Mobility Modeling and Traffic Analysis in Three-Dimensional High-Rise Building Environments

Tai Suk Kim, *Student Member, IEEE*, Jae Kyun Kwon, *Student Member, IEEE*, and Dan Keun Sung, *Member, IEEE*

***Abstract*—To efficiently plan future personal communications services, we need to solve various mobility/traffic problems in one-dimensional (1-D), two-dimensional (2-D), and three-dimensional (3-D) micro- or pico-cell environments. Although many users exhibit vertical motion inside elevators in high-rise buildings, there have been no studies regarding cell planning which take into account vertical motion with elevators. In this paper, we extend the previous 3-D indoor mobility modeling by considering the proper boundary conditions on each floor and vertical motions through elevators and modeling mobility in high-rise buildings in order to estimate the number of handoffs. We then propose a blocking probability model with mobility as a traffic model in 3-D indoor environments. Using this model, we can obtain the required number of channels per cell under the given blocking probability constraint. These results can be used in planning the networks of future personal communications services.**

***Index Terms*—Elevator, high-rise building, indoor, mobility, three-dimensional (3-D), traffic.**

I. Introduction

PERSONAL communications service (PCS) is an extension and integration of existing and future wireless communication network features and capabilities, ultimately allowing the general public to make calls to reach anyone, anywhere, and at any time. It is very important to analyze mobility and its effect on traffic in order to implement this PCS.

El-Dolil *et al.* [1] studied a one-dimensional (1-D) mobility problem for highway microcells, and Guerin [2] and Hong and Rappaport [3] modeled mobility and traffic with random direction motions in two-dimensional (2-D) environments, by examining the channel holding time. Foschini *et al.* [4] defined the parameter called *mobility* concerned with mobility, and suggested a traffic model for a given mobility. Meier-Hellstern and Alonso [5] analyzed mobility using a fluid flow model under the assumption that users randomly move. Cho [6] and Kim and Sung [7] suggested a mobility model in 2-D environments by considering turning motions in square-shaped micro- or pico-cell environments. Kim *et al.* [8], [9] modeled three-dimensional (3-D) user movements including vertical motions through staircases in indoor environments and analyzed traffic based on this mobility model by extending a 2-D mobility model [6], [7] and a traffic model with mobility [4].

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T. S. Kim was with the Department of Electrical Engineering, Korea Advanced Institute of Science and Technology, Taejon, Korea, and with Stanford University, CA USA. He is now with Samsung Electronics Company, Korea.

J. K. Kwon and D. K. Sung are with the Department of Electrical Engineering, Korea Advanced Institute of Science and Technology, Taejon, Korea.

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Although many users exhibit vertical motion inside elevators in high-rise buildings, there have been no studies on indoor cell planning which take into account vertical motion with elevators within buildings. Therefore, it is necessary to analyze mobility and investigate the effect of mobility on traffic with multielevators in high-rise buildings.

In this paper, we first model mobility in 3-D indoor environments. We consider some realistic motions in our model. Users move vertically only through elevators, move horizontally on a floor bounded by outer walls, and exit a building and vice versa through a gate. Then, we analyze traffic with mobility in 3-D indoor environments. The number of users in small indoor cells is generally small compared with outdoor cells. Therefore, the number of users per cell heavily varies due to mobility and call arrivals per cell depend on the number of busy users in the cell. We estimate the distribution of the number of users per cell for representing this variation and then calculate the blocking probability with mobility modifying the existing Engset model.

The remainder of this paper is organized as follows. A mobility model in 3-D indoor environments is proposed in Section II. In Section III, we propose a blocking probability model with mobility. Finally, conclusions are given in Section IV.

II. Mobility Model

In order to investigate the effects of handoffs in 3-D indoor environments on future networks, we need to model mobility. In this section, we propose an analytical mobility model in 3-D indoor environments to analyze mobility and then obtain the mean number of handoffs during a call.

A. Mobility Model

We define the following parameters in order to describe a mobility model:

- V horizontal motion speed;
- T call duration;
- X distance between two turning points of horizontally moving users;
- $R_{i,H}$ horizontal cell crossing rate in a floor region including boundary conditions and caused by outer walls on the ith floor;
- $R_{i,V}$ vertical cell crossing rate in an elevator region on the ith floor;
- R_E elevator cell crossing rate;

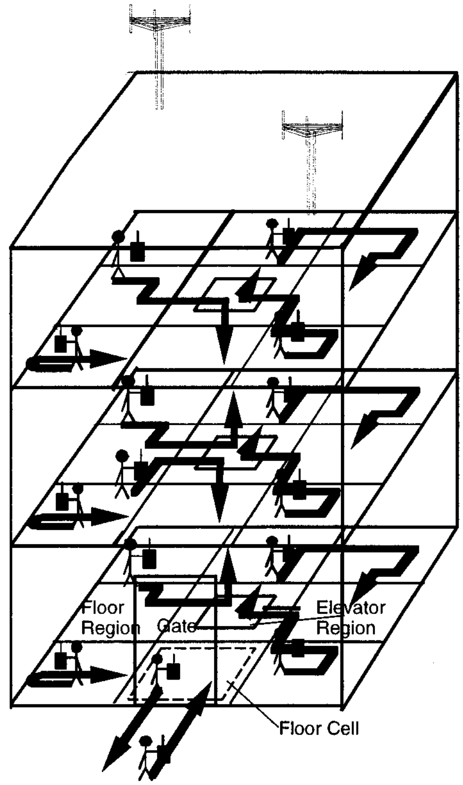

Fig. 1. Users' moving pattern.

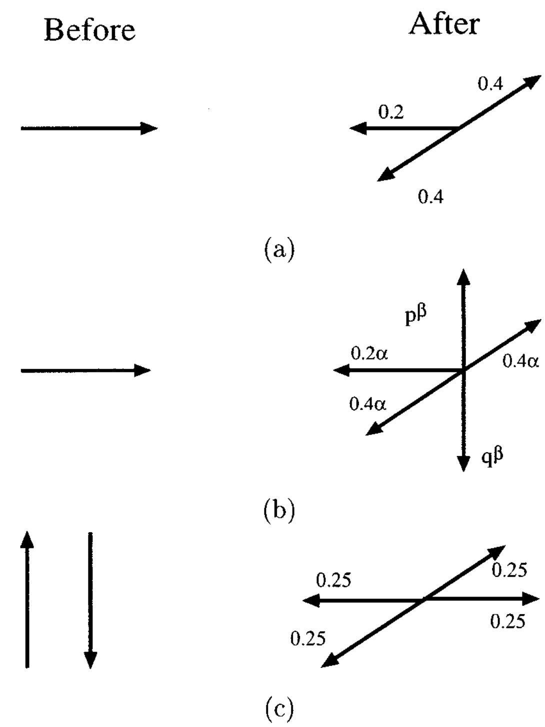

Fig. 2. Moving directions before and after turning point.

- H number of handoffs during a call;
- J journey time from waiting for an elevator until getting off the elevator: elevator cell residence time;
- d one side cell length;
- u one side gate length;
- A area of a cell on a floor;
- B area of an elevator region on a floor;
- C area of a floor;
- a square root of the number of floor cells per floor;
- α horizontal direction selection ratio after turning in elevator regions;
- β vertical direction selection ratio after turning in elevator regions.

We consider a K-story building $(K \geq 3)$. We describe users' motions in 3-D environments in the similar way to [8] and [9]. To model mobility, we make the following assumptions.

- Users move on square-shaped building floors, wait for elevators, or stay inside elevators.
- Idle and call durations are exponentially distributed with mean λ^{-1} and μ^{-1}, respectively.
- Horizontal speed is uniformly distributed with $[0, V_{\max}]$. However, a user moves with a horizontal speed of V during a call.
- Each cell station has a sufficiently large number of channels to ensure no handoff failures.
- The building consists of elevator/floor regions on each floor and elevators (Fig. 1).
- An elevator region consists of passages excluding elevators, includes elevator waiting regions, and is located in the center on each floor. The remaining region on each floor is called the floor region (Fig. 1).
- Users move horizontally or wait for elevators in the elevator region on each floor (Fig. 1).
- An elevator cell covers both users waiting for elevators in an elevator region and users inside elevators [10] and exists alone in the building.
- A floor cell covers horizontally moving users in both elevator region and floor region (Fig. 1).
- Horizontally moving users move straight until they change direction, i.e., turn right, left, or back, and then continue to move straight again. The distance between turing points is exponentially distributed (Fig. 1).
- When users arrive at the outer wall, they go back to the incoming direction without delay. The point at the outer wall is not regarded as a turning point (Fig. 1).
- There is a gate in the center of one side of an outer wall on the first floor. Users in the building can exit the building and vice-versa through a gate (Fig. 1).
- Direction changes in horizontal motion occur according to a Poisson process and the direction selection ratio at the turning point in horizontal motion is distributed with the ratio of 0.4, 0.2, and 0.4 to the left, back, and right, respectively, as shown in Fig. 2(a).
- When horizontally moving users on the ith floor change direction in the elevator region, they move horizontally or vertically with probability α_i or β_i ($\alpha_i + \beta_i = 1$, $p_i + q_i = 1$, $p_1 = 1$ on the first floor, ($q_K = 1$ on the Kth floor, $i = 1, 2, \ldots K$). The direction change probability is shown in Fig. 2(b).
- As soon as users choose the vertical direction in the elevator region, they handoff to the elevator cell: they begin to wait for elevators or enter an elevator without a wait.

- When vertically moving users change direction, i.e., just after the users leave an elevator on a floor, they move horizontally with identical probabilities for the four sides, as shown in Fig. 2(c).
- User density in the floor cells on each floor is identical for all floors.
- A horizontal handoff occurs when a conversing portable station crosses the floor cell boundary in horizontal motion.
- A vertical handoff occurs when a conversing portable station enters the elevator cell: the station begins to wait for elevators or enter an elevator without a wait.
- An elevator cell handoff occurs when a conversing portable station leaves an elevator.

Under the assumptions, we can derive the mean number of handoffs in the K-story building during a call. The horizontal cell crossing rate related to horizontal handoffs including boundary conditions caused by outer walls on the ith floor is expressed as

$$R_{i,H} = \begin{cases} \frac{E[V]}{d}\left(1 - \frac{1}{a} + \frac{u}{4da^2}\right), & \text{on the first floor} \\ \frac{E[V]}{d}\left(1 - \frac{1}{a}\right), & \text{otherwise} \end{cases} \tag{1}$$

where users on the first floor pass through a gate. The vertical cell crossing rate related to vertical handoffs on the ith floor is written as

$$\begin{aligned} R_{i,V} &= (\text{rate of turnings in the elevator region})\beta_i \\ &= \frac{\beta_i}{E\left[\frac{X}{V}\right]}. \end{aligned} \tag{2}$$

The elevator cell crossing rate related to elevator cell handoffs is given by

$$R_E = \frac{1}{E[J]}. \tag{3}$$

The mean number of handoffs in the K-story building during a call is as follows:

$$\begin{aligned} E[H] = E[T] \\ \cdot\left\{\sum_{i=1}^{K} E\left[\frac{N_F}{N}\right]\left(R_{i,H} + \frac{B}{C}R_{i,V}\right) + E\left[\frac{N_E}{N}\right]R_E\right\} \end{aligned} \tag{4}$$

where N, N_F, and N_E denote the total number of users in the building, the number of users per floor except the elevator cell, and the number of users in the elevator cell, respectively. We need to obtain the user stay probabilities as well as vertical direction selection ratio β_i.

User density on each floor except the elevator cell is identical for all floors under the above assumptions. The rates getting into and out of the elevator cell are the same in steady state

$$E\left[\frac{N_F}{N}\right] \cdot \frac{B}{C} \frac{\sum_{i=1}^{K}\beta_i}{E\left[\frac{X}{V}\right]} = E\left[\frac{N_E}{N}\right] \cdot \frac{1}{E[J]} \tag{5}$$

$$K \cdot E\left[\frac{N_F}{N}\right] + E\left[\frac{N_E}{N}\right] = 1. \tag{6}$$

From (5) and (6), we can derive user stay probabilities on each floor and in the elevator cell

$$E\left[\frac{N_F}{N}\right] = \frac{1}{K + \frac{B}{C}\frac{E[J]}{E\left[\frac{X}{V}\right]}\sum_{i=1}^{K}\beta_i} \tag{7}$$

$$E\left[\frac{N_E}{N}\right] = \frac{\frac{B}{C}\frac{E[J]}{E\left[\frac{X}{V}\right]}\sum_{i=1}^{K}\beta_i}{K + \frac{B}{C}\frac{E[J]}{E\left[\frac{X}{V}\right]}\sum_{i=1}^{K}\beta_i}. \tag{8}$$

From (4) to (8), the mean number of handoffs in the K-story building during a call can be converted into this form

$$E[H] = E[T] \cdot \left\{\sum_{i=1}^{K} E\left[\frac{N_F}{N}\right] R_{i,H} + 2E\left[\frac{N_E}{N}\right] R_E\right\}. \tag{9}$$

On the other hand, the rates at which users on the ith floor enter and leave the elevator cell on the boundary between the floor cell on the ith floor and the elevator cell are the same in steady state

$$\begin{aligned} \lambda_i &= \sum_{j=1,\, j\neq i}^{K} \lambda_j P_{ji} \\ 1 &= \sum_{j=1,\, j\neq i}^{K} P_{ij}, \qquad i = 1, 2, \ldots, K \end{aligned} \tag{10}$$

where λ_i is the user arrival rate in the elevator cell from the ith floor and P_{ji} is the transition probability that users on the jth floor choose the ith floor for vertical motion ($i \neq j$). If P_{ji} are given, the ratios of $\{\lambda_i,\, i = 1, 2, \ldots, K\}$ can be obtained.

The user arrival rates in the elevator cell $\{\lambda_i,\, i = 1, 2, \ldots, K\}$ are proportional to the vertical cell crossing rate on each floor from (2)

$$\frac{\beta_i}{\lambda_i} = \text{Constant}, \qquad i = 1, 2, \ldots, K. \tag{11}$$

As a result, β_i is determined according to λ_i.

B. Numerical Results

In order to verify the proposed mobility model in 3-D PCS environments, we analyze mobility under the following assumptions.

- A 10-story building of 60 m × 60 m × 30 m is considered [11], [12].
- An elevator region consists of passages excluding elevators, includes elevator waiting regions, and its size is 10 m× 10 m × 3 m.
- One side gate length is 10 m.
- Idle and call durations are exponentially distributed with a mean of 100 s and 500 s, respectively.
- Horizontal user speed is a constant of 2 km/h.

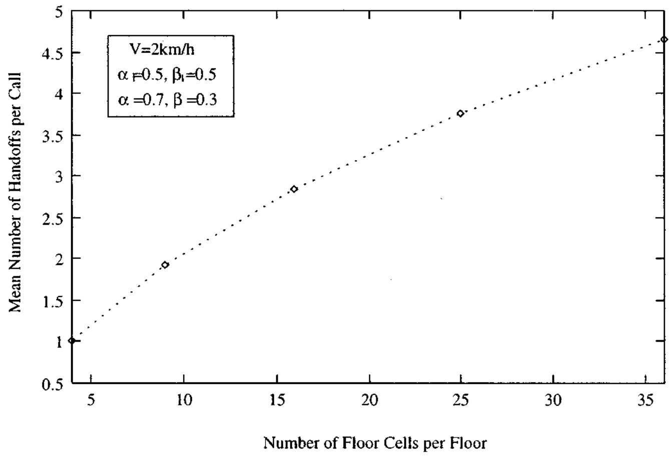

Fig. 3. Mean number of handoffs versus number of floor cells per floor.

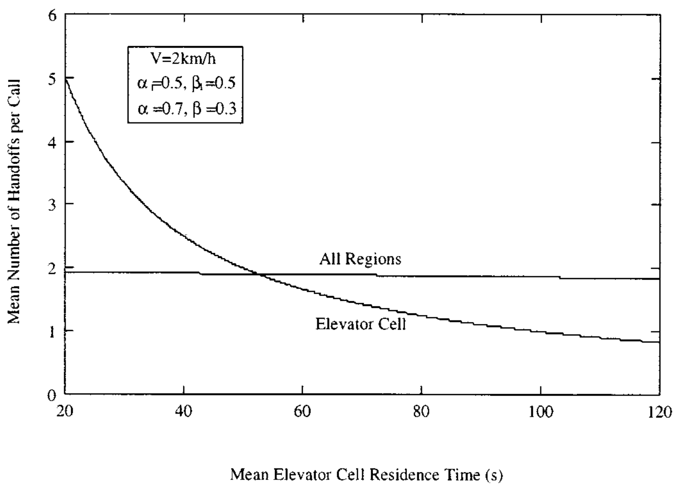

Fig. 4. Mean number of handoffs versus mean elevator cell residence time.

- Users have horizontal motions with a mean distance between turning points of 10 m in the floor region and elevator region.
- The total number of users inside the building is 1800.
- Transition probability $P_{1i} = 1/9$, $i = 2, 3, \ldots K$.
- Horizontally moving users determine the next direction randomly with $\alpha_1 = 0.5$ (horizontal motion) and $\beta_1 = 0.5$ (vertical motion) on the first floor at turning points in the elevator region.
- Transition probabilities $P_{i1} = 5/27$, $P_{ji} = 11/108$, $j \neq i$, $i, j = 2, 3, \ldots, K$: horizontally moving users determine the next direction randomly with $\alpha = 0.7$ (horizontal motion) and $\beta = 0.3$ (vertical motion) on the other floors at turning points in the elevator region.
- Mean elevator cell residence time is 30 s.
- The number of floor cells per floor is 9.

The effect of varing the number of floor cells per floor on the mean number of handoffs is shown in Fig. 3. Smaller floor cells yield more frequent handoffs.

Fig. 4 illustrates the mean number of handoffs during a call in the cases of moving users in the elevator cell and in all regions of the building. In both cases, the mean number of handoffs increases as the mean elevator cell residence time, $E[J]$ decreases. This decrease of $E[J]$ increases the mean number of elevator cell handoffs greatly while the mean number of all region handoffs a little, since the increase of elevator cell handoffs affects the number of all region handoffs insignificantly due to the user's short stay in the elevator cell of the building. Note that $E[J]$ can be decreased by increasing the number of elevators in the elevator cell and elevator speed.

III. Traffic Model

In this section, we derive a blocking probability model from the mobility model in Section II and determine the required number of channels per radio port to meet the blocking probability constraint in the implementation of indoor wireless networks.

A. Traffic Model

We introduce a parameter ζ denoting *mobility*. The mobility ζ represents the probability of releasing an occupied channel in a cell due to a handoff to another cell. Consequently, $1 - \zeta$ is the probability of releasing the occupied channel because of the call completion.

The number of handoffs during a call, $E[H]$ is expressed as

$$E[H] = E[G] - 1 \qquad (12)$$

where G and H are random variables representing the number of cells visited and handoffs during a call, respectively. The mean number of cells visited during a call in nonblocking models is given by

$$\begin{aligned} E[G] &= 1(1-\zeta) + 2\zeta(1-\zeta) + 3\zeta^2(1-\zeta) + \ldots \\ &= (1-\zeta)^{-1}. \end{aligned} \qquad (13)$$

Combining (12) and (13) yields

$$1 - \zeta = 1/(E[H] + 1). \qquad (14)$$

From (14), we can observe that ζ is obtained by the mean number of handoffs during a call.

The ratio of mean call to idle durations with mobility is

$$\overline{\rho} = \frac{1-\zeta}{1-(1-P)\zeta}\left(1 + \frac{P\zeta}{1-(1-P)\zeta}\right)\rho \qquad (15)$$

where P is both blocking and handoff failure probabilities when a handoff call has no priority over a new call and ρ is the ratio of mean call to idle durations of stationary users [9].

The number of users in small indoor cells is generally small compared with outdoor cells. Therefore, the number of users per cell heavily varies due to mobility and call arrivals per cell depend on the number of busy users in the cell. We estimate the distribution of the number of users per cell to represent this variation due to mobility and use an Engset blocking probability model.

Finally, we obtain the blocking probability model with mobility by predicting the probability of n users per cell, P_n and

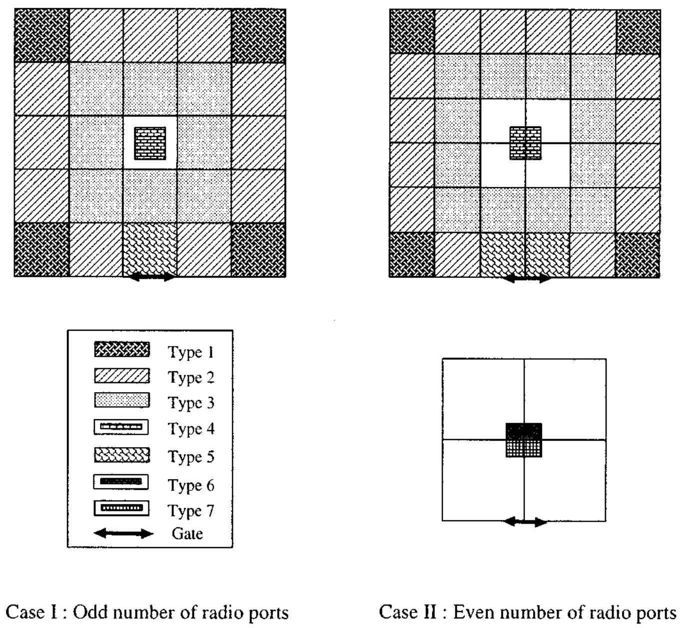

Fig. 5. Various types of floor cells in case of odd and even numbers of radio ports per floor.

modifying the existing Engset model [13]–[15] with the parameter $\overline{\rho}$

$$P_B = \sum_n P_n \frac{\binom{n-1}{c}\overline{\rho}^c}{\sum_{i=0}^{c}\binom{n-1}{i}\overline{\rho}^i} = \sum_{n>c}^{N} P_n \frac{\binom{n-1}{c}\overline{\rho}^c}{\sum_{i=0}^{c}\binom{n-1}{i}\overline{\rho}^i} \tag{16}$$

where N and c are the total number of users in the building and channels per cell, respectively, and P_n will be obtained later.

B. Mobility

We need to identify mobility ζ to obtain the parameter $\overline{\rho}$ in the blocking probability model with mobility in (16). We here derive mobility per cell based on the mean number of handoffs in 3-D indoor environments. We consider a mobility problem in the following two cases.

1) Odd Number of Radio Ports per Floor: Fig. 5 (Case I) shows various types of floor cells where the number of radio ports per floor is odd. The type 1 cell has two sides surrounded by outer walls, and thus half of the users arriving at cell sides return without handoffs. This reflects the fact that the factor 0.5 is multiplied by the mean number of 2-D handoffs [7] in computing the number of handoffs. The probability of releasing an occupied channel due to a call completion in type 1 cells is given by

$$1-\zeta_1 = \left[1 + 0.5 \cdot \frac{E[V]E[T]}{d}\right]^{-1}. \tag{17}$$

In the case of type 2 cells, one of the four sides corresponds to an outer wall and the factor 0.75 is thus included

$$1-\zeta_2 = \left[1 + 0.75 \cdot \frac{E[V]E[T]}{d}\right]^{-1}. \tag{18}$$

Since there are no outer boundary walls in type 3 cells, $1-\zeta_3$ is expressed as

$$1-\zeta_3 = \left[1 + \frac{E[V]E[T]}{d}\right]^{-1}. \tag{19}$$

The type 4 cell shows a central cell including one elevator region without its elevator waiting region

$$1-\zeta_4 = \left[1 + \frac{E[V]E[T]}{d} + \frac{B}{A}\frac{\beta_i E[T]}{E\left[\frac{X}{V}\right]}\right]^{-1} \tag{20}$$

and A and B denote the areas of a floor cell and an elevator region, respectively. On the first floor, users move through a gate. The type 5 cell includes the effect of handoffs through the gate

$$1-\zeta_5 = \left[1 + \left(0.75 + \frac{u}{4d}\right) \cdot \frac{E[V]E[T]}{d}\right]^{-1}. \tag{21}$$

The probability of releasing an occupied channel due to a call completion in the elevator cell is given by

$$1-\zeta_e = \left[1 + \frac{E[T]}{E[J]}\right]^{-1}. \tag{22}$$

2) Even Number of Radio Ports per Floor: Fig. 5 (Case II) shows various types of floor cells when the number of radio ports per floor is even. Utilizing procedures similar to those in the previous subsection, we obtain the four mobility factors, ζ_1, ζ_2, ζ_3, and ζ_e. Since the type 4 cell includes a quarter of the elevator region without its elevator waiting region, $1-\zeta_4$ is given by

$$1-\zeta_4 = \left[1 + \frac{E[V]E[T]}{d} + \frac{0.25B}{A}\frac{\beta_i E[T]}{E\left[\frac{X}{V}\right]}\right]^{-1}. \tag{23}$$

The type 5 cell includes the effect of handoffs through a gate on the first floor

$$1-\zeta_5 = \left[1 + \left(0.75 + \frac{u}{8d}\right) \cdot \frac{E[V]E[T]}{d}\right]^{-1}. \tag{24}$$

In the case of four cells per floor, there are some differences from the previous cell types 1–5. In type 6 cells, half of the four sides for each cell are surrounded by outer walls. Each cell includes a quarter of the elevator region. In this case, $1-\zeta_6$ is obtained by substituting $(E[V]E[T])/d$ in (23) into $[(0.5 \cdot E[V]E[T])/d]$. $1-\zeta_7$ in the type 7 cell is obtained by considering handoffs through the gate on the first floor and substituting $[(E[V]E[T])/d]$ in (23) into $[(0.5 + (u/8d) \cdot E[V]E[T])/d]$.

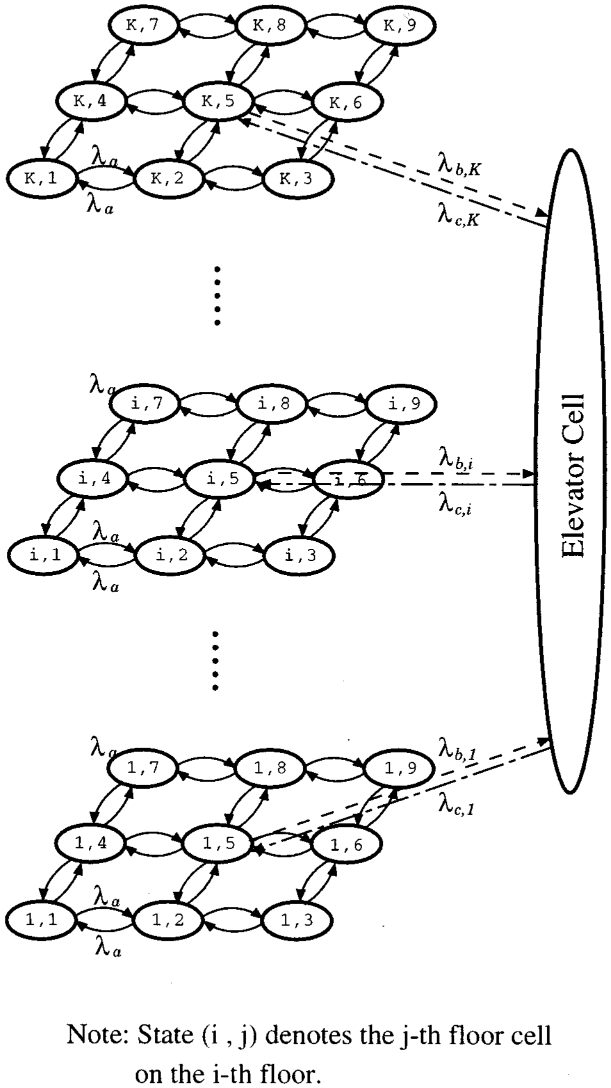

Fig. 6. State transition diagram.

C. Number of Users Per Cell

We need to find the probability of n users P_n to obtain the blocking probability in (16). If we can derive the probability that a user stays in a cell, p, we obtain the probability of n users in a cell

$$P_n = \binom{N}{n} p^n (1-p)^{N-n}. \tag{25}$$

For the probability p, we consider the continuous-time Markov chain (CTMC) in which each cell number is defined as a state. We can similarly solve the probability p regardless of the number of cells per floor.

As an example, we assume a case where there are nine floor cells per floor, as shown in Fig. 6. The rate at which the user in the floor cell leaves the cell horizontally is given by

$$\lambda_a = \frac{E[V]}{4d}. \tag{26}$$

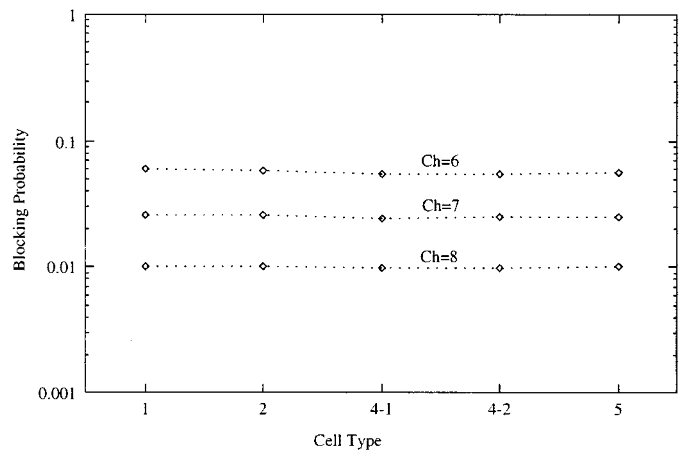

Fig. 7. Blocking probability for each floor cell type (nine floor cells).

The rate at which the user in the floor cell, including the elevator region without its elevator waiting region, leaves the cell vertically is written as

$$\lambda_{b,i} = \frac{B}{A} \frac{\beta_i}{E\left[\dfrac{X}{V}\right]}, \qquad i = 1, 2, \ldots, K. \tag{27}$$

And the rate at which the user in the elevator cell leaves the cell is given by

$$\sum_{i=1}^{K} \lambda_{c,i} = 1/E[J]. \tag{28}$$

Under the given MC and the assumption that user density in the floor cells on each floor is identical for all floors, we can derive the probability p of the user in the K-story building

$$p = \begin{cases} \dfrac{1/9}{K + \dfrac{B}{C} \dfrac{E[J]}{E\left[\dfrac{X}{V}\right]} \displaystyle\sum_{i=1}^{K} \beta_i}, & \text{in the floor cell,} \\[3ex] \dfrac{\dfrac{B}{C} \dfrac{E[J]}{E\left[\dfrac{X}{V}\right]} \displaystyle\sum_{i=1}^{K} \beta_i}{K + \dfrac{B}{C} \dfrac{E[J]}{E\left[\dfrac{X}{V}\right]} \displaystyle\sum_{i=1}^{K} \beta_i}, & \text{in the elevator cell.} \end{cases} \tag{29}$$

D. Numerical Results

To examine the effects of the number of channels and mobility, we now evaluate the blocking probability using the same assumptions as described in the previous numerical results.

Fig. 7 shows the blocking probabilities in each floor cell type for varying the number of channels per radio port when there are nine radio ports (floor cells) per floor. Type 4-1 and type 4-2 cells represent the floor cells on the first floor and

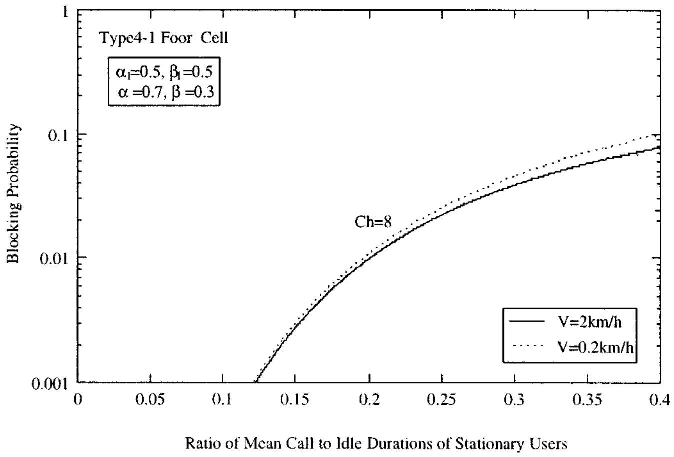

Fig. 8. Blocking probability versus ratio of mean call to idle durations of stationary users.

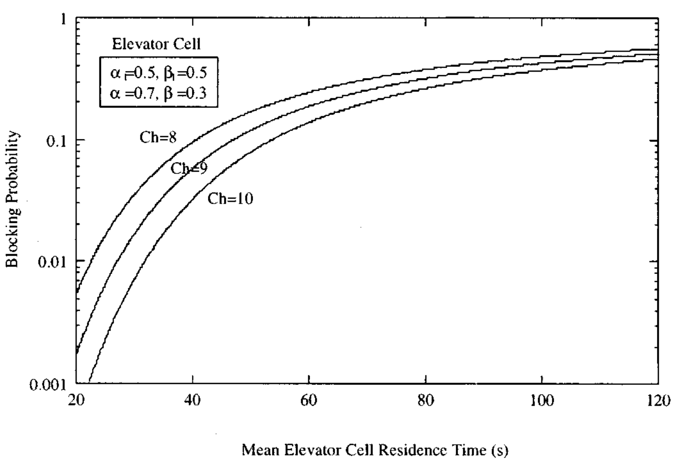

Fig. 9. Blocking probability versus mean elevator cell residence time.

the other floors among type 4 cells, respectively. The blocking probability decreases as the number of channels per radio port increases.

Through our analytical model, we next observe the effects of the ratio of mean call to idle durations of stationary users and the increase of mobility on blocking probability when there are nine radio ports per floor (Fig. 8). As the ratio of mean call to idle durations of stationary users increases, the corresponding blocking probability increases. We can observe that an increase of mobility causes a decrease of blocking probability. The increase of handoff failures due to increased mobility reduces the traffic load of mobile users. This reduced traffic load due to mobility results in lowering the blocking probability of new calls.

Fig. 9 illustrates the blocking probability in the elevator cell for varying the mean elevator cell residence time, $E[J]$. We can observe that a decrease of $E[J]$ causes a decrease of blocking probability in the elevator cell due to the reduction of channel holding time in the elevator cell. For example, nine channels are required for the elevator cell with a mean elevator cell residence time of 30 s under the requirement that the blocking probability does not exceed 0.02.

IV. Conclusion

We proposed a mobility model in 3-D indoor environments by considering the proper boundary conditions on each floor and vertical motions through elevators. We here assumed that users move vertically only through elevators, move horizontally on a floor bounded by outer walls, and exit a building and vice versa through a gate. We observed the mean number of handoffs in terms of the number of floor cells per floor, any change of user speed, and elevator cell residence time.

We extended the Engset blocking probability model and suggested a blocking probability model with mobility when the blocking probability constraint is given. We first obtained the mobility associated with the mean number of handoffs for each cell and then separately evaluated the blocking probability of each cell because mobility and the number of users (user density) for each cell depend on cell type. Using the blocking probability model, we obtained the required number of channels in the elevator cell for mean elevator cell residence time. For example, nine channels are required for the elevator cell with a mean elevator cell residence time of 30 s under the requirement that the blocking probability does not exceed 0.02.

The 3-D model combined with elevators can be used in the design and planning of integrated personal communication networks of indoor environments.

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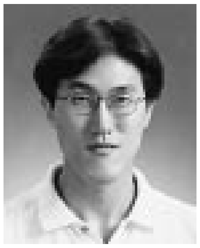

Tai Suk Kim (S'94) received the B.S., M.S., and Ph.D. degrees in electrical engineering from the Korea Advanced Institute of Science and Technology (KAIST), in 1993, 1995, and 1999, respectively.

He was a Postdoctoral Student in electrical engineering at Stanford University for one year. He is currently working at Samsung Electronics Company, Korea. His research interests include communication networks, mobility/traffic analyzes, and smart antenna systems.

Jae Kyun Kwon (S'96) received the B.S. and M.S. degrees in electrical engineering from the Korea Advanced Institute of Science and Technology (KAIST), in 1996 and 1998, respectively. He is currently working toward the Ph.D. degree in electrical engineering at KAIST.

His research interests include mobile communication networks, CDMA soft handoff, and mobility modeling.

Dan Keun Sung (S'80–M'86) received the B.S. degree in electrical engineering from Seoul National University, in 1975 and the M.S. and Ph.D. degrees in electrical and computer engineering from the University of Texas at Austin, in 1982 and 1986, respectively.

From May 1977 to July 1980, he was a Research Engineer with the Electronics and Telecommunications Research Institute, where he had been engaged in research on the development of electronic switching systems. In 1986, he joined the faculty of the Korea Institute of Technology and is currently a Professor of the Department of Electrical Engineering at the Korea Advanced Institute of Science and Technology (KAIST). His research interests include ATM switching systems, wireless networks, intelligent network performance and reliability of systems, mobile communication systems, wireless ATM, and CDMA system.

He is a member of IEICE, KITE, KICS, and KISS.