USER MOBILITY AND CHANNEL HOLDING TIME MODELING IN MICROCELLULAR SYSTEMS

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Abstract

In this paper, we provide a mathematical formulation to describe the random mobility of users in cellular radio systems. With this, we can also study the cell sojourn time (CST) distribution as well as the channel holding time (CHT) distribution. The study on user mobility enables to improve the resource management in cellular radio systems. We provide a versatile analysis tool that improves the limit of simplified analyses.

Key Words

Cellular radio system, channel holding time, mobility modeling

1. Introduction

In cellular radio telecommunication systems, the channel utilization is of great importance because it is resource management problem in view of economics [1-5],[8]. There are a number of works on the area of radio channel utilization. For the efficient radio channel utilization, both efficient algorithms and performance analyses of the algorithms are needed. Hence the relevant performance analysis is very important for system design and dimensioning, as much as for frequency allocation [1].

Unlike the early second generation of wireless communications, multimedia traffic will be served in the next generation. And the quality of service (QoS) parameters are needed to be evaluated under the more exact consideration to guide the system design, dimensioning, and architecture for the next generation multimedia services. Therefore, versatile models for more exact analysis of wireless communication systems are essential in the next generation. With the mobility model, we can also study the distribution of the channel holding time in cellular radio systems.

There have been many simplified analytical models and simulation models to approximate user mobility in cellular radio systems. Previous works in this area have shown that under the simplifying assumptions of constant-speed subscribers with randomly chosen fixed direction, the negative exponential closely approximates the CHT distribution [1], [3]. For the effective design and management of the next generation wireless communication systems which serve multimedia traffic, we should construct a versatile model and newly evaluate the QoS parameters such as carried load, handoff failure, and probability of blocking with a relevant CHT distribution.

We assume that there are two classes of users: "walking user" and "mobile user". The mobility pattern of mobile user is much more subject to the layout of roads than that of walking user. Unlike the simplified models, the consideration of site layout may better explain the mobile user mobility. Also, it may explain that walking user mobility, because we have a tunable mobility parameter in the model, which can be estimated through statistical analysis. The consideration is more significant as the cell size is smaller. Because the motion of a user on the roads is more sensitive to the number of handoffs as the cell size is smaller, the layout of roads has more significant explanatory power of the CHT distribution as well as the CST distribution. Previous mobility models with the assumption of linear motion of users are very useful in analyzing the cells with highway. Apart from that case, random mobility model is needed in urban microcellular systems. In this paper, we assume rect-linear site layout well known as Manhattan street model so as to analyze the urban microcellular systems. Furthermore, unlike most previous works that assume constant speed and randomly chosen fixed direction [1], we assume that a user would change the speed and direction with some stochastic characteristics. A user moves bearing one of 4 directions and one of two classes of speed levels in the model. Also, the user changes the direction state and speed state after a time unit. This state transition occurs stochastically with some characteristics. These characteristics mean that a fast user will be also fast after a time unit with higher probability and there is a tendency to move straight rather than to change his direction drastically.

This paper provides a practical user mobility model in microcellular systems. For the next generation multimedia and high quality telecommunication services, a versatile and practical mobility model is essential. The model with more significant traffic parameters improves the limit of simplified results.

2. Mobility Model

In general, users have variable mobility. That is, a mobile station (MS) changes the speed and direction continually during a call. We might find the more practical CHT distribution if we built up a model with the variable user mobility. To analyze the mobility, we consider the following three traffic conditions.

2.1 Site Layout

In practice, a mobile user usually moves along the street rather than he may go anywhere. This means that the layout of roads may have explanatory power for the CHT distribution as well as CST distribution. In urban microcellular systems, this explanatory power for CST is relatively greater than in the cellular systems with macro cells because the MS mobility to small cells is more sensitive than that to large cells in terms of the number of handoffs. Let us consider a cellular system with rect-linear site layout. We call a "junction point of two roads" a "lattice" and the distance between a lattice and its neighbors is d. Let us consider a cellular system consists of rectangular cells with side length $\sqrt{2}Ld$. Then there are $4L$ lattices on its 4 sides of cell boundary as shown in Figure 1.

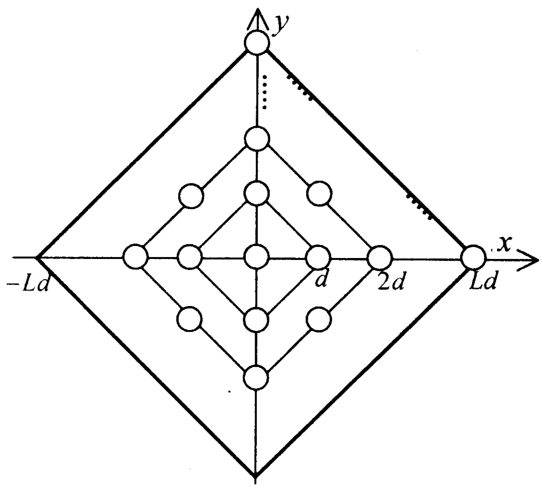


Figure 1. Rectangular cell structure with lattices

We define $L+1$ layer sets where k^{th} layer set has $4k$ lattices for $k=1,\cdots,L$ and 0^{th} layer has one as shown in Figure 1. It is assumed that a call either moves from his current lattice to adjacent one or stops there during a time unit. This means that a call has 2 speed states and 4 direction states defined in the following sections.

2.2 Speed

The speed of users is assumed to have the following properties.

(1) The various speed levels of users are classified into two states:
State 0 – speed is very low or a user stops,
State 1 – a user moves fast.

(2) The process of speed state has Markov chain property and the transition probability matrix is given by $S=\begin{bmatrix} s_{00} & s_{01} \\ s_{10} & s_{11} \end{bmatrix}$ where each element of S means the probability that a call will be in state j given that his current state is i and $0 < s_{ij} < 1$ for $\forall i,j$. In matrix S, $s_{i0}+s_{i1}=1$, for $i=1,2$ and the equilibrium probability vector, denoted by (φ_0,φ_1), is $\left(\frac{s_{10}}{s_{01}+s_{10}},\frac{s_{01}}{s_{01}+s_{10}}\right)$ [9].

2.3 Direction

(1) A user has 4 direction states $\{1,2,3,4\}$ as shown in Figure 2.

(2) Each state transition occurs at the lattice. And the candidate directions are:
no change with probability r_0;
turning left (right) with probability r_1 (r_1);
turning back with probability r_2,
where $r_0+2r_1+r_2=1$.

This means that users move linearly if and only if $r_0=1$.

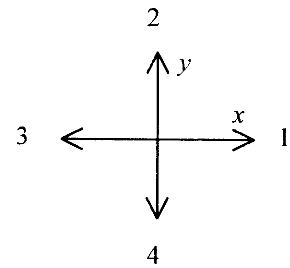


Figure 2. Moving direction states

3. Cell Sojourn Time

3.1 Cell Sojourn Time Distribution

To find the modeled CST distribution, we need some notations. Let the random variable X denote the number of time units till a random user exits his current cell. And X_n denotes the number of time units till a user exits its current cell given that he is in n^{th} layer set. Let $a_n(k)$ be the probability of $X_n=k$ given that the previous speed state is 1. Also, let $b_n(k)$ be that of $X_n=k$ given that the previous speed state is 0. Then we can find the following recurrence relation through counting of lattices (in Figure 1) in a certain layer set and conditioning of probability:

$$A(k)=CA(k-1) \text{ for } k>1$$

where

$$A(k)\equiv\left[a_0(k) \ \cdots \ a_L(k) \ b_0(k) \ \cdots \ b_L(k)\right]^T$$

and C is a $2(L+1)$ dimensional square matrix. From the recurrence relation, we can draw out

$$A(k)=C^{k-1}A(1).$$

C is diagonalizable if it has $2(L+1)$ independent eigenvectors. We consider this case in this paper. C is not diagonalizable for some special cases depend on transition probability matrix of speed state S which we can rarely experience.

If C is diagonalizable, we can easily get

$$A(k)=Q\Lambda^{k-1}Q^T A(1)$$

where $\lambda_0,\lambda_1,\cdots,\lambda_{2L+1}$ are the eigenvalues of C, Q is the orthonormal matrix of which columns are the eigenvectors corresponding eigenvalues of C, and

$$\Lambda = \begin{bmatrix} \lambda_0 & & \\ & \ddots & \\ & & \lambda_{2q+1} \end{bmatrix}.$$

To find the CST, another two notations are also needed. Let

$$T = \begin{bmatrix} \varphi_1 & & \varphi_0 & & \\ & \ddots & & \ddots & \\ & & \varphi_1 & & \varphi_0 \end{bmatrix}_{(L+1)\times(2L+2)}.$$

and u^T is a vector of weighting factors of the laysers, then the cell sojourn time distribution is

$$P(X = k) = u_H^T TQ\Lambda^{k-1}Q^T A(1).$$

Hence $P(X = k)$ is of the form

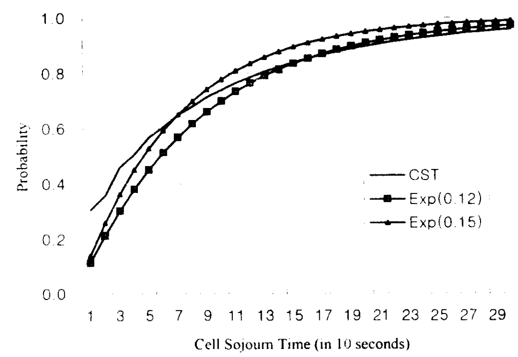
$$\sum_{i=0}^{2L+1} v_i \lambda_i^{k-1}$$

for some real values $v_0, \cdots, v_{2L+1}$. If C is diagonalizable, the equation $\det(C - \lambda I) = 0$ has $2(L+1)$ distinct roots $\lambda_0, \lambda_1, \cdots, \lambda_{2L+1}$. Hence we can easily conclude that the CST in our model is different from any of well-known distributions. u^T described above indicates that users are uniformly distributed in $L+1$ layers. Furthermore, we consider a general case of u^T, denoted by u_H^T, in consideration of handoff calls. Under the assumption of uniformly distributed users, new calls will be initiated uniformly and handoff calls will be initiated almost only in $(L+1)^{th}$ layer. Let α be the fraction of the average non-blocked new calls out of the average total number of calls in a cell..

It is clear that the fraction of handoff traffic rate in cell i is not a function of the number of calls in cell i, but a function of the number of calls in the neighboring cells of cell i.

3.2 Numerical Example

In the example, we consider urban CDMA network with rect-linear site layout with mobile users that have random mobility. We take the distance $d = 100m$ (in Figure 1), $r_0 = r_1 = r_2 = 25\%$ and $\alpha = 67\%$. In fact, the number of handoff calls (or the fraction $1-\alpha$) to a cell is determined by the total number of calls and the mobility parameters in the neighboring cells. And the length of a time unit, τ, is taken as 10 seconds. The mean CST is about $7.5\tau = 75$ seconds. The plot shows a CHT distribution from our model with $L = 10, s_{00} = 0.6$, and $s_{11} = 0.9$ comparing with two nearly fitted exponential distributions of which notation in the plot are Exp(0.12) and Exp(0.15). In this example, the cell side length, $\sqrt{2}Ld$, is about $1.4km$ and the mean call holding time is150 seconds and there are 33% call requests due to handoff and 67% due to new call. A moving user will be also moving with probability 90% and stop with 10%. Also, the average speed of a random user is $(\varphi_0 0 + \varphi_1 d)/\tau = 8m/\sec$. In steady state, a user stops with probability 20% and moves with 80% because $\varphi_0 = 0.2$ and $\varphi_1 = 0.8$. In this plot, we find "cross over points" between our CST distribution function and the two exponential distribution functions.



Also, it can be found that the exponential distribution with inverse mean 0.12, Exp(0.12), explains well the calls with relatively long CHT, while the exponential distribution with inverse mean 0.15, Exp(0.15), explains well those with relatively short one. From this, we can see that there is trade-off because an exponential distribution that explains well the calls with long CHT does not explain well those with short one, and vice versa.

4. Channel Holding Time

4.1 Channel Holding Time Distribution

Let Y be a geometrically distributed random variable (with inverse mean p) meaning the number of time units corresponding to "call holding time" and W be the random variable meaning the number of time units corresponding to "channel holding time". We assume that both normal call completion and abnormal termination (due to power-control outage, and so on) determine the call holding time, Y. And it stands to reason that assuming that X and Y are independent. At this point we can find the mean path length during a call holding time is $d\varphi_1/p$.

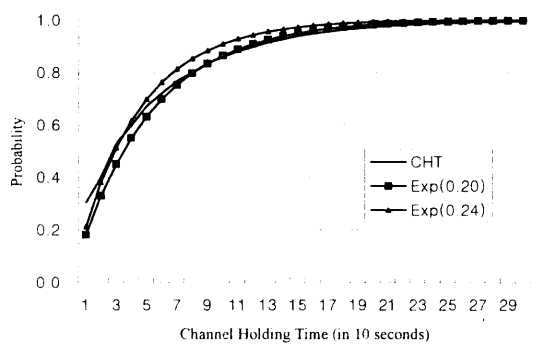
Since a channel holding time by a subscriber in a cell is determined by hanging-up or by handing-off, we can get the following: $W = \min(X, Y)$. Therefore we can find the CHT distribution is as follows:

$$P(W = k) = u_H^T TQ \times \begin{bmatrix} (q\lambda_0)^{k-1}(q + \frac{p}{1-\lambda_0}) & & \\ & \ddots & \\ & & (q\lambda_{2L+1})^{k-1}(q + \frac{p}{1-\lambda_{2L+1}}) \end{bmatrix} \times Q^T A(1)$$

where $q = 1 - p$.

4.2 Numerical Example

We also take the distance $d = 100m$. The plot shows a CHT distribution from our model with $L = 10, s_{00} = 0.6, s_{11} = 0.9$, and $p = 1/15$ comparing with two nearly fitted exponential distributions of which notation in the plot are Exp(0.20) and Exp(0.24). We consider an arbitrary cell i of which side length, $\sqrt{2}Ld$, is about $1.4km$ and the mean call holding time is 150 seconds. The mean CHT is about 46 seconds.



Hence the average number of handoffs per call in cell i is 3.26. This means that the fraction of handoff-out calls in cell i is $\frac{1}{1+3.26} = 23\%$. It is clear that the handoff calls in cell i is not from cell i but from the neighboring cells of cell i. And the mean path length of a user is $d\varphi_1/p = 1.2km$. A moving user will be also moving with probability 90% and stop with 10%. In steady state, a user stops with probability 20% and moves with 80% because $\varphi_0 = 0.2$ and $\varphi_1 = 0.8$. In this plot, we find cross over points between our CHT distribution function and the two exponential distribution functions. Also, it can be found that the exponential distribution with inverse mean 0.20, Exp(0.20), explains well the calls with relatively long CHT,, while the exponential distribution with inverse mean 0.24, Exp(0.24), explains well those with relatively short one. From this, we can see that there exists trade-off because an exponential distribution that explains well the calls with long CHT does not explain well those with short one, and vice versa. These two kinds of disagreements in CHT distribution can be explained by the effect of handoffs. This means that the CST distribution that is different enough from the exponential distribution can directly affect the CHT distribution. This also means that whatever the parameter is, system modeling with the exponential distribution instead of a CHT distribution based on practical traffic situation may bring about some significant errors for both a random call with a long CHT and a random call with short one. Therefore, we can safely conclude that we are able to reduce a fraction of the some errors in analyzing of performance measures such as call blocking probability, handoff failure, and carried load due to using exponential model.

5. Conclusion

This paper has focused on the derivation of a mathematical model for the random user mobility and the distribution of channel holding time in urban microcellular systems in consideration of practical user mobility patterns. And, in this paper the traffic situation is reduced to the assumption of variable user mobility (i.e., variable changes in moving speed and direction in rect-linear street layouts). Under the specified mobility parameters, the distribution of CHT in the model shows disagreement with negative exponential distribution as mentioned earlier. Applications of this kind of practical mobility model, the system design and architecture will be guided effectively in the next generation wireless communications.

References

[1] R. A. Guérin, "Channel Occupancy Time Distribution in a Cellular Radio System," *IEEE Trans. Veh. Technol.*, vol. VT-35, no. 3, pp.89-99, Aug. 1987.

[2] *IEEE Commun. Mag.*, Special Issue on Mobile Commun., vol. 24, Feb. 1986.

[3] Bijan Jabbari, "Teletraffic Aspects of Evolving and Next-Generation Wireless Communication Networks," *IEEE Pers. Commu.*, vol. 3, no. 6, pp. 4-9, Dec. 1996.

[4] B. Jabbari, Y. Zhou, and F. Hiller, "Random Walk Modeling of Mobility in Wireless Networks," *IEEE/VTC* 48th Vehicular Technology Conf., Ottawa, Canada.

[5] M. M. Zonoozi, and P. Dassanayake, "User Mobility Modeling and Characterization of Mobility Pattern," *IEEE J-SAC*, Vol.15, No. 7, pp. 1239-1252, Sep. 1997.

[6] A. J. Viterbi, *CDMA – Principles of Spread Spectrum Communication*, Addison-Wesley, 1995.

[7] F. D. Priscoli and F. Sestini, "Effects of Imperfect Power Control and User Mobility on a CDMA Cellular Networks," *IEEE JSAC*, vol. 14, no. 9, pp. 1809-1817, Dec. 1996.

[8] V. H. MacDonald, "The Cellular Consept," *Bell Syst. Tech. J.*, Vol. 58, pp. 15-42, Jan. 1979.

[9] R. W. Wolff, Stochastic Modeling and the Theory of Queues, Prentice-Hall, 1989.