation and to enable the derivation of parameter statistics, we define a Cartesian co-ordinate system (x, y) in addition to the polar co-ordinates.

Assuming the initial direction of a mobile to be uniformly distributed between $[-\pi, \pi)$, the probability density of the start angle φ_0 is also uniformly distributed [9].

On the other hand, the handover-call cells (Fig. lb) have their starting point somewhere on their boundaries. In this case, the probability density function of direction for a boundary crossing mobile has a bias toward the normal [10]:

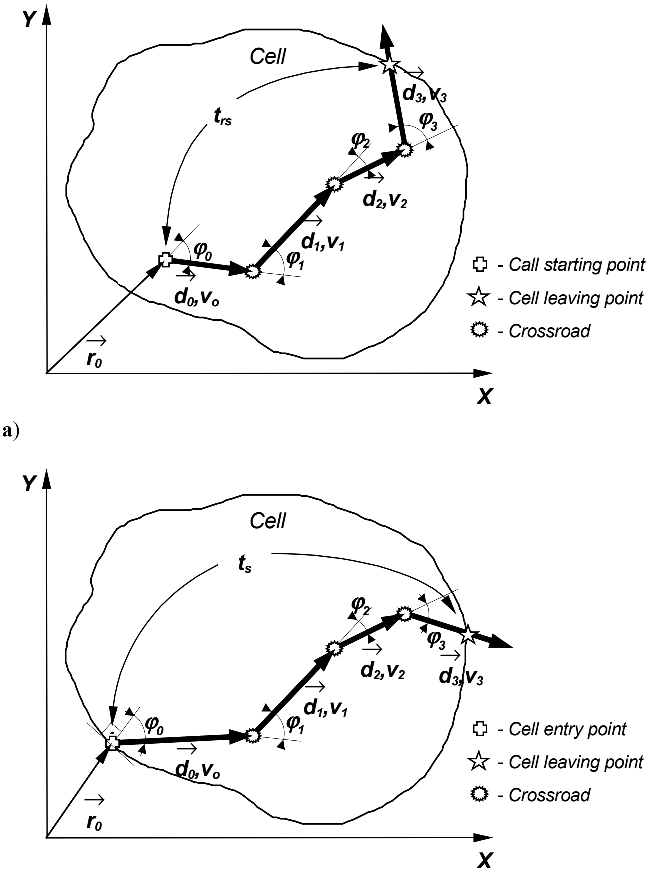

Fig. 1. Tracing a mobile within the cell. **a**) Remaining sojourn time in the call-initiated cell; **b**) Sojourn time in the handover-call cell.

$$p.d.f.(\varphi_0) = \frac{1}{2}\cos\varphi_0 \quad \text{for} \quad -\frac{\pi}{2} \le \varphi_0 < \frac{\pi}{2} \tag{2}$$

The relative direction changes at each crossroad, φ_i, depend on the street network pattern and the traffic situation. The angle φ_i can be expressed by the realization of one of four random variables. Each random variable is assumed to be normally distributed, with estimated means 90° apart. The probabilities when assigning variables to φ_i depend on traffic regulations and driver behavior (e.g., traffic users are more likely to turn right than left). Therefore, the probability density function of φ_i follows as:

$$p.d.f.(\varphi_i) = p_0\frac{1}{\sigma_\varphi\sqrt{2\pi}}e^{-\frac{\varphi_i^2}{2\sigma_\varphi^2}} + p_{90}\frac{1}{\sigma_\varphi\sqrt{2\pi}}e^{-\frac{\left(\varphi_i-\frac{\pi}{2}\right)^2}{2\sigma_\varphi^2}} + p_{-90}\frac{1}{\sigma_\varphi\sqrt{2\pi}}e^{-\frac{\left(\varphi_i+\frac{\pi}{2}\right)^2}{2\sigma_\varphi^2}} + p_{180}\frac{1}{\sigma_\varphi\sqrt{2\pi}}e^{-\frac{(\varphi_i-\pi)^2}{2\sigma_\varphi^2}} \tag{3}$$

where:

$p_{0°}, p_{90°}, p_{-90°}, p_{180°}$ - direction change probabilities,

$p_{0°} + p_{90°} + p_{-90°} + p_{180} = 1$,

σ_φ - standard deviation of direction distributions, assumed to be equal for all four distributions.

The value of σ_φ depends on the road network pattern. A discrete and irregular road network pattern shows a higher value than a Manhattan grid where the streets are perpendicular to each other.

The street lengths between crossroads, d_i, in European cities may also be described by a random variable. The projections of two arbitrary streets for the *X*- and *Y*-axis have been plotted in Fig. 2.

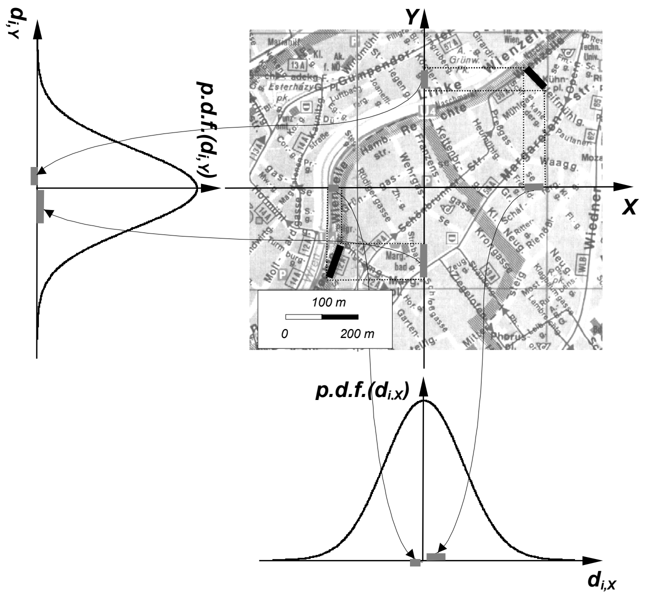

Fig. 2. Derivation of the p.d.f. of street length.

Since the streets take a random course with respect of the axes of a Cartesian co-ordinate system, their projections $d_{i,X}$ and $d_{i,Y}$ can be regarded as normally distributed random variables. In areas with an irregular street pattern the random variables $d_{i,X}$ and $d_{i,Y}$ can be characterized as statistically independent and normally distributed, with zero mean and the same variance. Therefore, the street-length between crossroads:

$$d_i = \sqrt{d_{i,X}^2 + d_{i,Y}^2} \tag{4}$$

turns out to be Rayleigh distributed:

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

$$\text{where} \quad \sigma_d = \overline{d}\sqrt{\frac{2}{\pi}} \tag{5}$$

The mean street length $\overline{d}$ may differ somewhat within the different parts of the city. Calculations for Vienna, Austria, show that $\overline{d}$ =70-100 m in the city center, whereas it amounts to $\overline{d}$ =100-170 m in the outskirts.

Though the heterogeneous street pattern of an urban setting provides subscribers with a lot of choices where to drive, they mostly use major roads. Urban traffic planners encourage this by a number of traffic regulations. When the majority of terminals travel on major roads only, the probability density of d_i can be approximated by a Rice-distribution:

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

$$\text{where} \quad I_0(x) = \frac{1}{\pi}\int_0^{\pi} e^{x\cos\theta} d\theta \qquad (6)$$

$$0.75\ \bar{d}\sqrt{\frac{2}{\pi}} < \sigma_d < 1.5\ \bar{d}\sqrt{\frac{2}{\pi}}$$

Here $\bar{d}$ is the average length of major roads between two consecutive crossroads, and $\sigma_d^{\,2}$ is the variance of the length of minor city roads between two consecutive crossroads (i.e., it is the same as in (5)). The function I_0 is the modified Bessel function of first kind and order zero.

The model avoids becoming excessively involved by assuming that the velocity of the subscriber unit does not change while covering the distance d_i, which allows an equation with *average* velocities v_i. In analogy with the calculation of street-length statistics it is reasonable to assume that the average velocity is Rayleigh/Rice distributed. As mentioned, traffic is bundled on major roads where the average speed might be higher than in the urban streets. Measurements in Helsinki [11] and Vienna suggest to add a second term to the speed distribution to account for this effect. We add such a term and assume that the velocity of subscribers on major roads is normally distributed, and get a more accurate description of the actual velocity distribution:

$$p.d.f.(v_i) = (1 - p_{mr})\frac{v_i}{\sigma_v^{\,2}} e^{-\frac{v_i^2+\bar{v}^2}{2\sigma_v^{\,2}}} I_0\left(\frac{v_i \bar{v}}{\sigma_v^{\,2}}\right) + + p_{mr}\frac{1}{\sigma_v\sqrt{2\pi}} e^{-\frac{(v_i-\bar{v}_{mr})^2}{2\sigma_v^{\,2}}} \quad \text{for} \quad v_i > 0 \qquad (7)$$

where:

p_{mr} - probability (percentage) of fraction of cars on major roads,

$\bar{v}$, $\bar{v}_{mr}$ - mean velocities of city and major-road traffic,

σ_v - velocity deviation.

To verify this distribution and to estimate its parameters, we have taken test measurements. A car especially equipped for measurements was used. A speech quality measurement system *(Q-Voice* from Ascom Infrasys AG, Switzerland) was used to initialize and perform a lot of calls. During each call, all the network related data were gathered, recorded (speech quality, received quality, handover processing, signaling issues etc.), and stored over a very fine time reference. Also, a *GPS* location receiver recorded, for each of these measurements, the corresponding position of the test car. Therefore, we could collect a very fine statistic of the mean car velocity from one crossroad to the next crossroad in city area of Vienna. Figure 3 shows the measurement results for the velocity distribution in the city of Vienna (2nd District, Praterstern). The velocity model we propose (equ. 6) describes the actual velocity distribution very well. Through chi-square goodness-of-fit test we could also determine the model parameters and got the following values of the parameters: p_{mr} = 0.56, $\bar{v}$ = 10 km/h, $\bar{v}_{mr}$ = 40 km/h, σ_v = 10 km/h.

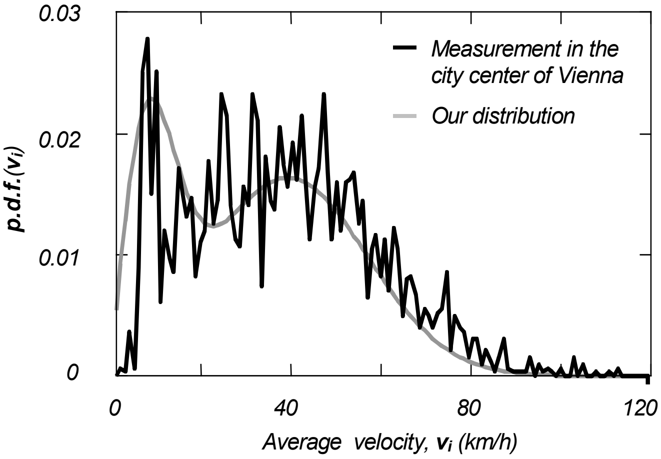

Fig. 3. The p.d.f. of average velocity.

III. Mobility-Model Validation

The value of the individual street length between crossroads, d_i, and the corresponding average velocities, v_i., being known, we are now in the position to validate our model. To do so, we chose to calculate the sojourn times, t_s and t_{rs}. For one, there are detailed results [9] for this important parameter available derived from entirely different considerations, for the other, sojourn times provide the basis for many teletraffic planning issues (e.g. paging area planning, handover strategies, cell layout, channel assignment).

Simulations based on the presented mobility model enable the calculation of the distributions of the sojourn times for cells of arbitrary shape. To reflect, as far as possible, a truly typical case, the simulation must incorporate a sufficiently large mobile population. This will minimize the influence of initial conditions and the variation of the stochastic processes. In the simulation tool we wrote (Fig. 4), a mobile population of 2,500 mobile users drives the statistics of the boundary crossing phenomena to reach the steady state condition. A uniform distribution is assumed for initial spatial location of the users. This assumption is reasonable, as the relative orientation of streets varies randomly in a cellular network, giving on the average an approximately uniform distribution of possible directions. (We note in passing that a suitable selection of input parameters will allow modification of this assumption 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 equal probability. Depending on the structure of the cellular coverage area, a subscriber unit may move toward the destination point via different paths. But, in any case, the mobile direction should be biased towards the direction of its destination. The amount of deviations of a mobile user from its current direction at successive intervals is represented by relative angle changes after each crossroad. The probability distribution of the variation of the mobile direction along its path was taken in accordance with (3). The limits of the distribution were in the range of $[-\pi, \pi)$ with respect to the current direction. The changes in direction occur in time steps that are street-length and speed dependent. The motivation for this choice for mobility modeling 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 (rapid changes of mobile velocity after each crossroad are very unlikely). However, the driver might be on his way to some remote location, possibly involving immediate a change of velocity, for example, he might be looking for a parking space or a close-by address requiring multiple successive velocity changes. The speed of mobile units was chosen to be a realization of a random variable with probability density function as proposed in (7). The choice of such a modeling way seems reasonable since the higher the speed value, the less likely is its occurrence.

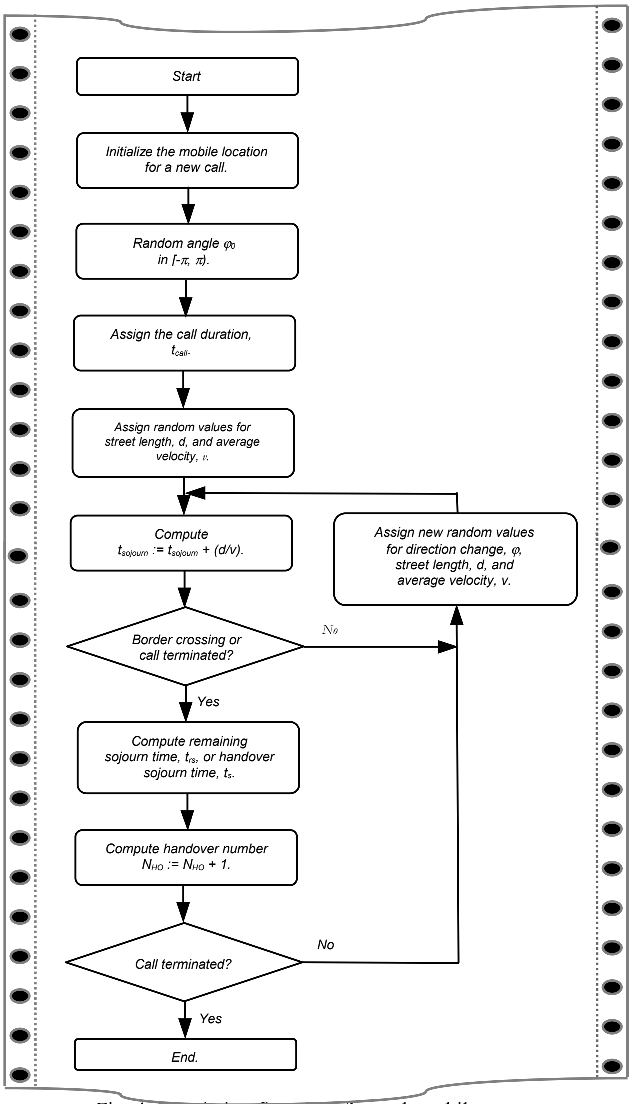

Fig. 4. Simulation flowchart for each mobile user.

As an example, we calculated sojourn times and remaining sojourn times for an ideal hexagonal cell with r =500m situated in the city center of Vienna (Fig.5). Only ten mobility parameters have to be known for this calculation: $p_{0°} = 0.785$, $p_{90°} = 0.085$, $p_{-90°} = 0.125$ (i.e., right turns are more frequent than left ones), $p_{180} = 0.005$, $\sigma_\varphi = 0.125\pi$, $\overline{d}$ =100m, $p_{mr} = 0.56$, $\overline{v} = 10$ km/h, $\overline{v}_{mr} = 40$ km/h, $\sigma_v = 10$ km/h. These parameters had been determined by analyzing the Vienna city map and by observing local traffic. The sojourn times were fitted to a gamma distribution [2], which was found as an analytical solution in [9], and tested this fit by applying the chi-square goodness-of-fit test. Thus, our proposed mobility model passes the first validation test.

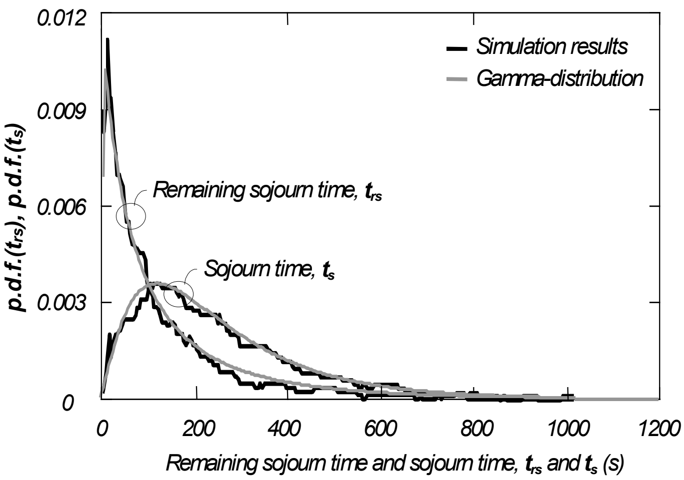

Fig. 5. The p.d.f. of remaining sojourn time and sojourn time for a hexagonal cell.

For further model validation we monitored a real cellular radio network operating with TETRA technology. We considered a cell located in the same area in which our previous simulation had been done. This real cell had a shape and a dimension very close to the hexagonal one (the gray cell in Fig. 6).

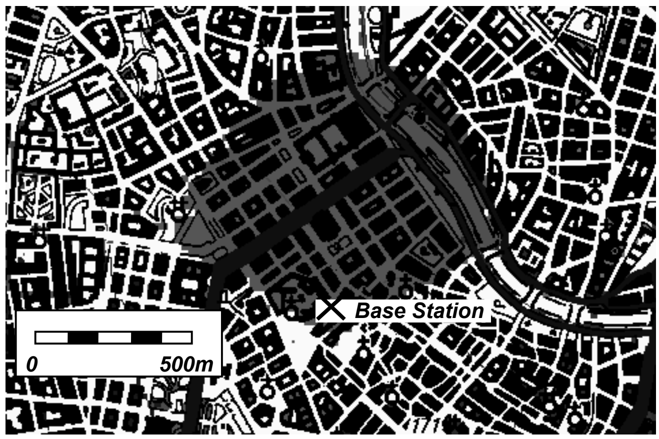

Fig. 6. A sectored cell of the real cellular TETRA network in the city center of Vienna, Austria

The mean and the variance of sojourn time and remaining sojourn time, collected by observing the mobility behavior of real users in the cell of Fig.6 are shown in Table 1 under "Measurement". The statistics of these measured real sojourn times shows excellent agreement with the results of the previous simulation (”Simulation Statistical Model” in Table 1).

Tab. 1. The sojourn times statistics obtained by simulation and measurement on a real cellular radio network

		Simulation Statistical Model	Measurement	Simulation Pattern Tracing
Sojourn Time, t_s	$\overline{t_s}$,(sec)	197.6	205.3	219.7
	σ_{ts} ,(sec)	14.3	12	13.2
Remaining Sojourn Time, t_{rs}	$\overline{t_{rs}}$,(sec)	102.3	98.5	95.6
	σ_{trs} ,(sec)	11.7	9.6	12.1

As a still further test, we created a large and complex database along the considerations in [8] that contained the street network within the real cell and all parameters related to the users´ movement behavior. Then by using a street pattern tracing software tool similar to the one described in [11] and [12], we calculated the sojourn times statistics again. The data obtained in this way (“Simulation Pattern Tracing” in Table 1) confirmed the validity and accuracy of our mobility model. As the creation of such a database is very time consuming, because of the large number of parameters that are difficult to obtain, it makes sense to use it for validation, but not for planning of a real cellular network.

IV. Mobility and Teletraffic-Models Integration

This section discusses the integration of models used for the mobility behavior and the teletraffic statistics. The assumptions made for the teletraffic statistics are classical. Namely, the total call duration is taken to be exponentially distributed with *1/* $_c$ as mean call duration. The arrival of new calls is assumed to be a Poisson process with parameter λ_c as mean arrival rate. We assume that the total service time and the terminal motion are independent, i.e., the vehicle motion is taken to have no influence on the call duration. This ignores the possibility that people blocked in traffic jams might have longer communication times than the typical customer.

In order to model various scenarios of user mobility and teletraffic using our mobility model we propose the procedure of Fig. 7. The objective of the integrated simulation environment is to generate sufficient data to examine the boundary crossing probabilities and other related parameters as a function of cell size and shape, mobile user behavior and geographical environment. . Thus by computer simulations of terminals that are allowed to move freely with randomly varying velocities and directions within realistic environments we obtain statistical estimates of the cell boundary crossings and all other related parameters. In order that this simulation model can be used in a variety of tasks, flexibility is provided in terms of its inputs and outputs, A deeper and more detailed description and presentation of various simulation results and implementations can be found in [13].

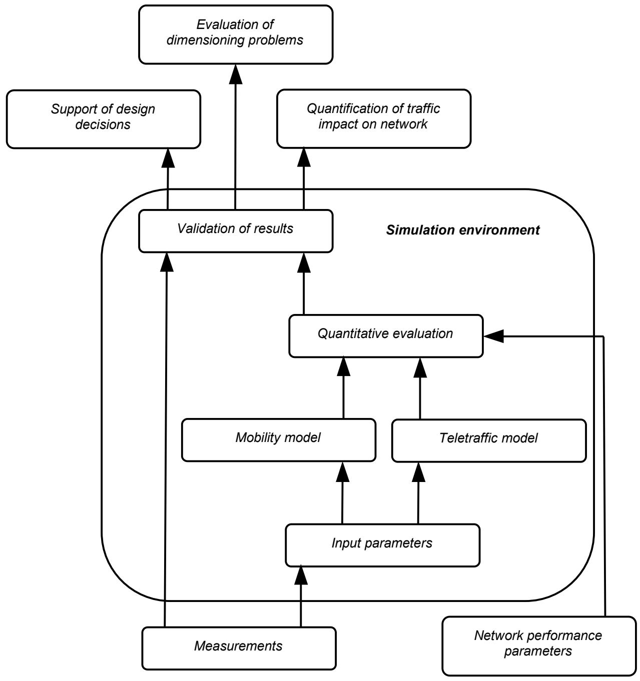

Fig. 7. Integrated simulation environment.

V. Conclusions

We propose a mobility modeling approach for vehicle-borne terminals in urban environments. It accounts for arbitrary urban street patterns and realistic terminal movements by a limited number of parameters that can be easily measured or derived from city

The analytically defined mobility model enables computer simulations of cell sojourn time distributions for arbitrary cell shapes. In accordance with previous, analytical calculations we found that the cell sojourn times follow the generalized gamma distribution. Further validation, independently via a street pattern tracing software tool and via measurements taken in a live cellular network, confirmed the model accuracy.

The major advantages of the model are: *a*) the simple closed form solutions, *b)* its independence from the applied radio resource management scheme, and *c*) its accuracy. Our method incorporates all the above mentioned features. From the time it takes a busy mobile user to leave a cell area, a core result when applying our model, the cell border crossing rate, the handover rate, and the channel holding time within a cell follow immediately. As such, our model can serve as a basis for the whole range of design aspects of macrocells in third-generation mobile radio systems (e.g., location and paging area planning, handover strategies, cell layout, channel assignment schemes).

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Plamen I. Bratanov (M'85)
Plamen I. Bratanov was born in Gorna Orjahovitza, Bulgaria, in 1968. He received the Dipl.Ing. and Dr.techn. degrees (with highest honors) from the Technische Universität Wien (TU Wien). In 1999, he was appointed Associated Professor of Radio Propagation and Antenna Technique at the Alfonso X El Sabio Universidad, Madrid, Spain.
Since January 2000, he has been with the Information and Communication Networks Department of Siemens AG Österreich. His research interests include professional mobile communications and applications, radio network planning and optimization, and WLAN applications. From September 2000 to February 2002, he was a visiting professor of Telecommunications at Fachhochschule Joanneum, Graz, Austria.

Ernst Bonek (M'73, SM'85)
Ernst Bonek was born in Vienna, Austria, in 1942. He received the Dipl.Ing. and Dr.techn. degrees (with highest honors) from the Technische Universität Wien (TU Wien). In 1984, he was appointed Full Professor of Radio Frequency Engineering at the TU Wien. His field of interest is mobile communications at large. Recent contributions concern smart antennas, the characterization of mobile radio channels, and advanced antennas and receiver designs. Altogether, he authored or co-authored some 160 journal and conference publications. He holds several patents on mobile radio technology. He co-authored the book “Data Transmission over GSM and UMTS” by Springer Verlag, and co-edited “Technology Advances in UMTS” by Hermes Penton Publications.
From 1985 to 1990, he served the IEEE Austria Section as a Chairman. From 1991 to 1994 he was a council member of the Austrian Science Fund, acting as speaker for engineering sciences. From 1996 to 1999 he served on the Board of Directors of the reorganized Post and Telekom Austria. He participated in the European research initiative COST 259 as chairman of the working group on Antennas and Propagation, and continues to serve in this position in COST 273. In URSI, he is presently chairman of Commission C “Signals and Systems”. He is an Area Editor of "Wireless Personal Communications".