Subscriber Mobility Modeling in Wireless Networks

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In this paper, a simplified model for user mobility behavior for wireless networks is developed. The model takes into account speed and direction of motion, the two major characteristics of user mobility. A user mobility simulation based on the model is developed, and its results are compared with those in published work. The transient performance metrics of a mobile network are analyzed in terms of trajectory prediction, mean location update rate, and new/handoff call residence time distribution. The proposed mobility model yields results that match very well with those obtained from previously reported complex mobility models.

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1. INTRUDCTION

The challenge of supporting rapidly increasing number of mobile subscribers, while constrained by limited radio spectrum, is being met through increasingly smaller radio cell sizes. However, this results in increased signaling for location management procedures, which reduces the bandwidth available for user traffic, as well as additional transmission and processing requirements on the mobile network. The fundamental procedures that make up the basis for location management are location updates and pages. At one extreme, the location of a subscriber is maintained on a per cell basis. Whenever the mobile terminal moves to a new cell, which may happen very frequently in case of an automobile-mounted mobile terminal, a location update is triggered. This is clearly inefficient in terms of bandwidth and base station processing power usage. However, paging messages need only be sent to one cell, since the exact location of the subscriber is known. At the other extreme of location updating, all the cells in the network belong to one location area. In this case, location updates are not required at all but, for every incoming call, the network must page every cell. This approach is also unsatisfactory due to high paging traffic processing.

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To improve the situation described above, different location management techniques have been proposed to reduce the signaling required to locate any active subscriber on the network [Cho 1994;, Hong et al. 1986]. All such techniques make use of subscriber mobility models to determine the cells where the subscriber is most likely to be located. Mobility models also play an important role in examining different issues involved in wireless mobile networks such as handover, offered traffic, dimensioning of signaling network, user location update, paging, and multi-service provider network management.

In the general case, a mobility model should take into consideration changes of both speed and direction of a mobile terminal. Since the moving direction and speed of a mobile terminal are both random variables, the path of a mobile terminal is a random trajectory. Tracing this trajectory requires a systematic formulation of geometrical, speed and time relations that govern the complex problem of random movement [Liu et al. 1998]. A review on the available literature on this subject reveals that Hong and Rappaport [Hong et al.1986] modeled the mobility with random direction motions in two-dimensional environments. Cho [Cho 1994], studied the effect of terminal mobility in rectangular shaped urban micro cellular systems, and Kim et al. Kim et al. [2000] estimated the number of handoffs in three-dimensional indoor environments. However, these studies were mainly concerned with the problems of handoff as opposed to location management. Markoulidakis et al. [1997] proposed a mobility model based on the transportation model. This model generalizes the mobility behavior of people, hence making it difficult to use the model to study mobility management procedures in a system. Therefore, the model is only suitable for planning purposes. Zonoozi and Dassanayake [1997] proposed a mobility model, that takes into account most of the possible mobility-related parameters. Pollini et al. [1995] evaluated the signaling traffic volume for mobile and personal communications. They [Pollini et al. 1995] considered the simple terminal mobility model and evaluated the performance of mobile networks in terms of the mean number of location updates or handoff calls at steady state. However, terminal mobility behaviors can vary according to time periods. For example, during an office-going hour, most of the mobile users move from home to offices, and they return home from their offices during the office closing-hour. Mobility management traffic also varies according to the users' initial positions. Therefore, characterization of mobility management traffic in the transient period is sometimes more important than that of steady-state. Most models proposed in the above-cited literature are complicated, and require a lot of computing resources and time, making them unsuitable for real-time purposes. There is also a tendency of working backwards, that is, mobility attributes such as velocity or the cell residence time are assumed to follow a particular distribution without any real-life data used to justify the assumptions.

The focus of this paper is the proposal of a simple but yet realistic mobility model for wireless networks. The model takes into account the two major characteristics of user mobility, namely, randomly changing speed and randomly changing direction. The simplicity of the proposed model makes it suitable for use in real-time simulation situations. The model produces reliable results because at every moment in time, it considers four major mobility attributes: direction, position, speed and acceleration. Unlike previous work, no particular distribution is assumed for any of the attributes of mobility or the associated network performance metrics. Therefore, the model is based on the basic principles of mobility. A user mobility simulation based on the model is developed, and the transient performance metrics of a mobile network are analyzed in terms of trajectory prediction, mean location update rate, and new/handoff call residence time distribution.

The outline of this paper is as follows. In Section 2, the structure of location areas of mobile networks and the description of terminal mobility are introduced. The section also deals with the analysis of trajectory prediction, mean location update rate, and new/handoff call residence time distribution. Section 3 covers the performance evaluation of the proposed mobility model, and the results obtained are compared with those in published literature. Finally, Section 4 presents the main conclusions.

2. PROPOSED MOBILITY MODEL

In this paper, the following assumptions are made for computational and geometrical simplicity.

- A1) Square cell shape, each cell is of size d
- A2) Each location Area (LA) has a square shape of size D.

Figure 1 shows an example of the arrangement of cells and LAs in a given service area. First note that the behaviors of mobile users can vary according to time periods in a day. For example, during the office-going hour, most mobile users move from their homes to offices, while during the office-closing hour the users move from offices to their homes.

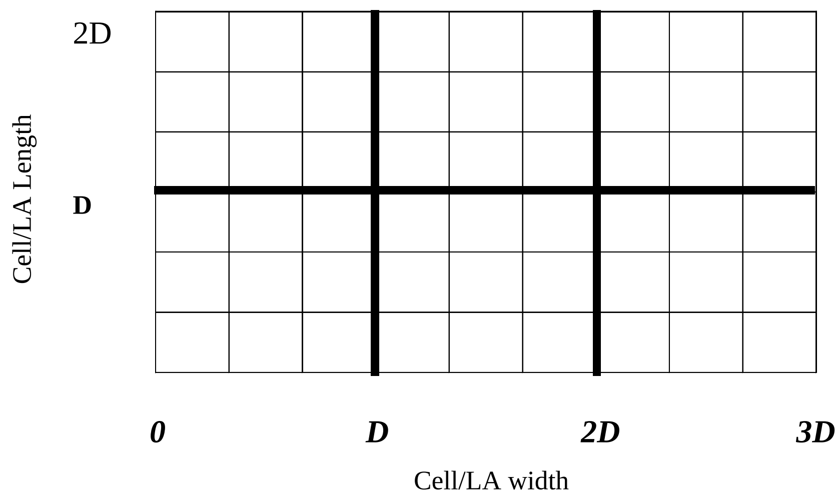

Figure 1. The assumed wireless service area

However, some mobile users (for example, salesmen) move from place to place during the daytime. Based on the foregoing, user mobility is modeled considering these user behaviors, as reflected in the following assumptions:

- A3) Movement direction changes occur after a fixed time interval.
- A4) Mobile users change their direction with probabilities p_x, q_x, p_y and q_y for forward, backward, up and down directions, respectively, where, $p_x + q_x + p_y + q_y = 1$.
- A5) The acceleration of a mobile user is a random variable that is correlated in time.

Assumption A4) follows from the assumed square shape for cells and location areas.

2.1. Trajectory Prediction

In predicting the trajectory of motion for a user, the first step is to specify the probabilities p_x, q_x, p_y and q_y. Let *(v, w)* denote the current location of a user whose destination location (selected randomly in the service area) is denoted by *(i, j)*. Expressions for calculating the probabilities p_x, q_x, p_y and q_y of selecting directions are given in Table 1. These expressions are derived assuming knowledge of user destination, and that users take the shortest route to destination. Secondly, the probability distribution takes into account the fact that some users may choose to take a longer route to the destination. The four moving directions, namely; forward, backward, up and down are boundaries to four possible quadrangles into which a user may move. To take the shortest distance to destination, the user must move in a direction whose *x* (i.e., forward or backward) and *y* (i.e., up or down) components are in the same directions as the two moving directions that make up the boundary into which the destination coordinates are located. For example, if $v > i$ and $w > j$, moving in forward or up directions means moving further away from the destination. Hence, the user must move, with a high probability, in directions with backward and down components in order to reach the destination. In other words, the forward and upward moving directions have small moving probability which we assume to be equal, that is, $p_x = p_y$. By the total probability theorem and from Assumption A4:

$$p_x = p_y = 0.5\left[1-\left(q_x + q_y\right)\right] \tag{1}$$

Equation (1) is the entry in row 1, column 2 of Table 1. The other entries in rows 2 to 4 of column 2 corresponding to other possible user's current location relative to the destination are derived in the same manner. It now remains to derive the expressions for q_x and q_y. First note that dx and dy are the respective x and y components of the distance between a user's current location and the destination. Now, if $dx > dy$ the user must give a higher priority to moving in the direction of the longer of the two distances. Therefore, $q_x > q_y$ whose expressions (row 1, column 3 of Table 1) are given by:

$$q_x = 0.4 + 0.3\left[\left(dx - dy\right)/dx\right] \tag{2a}$$

$$q_y = 0.4 - 0.2\left[\left(dx - dy\right)/dx\right] \tag{2b}$$

An explanation of eqn. (2) is given as follows: Based on the condition that $q_x > q_y$, the multiplicative factor in the second term on the right hand side of eqn. (2b) is not equal to that of eqn. (2a) and this is intended to address the fact that priority given to one moving direction is not always equal to the resentment towards another direction. If at some moment during the movement dy becomes longer than dx, then q_y and q_x will trade places, as shown by the entries in row 2, column 3 of Table 1. The other entries in rows 3 to 8, column 3 of Table 1 are developed using similar reasoning. The foregoing demonstrates the variation of the probabilities representing user mobility behavior with respect to user's current location relative to the destination. In addition, the probabilities can also vary according to time periods. For example, during the office-closing hour, a user generally returns home. Therefore, the probability of selecting a moving direction towards his/her home is higher than those of the other directions.

Table 1: Moving direction selection probabilities of a user at location *(v,w)* with destination location *(i,j)*

Current Location	Moving Direction Selection Probabilities		Condition
(v,w) for *v>i* and *w>j*	$p_x = p_y = 0.5[1-(q_x+q_y)]$	$q_x = 0.4 + 0.3[(dx-dy)/dx]$ $q_y = 0.4 - 0.2[(dx-dy)/dx]$	*dx>dy*
		$q_y = 0.4 + 0.3[(dy-dx)/dy]$ $q_x = 0.4 - 0.2[(dy-dx)/dy]$	*dy>dx*
(v,w) for *v>i* and *w<j*	$p_x = q_y = 0.5[1-(q_x+p_y)]$	$q_x = 0.4 + 0.3[(dx-dy)/dx]$ $p_y = 0.4 - 0.2[(dx-dy)/dx]$	*dx>dy*
		$p_y = 0.4 + 0.3[(dy-dx)/dy]$ $q_x = 0.4 - 0.2[(dy-dx)/dy]$	*dy>dx*
(v,w) for *v<i* and *w>j*	$p_y = q_x = 0.5[1-(q_y+p_x)]$	$p_x = 0.4 + 0.3[(dx-dy)/dx]$ $q_y = 0.4 - 0.2[(dx-dy)/dx]$	*dx>dy*
		$q_y = 0.4 + 0.3[(dy-dx)/dy]$ $p_x = 0.4 - 0.2[(dy-dx)/dy]$	*dy>dx*
(v,w) for *v<i* and *w<j*	$q_y = q_x = 0.5[1-(p_x+p_y)]$	*px = 0.4 + 0.3[(dx-dy)/dx]* *py = 0.4 – 0.2[(dx-dy)/dx]*	*dx>dy*
		py = 0.4 + 0.3[(dy-dx)/dy] *px = 0.4 – 0.2[(dy-dx)/dy]*	*dy>dx*

Note: In the Table, dx =\| v-i \| , dy = \| w-j \|

Having specified the movement probabilities, the next step in predicting the trajectory of motion is to derive the dynamic equations for continuous-time movement, presented as follows. In two-dimensional Cartesian coordinates, subscriber movement can be described by a vector equation of the form $\mathbf{R}\left(t\right) = \left[x(t), v_x(t), y(t), v_y(t)\right]$ where *x(t)* and *y(t)* represent the position at time t, and $v_x(t)$ and $v_y(t)$ represent the relative speed along the x and y direction during the time interval dt between times *t* and *t+dt*. Furthermore, let $\mathbf{A}\left(t\right) = \left[a_x(t), a_y(t)\right]$ denote the two-dimensional random acceleration vector. From Assumption A5), it follows that if a mobile is accelerating at a rate **A***(t)* at time *t*, it continues to accelerate at this rate for a small time interval *dt*. Hence, the relative movement in the *x* and *y* directions is described using the equations of motion at constant acceleration for every small time interval *dt*. The velocity in the *x* direction, $v_x(.)$, is given by:

$$v_x(t + dt) = v_x(t) + a_x(t)dt \tag{3}$$

The distance S_x covered in the *x* direction during the time interval *dt* is determined by the equation:

$$S_x(t) = \begin{cases} \dfrac{\left[v_x(t+dt)\right]^2 - \left[v_x(t)\right]^2}{2a_x(t)}, & a_x(t) \neq 0 \\ v_x(t)dt \quad , & a_x(t) = 0 \end{cases} \tag{4}$$

Let *P(x)* denote the probability of the direction selected along the *x* direction. That is, *P(x)* equals p_x or q_x for the forward or backward direction, respectively. The expected distance covered in the *x* direction, $E\left[S_x(t)\right]$, is then given by:

$$E\left[S_x(t)\right] = P(x)S_x(t) \tag{5}$$

By replacing *x* with *y* in eqns. (3) to (5), the corresponding equations of motion in the y direction are obtained. The expected distance covered during time interval *dt* can then be written as:

$$E\left[S(t)\right] = \begin{cases} E\left[S_x(t)\right] \\ E\left[S_y(t)\right] \end{cases} \tag{6}$$

Equation (6) is the main result for predicting the trajectory of a mobile user during the time interval *dt*.

Location Update. Location update (LU) is the process by which a mobile terminal (MT) makes its position known to the network. This is performed either by zone, distance or timing method. The zone method is considered in this paper. Zone based location updating requires splitting of the whole service area into zones called location area (LA) as shown in Figure 1. Location updating is performed every time the MT crosses the LA boundary. Mobility and LA size are related to LU through the location update rate, $\lambda_{LU}(t)$, given by:

$$\lambda_{LU}(t) = \frac{E\left[S(t)\right]}{D} \tag{7}$$

where *E[S(t)]* is given by eqn. (5). Clearly $\lambda_{LU}(t)$ is time-dependent**.**

2.2. Handoff

When a mobile user engaged in conversation travels from one cell to another cell, the call must be transferred to the new base station to prevent abrupt termination of the call. This ability for call transfer is referred to as handoff in mobile cellular systems. Handoff is related to mobility and cell size through a parameter called handoff rate, $\lambda_{HO}(t)$, and is written as

$$\lambda_{HO}(t) = \frac{E\left[S(t)\right]}{d} \tag{8}$$

Therefore, the expected handoff rate $E\left[\lambda_{HO}(t)\right]$ is then given by

$$E\left[\lambda_{HO}(t)\right] = P_{HO}\lambda_{HO}(t) \tag{9}$$

where P_{HO} is the handoff probability associated with either the new call residence time or handoff call residence time. New call residence time is defined as the length of time that a call originating from a cell stays in that cell before crossing into another cell. In other words, handoff is initiated when the call duration exceeds the new call residence time. Similarly, handoff residence time is the time a handoff call stays in a cell before crossing into another cell. That is, handoff of a previously handoff call is triggered when the call duration is greater than the handoff call residence time. The next step in the analysis is to calculate the expressions for the handoff probability associated with new call and handoff call residence times.

2.3. Handoff Probability due to New Call Residence Time

The probability density function for the new call residence time, (t), is given by [3]:

$$\alpha(t) = \begin{cases} \dfrac{8R}{3\pi V_m t^2}\left\{1-\left[1-\left(\dfrac{V_m t}{2R}\right)^2\right]\right\}^{\frac{3}{2}}, & 0 \le t \le \dfrac{2d}{V_m} \\ \dfrac{8r}{3\pi V_m t^2}, & t > \dfrac{2d}{V_m} \end{cases} \tag{10}$$

where V_m and R are the speed and cell radius respectively d is the cell diameter which we approximate to the cell length d in the proposed mobility model. Equation (10) is derived under the assumptions of constant speed and one direction of movement in an hexagonal-shaped cellular structure. We adopt eqn. (10) in this paper but replace the constant speed with mobile expected speed and also select the cell size assuming the square cell area is equal to the hexagon area. The handoff probability due to new call residence time is determined by numerical integration of the modified version of eqn. (10).

2.4. Handoff Probability due to Handoff Call Residence Time

By definition, a handoff call is itself handed off if the call duration, T_{call} exceeds the handoff call residence time, T_{res}. The handoff probability due to handoff call residence time, b is given by:

$$\beta = Pr\left\{T_{call} > T_{res}\right\} \tag{11}$$

It turns out that both T_{call} and T_{res} are random variables so that is determined from knowledge of their respective distribution functions. Voice call duration is assumed, in most analysis, to be exponentially distributed whereas the distribution for cell residence time is strongly dependent on the mobility model [Fang et al. 2002]. Since our proposed mobility model makes no assumption regarding cell residence time, eqn. (11) cannot be used. Instead, in this paper, we assume that the probability density function (pdf) for handoff call residence time is a scaled version of that for new call residence time where the scaling factor M is greater than unity. A scaling factor greater than unity is selected to minimize the number of interruptions experienced by previously handed off calls.

3. PERFORMANCE EVALUATION

In this section, performance of the proposed mobility model is evaluated using Monte Carlo simulation approach making use of the equations derived in Section 2. A number of simulations are carried out to determine how well the simulation tool predicts the cells the user is most likely to cross. Secondly, other mobility parameters are deduced from the simulations. Simulation results are generated assuming the following network and mobility parameter values:

- Size of service area: 12 km x 12 km
- Cell of square shape, d = 4 km
- Four cells per location area
- Acceleration is selected randomly in the range: [-5, 5] m/s^2.
- Speed is selected randomly in the range: [30, 60] km/hr.
- Scaling factor for pdf of handoff call residence time, M: 2

Simulation results are discussed under appropriate sub-headings.

3.1. Trajectory Prediction

Given the initial location and the destination of a subscriber, the model was simulated several times to determine the subscriber trajectory. Figure 2 shows the predicted trajectory in three of the simulation runs. Figure2 is useful for cellular network design because it predicts the cells that a mobile terminal in motion will pass through, so that resources are reserved to serve the MT in case it arrives at the cell boundary while engaged in a call.

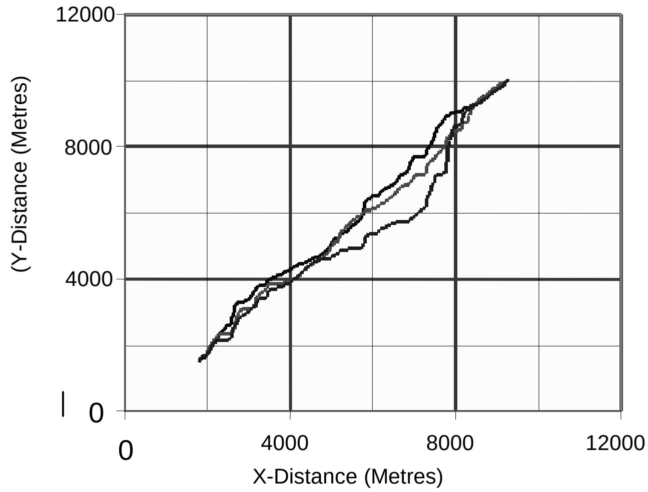

Figure 2. Predicted motion trajectory for three mobility simulations

3.2. Location Update Rate

Figure 3 shows the calculated location update rate plotted as a function of the location area (LA) size. The results indicate that location update rate can be modeled as a decaying exponential function. Also shown in Figure 3 is the calculated location update rate based on the fluid flow mobility model [Thomas et al. 1988]. There is very good agreement between the predicted location update rates by the two models.

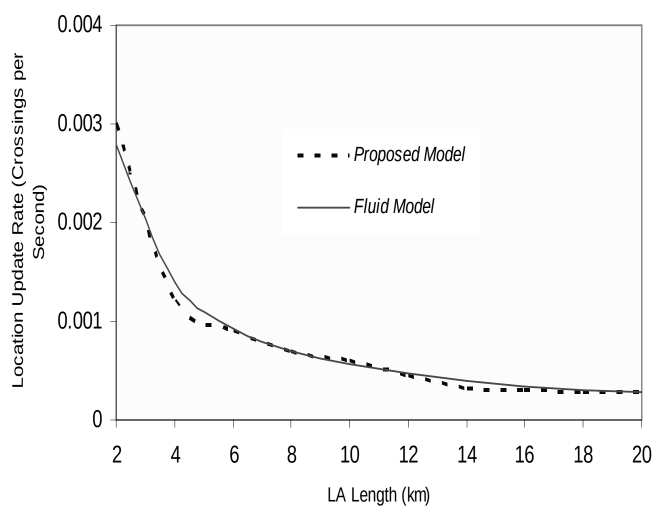

Figure3. Variation of location update rate with LA size

3.3. Handoff Rate

As a prelude to presenting the calculated handoff rate, we first show in Figure 4 the probability distribution for new call residence time obtained using our simplified mobility model compared with that of a previously proposed model by Zonoozi and Dassanayake [Zonoozi et al. 1997]. The results presented in Figure 4 are generated for a cell size *d* of 4 km. For new call residence times less than 2.5 minutes, the proposed model predicts a higher handoff probability than that of Zonoozi and Dassanayake's model where the new call residence time is assumed to have the gamma distribution function [Zonoozi et al. 1997]. It is interesting to find that, beyond new call residence time of 2.5 minutes, our results agree with those in Reference [Zonoozi et al. 1997], that new call residence time follows the gamma distribution.

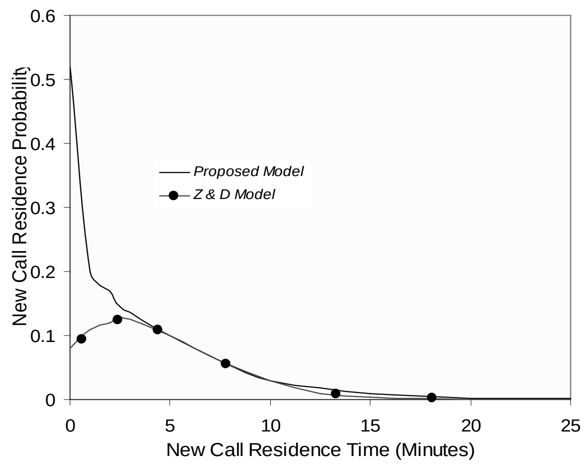

Figure 4. Probability distribution for new call residence time

Figure 5 depicts the average number of handoffs per call determined by the proposed mobility model. Results obtained with Zonoozi and Dassanayake's [Zonoozi et al. 1997] and fluid flow [Thomas et al. 1988] models are shown for comparison. In the calculations, the average call duration $\overline{T}_{call}$ is assumed to be 120 seconds. The results shown in Figure 5 assume the worst case scenario that all moving mobile terminals are engaged in a call. It is seen that the handoff rates predicted by the proposed mobility model are roughly equal to those predicted by the fluid flow model but are slightly higher than those predicted using Zonoozi and Dassanayake's model. Lower handoff rate is achieved with Zonoozi and Dassanayake's model because the model predicts a lower average speed than that obtained with the proposed model.

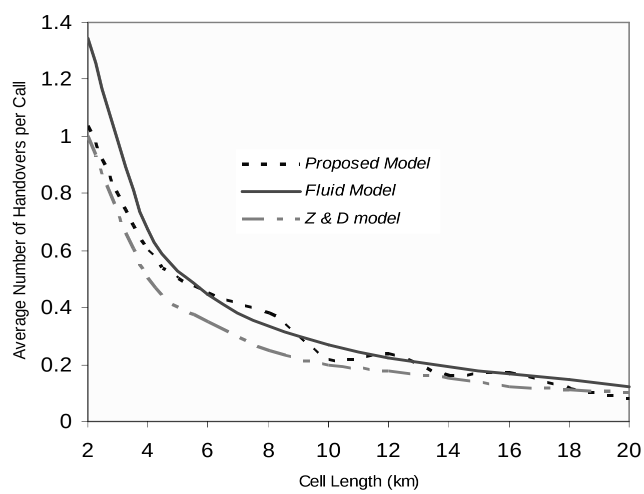

Figure 5. Variation of average number of handovers with cell size
(assumed average call duration = 120 secs.)

4. CONCLUSIONS

A simple mobility model that does not assume any specific distribution for the underlying mobility parameters is proposed. The mobility model is based on user speed and direction of motion selected according to user behavior. Analytical expressions are derived for the expected distance traveled as function of time along with the expressions for network performance metrics related to mobility management. A Monte Carlo simulation of the proposed mobility model was conducted and results are compared with those from previous work in the published literature. It is concluded from the results that location update rate can be represented by a decaying exponential function, and the new call residence time (exceeding 2.5 minutes) follows the gamma function. Agreement of the results from the simplified model demonstrates its usefulness as a viable candidate for location management planning in practical mobile radio networks.

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