論 文

A Mobility Model in 3-Dimensional PCS Indoor Environments

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SUMMARY We need to solve various mobility problems in 1-dimensional, 2-dimensional, and 3-dimensional micro- or pico-cell environments for efficiently planning personal communications services. However, mobility problems have been thus far studied in 1- and 2-dimensional cell structures. In this paper, we extend the previous mobility modeling from 1- or 2-dimensional space to 3-dimensional indoor building environments by considering proper boundary conditions on each floor and analytically model the mobility in the multi-story buildings to estimate the number of handoffs and then verify this mathematical model by computer simulations. The computer simulation results agree very well with the analytical ones. These results can be utilized in the network plannings of future personal communications services.

***key words*:** *PCS, 3-dimension, mobility, handoff, indoor environments*

1. 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 the mobility and its effect on PCS networks in order to implement this PCS.

Mobility problems in mobile communications have been mainly studied by simulations and analytical approaches. Simulation models [9]-[11] may represent the specific mobility patterns in indoor environments with radio propagation phenomena. However, simulation models may not sufficiently represent the user mobility in the general environments because simulation results lack mathematical reasonings of model parameter values. And since the change in environment parameters requires a new simulation, simulations may usually require high cost. In this sense, it is very difficult to characterize the general properties of user mobility by using simulation. On the other hand, several analytical approaches have been employed to characterize the user mobility in mobile communications and/or PCS communications. These approaches generally give good physical insights and mathematical reasonings. However, they may not sufficiently represent the user mobility in real environments because of the complexity. Thus, we usually need to simplify the mathematical model for mathematical convenience in order to circumvent its complexity. There is still a tradeoff between the simplification of mathematical model and the accuracy of system model. So far, several studies have used these approaches. El-Dolil et al. [1] studied the 1-dimensional mobility problem of highway microcells and Guerin [2] and Hong and Rappaport [3] modeled the mobility with random direction motions in 2-dimensional environments, by examining the channel holding time. Thomas et al. [5] analyzed the mobility by using a fluid flow model under the assumption that users randomly move. In case of PCS, turning motions in square-shaped micro- or pico-cell environments may be suggested by considering artificial structures, such as roads lined with buildings and passages between buildings. Recently, a mobility model was suggested in 2-dimensional environments considering turning motions in square-shaped micro- or pico-cell environments [7]. Y. Jun and S. Cheng [8] proposed the mobility model in 3-dimensional environments based on Hong and Rappaport's work [3]. However, this model is far from the real 3-dimensional environments especially in up-down (vertical) motions. They assumed that up-down motions can occur in any place of the plane. However, it is reasonable that users have up-down (vertical) motions only through the staircase in 3-dimensional indoor environments.

In this paper, we model the mobility in 3-dimensional PCS indoor environments with some

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boundary conditions on each floor and then obtain the mean number of handoffs. This paper is organized as follows. A mobility model in 3-dimensional PCS indoor environments is proposed in Sect. 2. In this section, we extend our turning motion model in 2-dimensional environments [7] to that in 3-dimensional environments by considering proper boundary conditions on each floor and vertical motions in staircase regions. We obtain the mean number of handoffs from this model. In Sect. 3, we verify our mobility model by using computer simulation. Finally, conclusions are given in Sect. 4.

2. Mobility Model

In order to investigate the effects of handoffs on 3-dimensional PCS networks, we need to model the mobility. In this section, we propose an analytical mobility model in 3-dimensional indoor environments to analyze the mobility and then obtain the mean number of handoffs from it. We first model the mobility in the vertically unbounded building and then model the mobility in the bounded multistory building by considering the boundary conditions. Note that users move in the same manners for each floor in "unbounded" buildings, while users move differently on the highest or lowest floor in "bounded" buildings, compared with the middle floors.

2.1 Mobility in Unbounded Buildings

We consider users' motions in the vertically unbounded building and describe users' motions in 3-dimensional environments, compared with the mobility model in [7]. First, there are outer walls and users cannot move through the outer walls in the building. Second, users in vertical motions change the directions whenever they arrive at the new floor. Finally, users have vertical motions only through the staircase in 3-dimensional environments. We have the following assumptions to model the mobility:

- Users move on the square-shaped floors of a building.
- Idle duration and call duration are exponentially distributed with the mean λ^{-1} and μ^{-1}, respectively.
- Horizontal and vertical speeds are uniformly distributed with $[0, V_{max}]$ and $[0, V'_{max}]$, respectively. However, a user moves with the horizontal and/or vertical speed(s) of V and/or V', respectively, during a call.
- Each cell station has a sufficiently large number of channels to support no handoff failures.

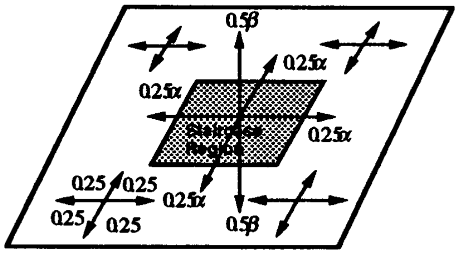

Fig. 1 Direction selection ratios at various turning points (unbounded).

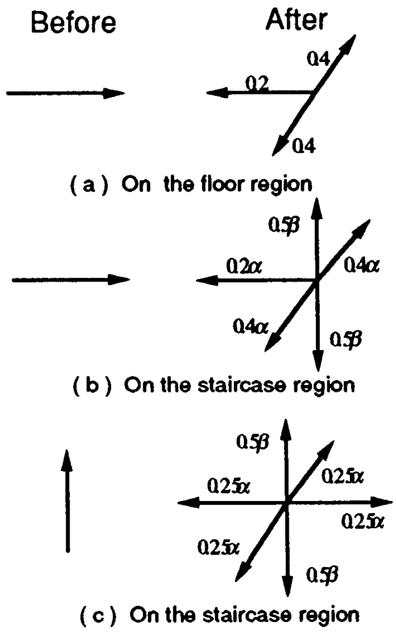

Fig. 2 Moving directions with the probability of horizontal and vertical motions, α and β, respectively, after direction changes (unbounded).

- Users move straight until they change directions, i.e. turn right, left, or back and then continue to move straight again.
- Direction changes occur according to Poisson process and the direction selection ratio at the turning point in horizontal motion is uniformly distributed by the ratio of 0.4, 0.2, and 0.4 to the left, back, and right, respectively, as shown in 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.
- If the turning point is located on the staircase region and users arrive there, they move horizontally or vertically with the probability of α and $\beta(\alpha+\beta=1)$, respectively. The probability of direction changes is shown in Fig. 2.

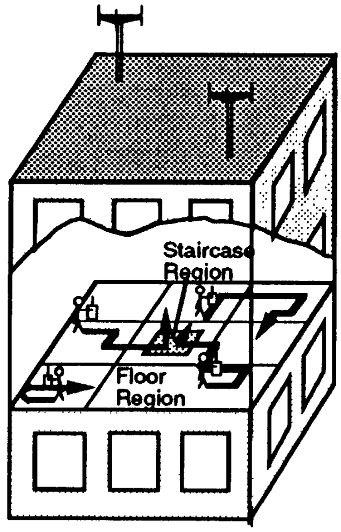

Fig. 3 Moving pattern of users (unbounded).

- The height of portable stations is half of the height of the floor when users walk on the floor.
- A handoff occurs when a portable station crosses the cell boundary.

Figure 3 shows a typical moving pattern of users on one floor based on the above assumptions. Users' moving behaviors are also assumed to be statistically the same on every floor. We define the following parameters in order to describe a mobility model:

- V the horizontal motion speed
- V' the vertical motion speed
- T the call duration
- X the distance between two turning points
- W the elapsing time between two turning points
- M the number of direction changes during a call
- H_T the number of handoffs between two turning points
- H_P the number of handoffs under the assumption that horizontal and vertical motions occur at every turning point
- H the number of handoffs under the above assumptions
- d the one side length of cells
- h the height of a floor
- a the square root of the number of cells per floor

We first consider a simple, but rather impractical 3-dimensional mobility model in which both horizontal and vertical motions are possible at every turning point. The mean elapsing time between two neighboring turning points, $E[W]$ is given by this equation

$$E[W]=\alpha\cdot\frac{E[X]}{E[V]}+\beta\cdot\frac{h}{E[V']}. \qquad (1)$$

The mean number of direction changes during a call duration, $E[M]$ is written as

$$E[M]=\frac{E[T]}{\alpha\cdot\frac{E[X]}{E[V]}+\beta\cdot\frac{h}{E[V']}}. \qquad (2)$$

The mean number of handoffs between two neighboring turning points is obtained by considering the horizontal and vertical motions. A factor $(1-1/a)$ is included because there are no handoffs when users encounter the outer wall during their movements:

$$E[H_T]=\alpha\cdot\frac{E[X]}{d}(1-1/a)+\beta\cdot 1. \qquad (3)$$

Combining (1)-(3) yields the mean number of handoffs:

$$E[H_P]=\frac{E[T]\left(\alpha\frac{E[X]}{d}(1-1/a)+\beta\right)}{\alpha\frac{E[X]}{E[V]}+\beta\frac{h}{E[V']}}. \qquad (4)$$

From now on, we consider a 3-dimensional mobility model in which there are vertical motions on the staircase region. The staircase region consists of a staircase for vertical motions and passages for horizontal motions, and its size is fixed. In steady state, the number of users is in equilibrium vertically and horizontally at the boundary of staircase regions. Therefore, the number of users per unit area on the staircase region is more than that on the floor region. We denote δ as an increasing factor due to the larger number of users on the staircase region. The mean number of horizontal motion handoffs in 3-dimensional environments is the same as the mean number of handoffs [7] in 2-dimensional environments:

$$\begin{aligned}B(1+\delta)\cdot&\frac{E[T]\left(\alpha\frac{E[X]}{d}(1-1/a)\right)}{\alpha\frac{E[X]}{E[V]}+\beta\frac{h}{E[V']}}\\&+(C-B)\cdot\frac{E[V]\cdot E[T]}{d}(1-1/a)\\&=C\cdot\frac{E[V]\cdot E[T]}{d}(1-1/a),\end{aligned} \qquad (5)$$

where B and C are the areas of a staircase region and a floor, respectively. It follows that is expressed as

$$\delta=\frac{\beta}{\alpha}\cdot\frac{h}{E[X]}\cdot\frac{E[V]}{E[V']}. \qquad (6)$$

The mean number of vertical motion handoffs on one floor is identical to that on the neighboring floor. Finally, we obtain the mean number of handoffs during a call by considering the effect of the increasing factor δ:

$$E[H] = \frac{C-B}{C+B\delta}\cdot\frac{E[V]\cdot E[T]}{d}(1-1/a) + \frac{B(1+\delta)}{C+B\delta}\cdot\frac{E[T]\left(\alpha\frac{E[X]}{d}(1-1/a)+\beta\right)}{\alpha\frac{E[X]}{E[V]}+\beta\frac{h}{E[V']}}. \tag{7}$$

2.2 Mobility in Bounded Buildings

We consider the bounded K-story building as a more practical environment ($K \geqq 3$). Although users' moving behaviors in both the bounded building and the unbounded building are similar in many points, they are different in several points. Users on the first floor cannot go downstairs and users on the K-th floor cannot go upstairs. Users in the building can move through the gate. We have the following assumptions which are different from those described in Sect. 2.1:

- When users on the 2nd, $\cdots$, $(K-1)$-th floors change their directions on the staircase region, they move horizontally or vertically with the probability of α_i and β_i ($\alpha_i+\beta_i=1$, $i=2, \cdots, K-1$), respectively. Users on the 2nd, $\cdots$, $(K-1)$-th floors move in the same manners as those of the unbounded building.
- There is a gate in the center of one side outer wall on the first floor. Users in the building can move out to the outside of the building and vice versa.
- When users in horizontal motions on the first floor or K-th floor change their directions on the staircase region, they move horizontally or vertically with the probability of (α_1, α_K) or (β_1, β_K)($\alpha_1+\beta_1=1$, $\alpha_K+\beta_K=1$), respectively. The probability of direction changes is shown in Fig. 4(a).
- When users in vertical motions on the first floor or K-th floor change their directions on the staircase region, they move horizontally with the identical probabilities for four sides, respectively, as shown in Fig. 4(b).
- Users' densities on the floor regions are the same for all floors.

Figure 5 depicts a typical moving pattern of users in the bounded building based on the above assumptions.

There are some differences among users' moving patterns on the floors of the building due to the boundary conditions. The mean number of handoffs on the 2nd, $\cdots$, $(K-1)$-th floors is the same as those of the unbounded building and is given by this equation

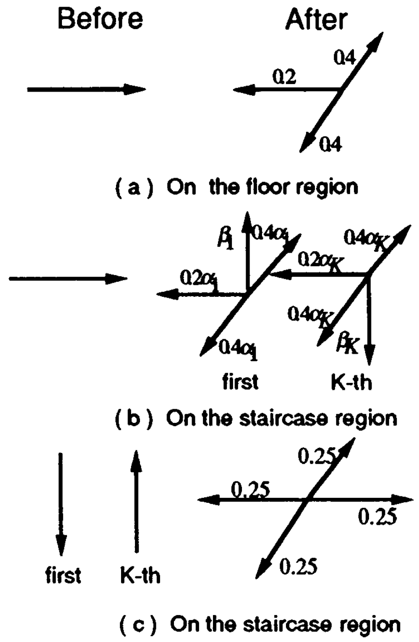

Fig. 4 Moving directions before and after turning point (bounded).

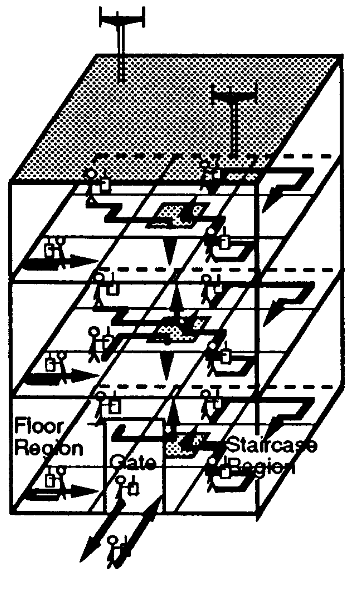

Fig. 5 Moving pattern of users (bounded).

$$E[H_i] = \frac{C-B}{C+B\delta_i}\cdot\frac{E[V]\cdot E[T]}{d}(1-1/a) + \frac{B(1+\delta_i)}{C+B\delta_i}\cdot\frac{E[T]\left(\alpha_i\frac{E[X]}{d}(1-1/a)+\beta_i\right)}{\alpha_i\frac{E[X]}{E[V]}+\beta_i\frac{h}{E[V']}} \quad (i=2, \cdots, K-1), \tag{8}$$

where δ_i is an increasing factor due to the larger number of users on the staircase regions.

Horizontally moving users before the turning point on the staircase region move horizontally or vertically after turning, while vertically moving users move horizontally at the turning point. The mean number of handoffs on the K-th floor is expressed as

$$E[H_K] = \frac{C-B}{C+B\delta_K}\cdot\frac{E[V]\cdot E[T]}{d}(1-1/a) + \frac{B(1+\delta_K)}{C+B\delta_K}\left[V_K\cdot\frac{E[V]\cdot E[T]}{d}(1-1/a) + P_K\cdot\frac{E[T]\left(\alpha_K\frac{E[X]}{d}(1-1/a)+\beta_K\right)}{\alpha_K\frac{E[X]}{E[V]}+\beta_K\frac{h}{E[V']}}\right] \quad (9)$$

where V_K, P_K and δ_K are the ratios of the number of horizontally moving events, vertically moving events just before the turning point on the staircase region per unit time, and an increasing factor due to the larger number of users on the staircase region on the K-th floor, respectively ($V_K+P_K=1$). When users on the first floor move out of the building, handoffs occur. By considering the handoffs in the gate, we use the factor $(1-1/a+1/4a^2\cdot u/d)$ instead of $(1-1/a)$ in Eq.(9) where u is the horizontal length of the gate. It follows that the mean number of handoffs is given by:

$$E[H_1] = \frac{C-B}{C+B\delta_1}\cdot\frac{E[V]\cdot E[T]}{d}\left(1-\frac{1}{a}+\frac{1}{4a^2}\cdot\frac{u}{d}\right) + \frac{B(1+\delta_1)}{C+B\delta_1}\left[V_1\cdot\frac{E[V]\cdot E[T]}{d}\left(1-\frac{1}{a}+\frac{1}{4a^2}\cdot\frac{u}{d}\right) + P_1\cdot\frac{E[T]\left(\alpha_1\frac{E[X]}{d}\left(1-\frac{1}{a}+\frac{1}{4a^2}\cdot\frac{u}{d}\right)+\beta_1\right)}{\alpha_1\frac{E[X]}{E[V]}+\beta_1\frac{h}{E[V']}}\right] \quad (10)$$

where δ_1 is an increasing factor due to the larger number of users on the staircase region on the first floor. The mean number of handoffs in the K-story building during a call is written as

$$E[H] = \sum_{i=1}^{K}\frac{N_{F_i}}{N}\cdot E[H_i], \quad (11)$$

where N and N_{F_i} are the total number of users in the building and the number of users on the i-th floor. The mean number of horizontal motion handoffs in 3-dimensional environments is the same as the mean number of handoffs in 2-dimensional environments. If we especially consider the mean number of handoffs on the K-th floor, we have the following relation:

$$(C-B)\frac{E[V]\cdot E[T]}{d}(1-1/a) + B(1+\delta_K)\left[V_K\cdot\frac{E[V]\cdot E[T]}{d}(1-1/a) + P_K\cdot\frac{E[T]\left(\alpha_K\frac{E[X]}{d}(1-1/a)\right)}{\alpha_K\frac{E[X]}{E[V]}+\beta_K\frac{h}{E[V']}}\right] = C\cdot\frac{E[V]\cdot E[T]}{d}(1-1/a). \quad (12)$$

The mean number of vertical motion handoffs on one floor is also identical to that on the neighboring floor:

$$B(1+\delta_K)\cdot P_K\cdot\frac{\beta_K}{\alpha_K\frac{E[X]}{E[V]}+\beta_K\frac{h}{E[V']}} = B(1+\delta_{K-1})\cdot\frac{\beta_{K-1}/2}{\alpha_{K-1}\frac{E[X]}{E[V]}+\beta_{K-1}\frac{h}{E[V']}}. \quad (13)$$

The mean number of direction changes has the similar relation to the mean number of handoffs by dividing Eq.(12) by $\frac{E[X]\cdot E[T](1-1/a)}{d}$:

$$(C-B)\frac{E[V]}{E[X]} + B(1+\delta_K)\cdot\left[V_K\cdot\frac{E[V]}{E[X]} + P_K\cdot\frac{\alpha_K}{\alpha_K\frac{E[X]}{E[V]}+\beta_K\frac{h}{E[V']}}\right] = C\cdot\frac{E[V]}{E[X]}. \quad (14)$$

It follows that the mean rate of horizontal motion selections at the turning points on the staircase region is expressed as

$$B(1+\delta_K)\left[V_K\cdot\frac{E[V]}{E[X]} + P_K\cdot\frac{\alpha_K}{\alpha_K\frac{E[X]}{E[V]}+\beta_K\frac{h}{E[V']}}\right] = B\cdot\frac{E[V]}{E[X]}. \quad (15)$$

The mean rate of vertical motion selections at the turning points on the staircase region has the same form as Eq.(13). From Eqs.(8)-(11)), we can see that V_i, δ_i, and N_{F_i} are required in order to obtain the mean number of handoffs during a call. At the turning points on the staircase region on the K-th floor in steady state, the mean rate of events that users moved horizontally just before turning, $\lambda(in)_P$ is identical to the mean rate of events that users move horizontally after turning, $\lambda(out)_P$. There is the similarity between $\lambda(in)_V$ and $\lambda(out)_V$ in vertical motions. The ratio of P_K and V_K is the same as that of $\lambda(in)_P$ and $\lambda(in)_V$. Utilizing Eqs.(13) and (15),

$$\lambda(in)_P : \lambda(in)_V = \lambda(out)_P : \lambda(out)_V$$

$$P_K : V_K = B\cdot\frac{E[V]}{E[X]} :$$

$$B(1+\delta_{K-1})\cdot\frac{\beta_{K-1}/2}{\alpha_{K-1}\frac{E[X]}{E[V]}+\beta_{K-1}\frac{h}{E[V']}}=\alpha_{K-1}:\frac{\beta_{K-1}}{2}. \quad (16)$$

From Eqs. (13), (15), and (16), we can determine α_K and β_K to satisfy the balance equation (13) when α_{K-1} and β_{K-1} are fixed, or vice versa. Using α_K, we can obtain δ_K in Eq. (15). If we consider the mean number of handoffs on the first floor, we can obtain the similar equations Eqs. (12)-(16). Thus we derive the number of users for each floor, N_{F_i} under the assumption that users' densities on the floor regions are the same for all floors:

$$N_{F_1}:(C+B\delta_1)=\cdots=N_{F_i}:(C+B\delta_i)=\cdots=N_{F_K}:(C+B\delta_K) \quad (17)$$

$$\sum_{i=1}^{K} N_{F_i}=N \quad (18)$$

According to the above procedures, we can obtain the mean number of handoffs during a call by computing Eq. (11) with V_i, δ_i, and N_{F_i}.

3. Numerical Results

In order to verify the proposed mobility model in 3-dimensional PCS environments, we take simulations under the following assumptions:

- A 3-story building with 60 m×60 m×9 m is considered.
- A staircase region consists of staircases and passages and its size is 10 m×10 m×3 m.
- Call duration and idle duration are exponentially distributed with the mean of 100 sec. and 500 sec., respectively.
- The height of portable stations of horizontally moving users is 1.5 m above the bottom for each floor.
- Horizontal and vertical speeds are uniformly distributed with [0, 4] km/h and [0, 4/3] km/h, respectively. A user moves with the horizontal and/or vertical speed(s) during a call. The horizontal speed is three times faster than the vertical speed.
- Users have horizontal motions with the mean distance between turning points, 10 m on the floor region, while they have vertical or horizontal motions with the distance between turning points, 3 m and the mean distance between turning points, 10 m, respectively, on the staircase region.
- The point at the outer wall is not regarded as a turning point when a user arrives at an outer wall.
- The number of incoming and outgoing users through the gate in the building gate is in equilibrium.
- There are 540 users in total inside the building. $\alpha_2=0.7$, $\beta_2=0.3$, and $\alpha_1=\alpha_3=0.78$, $\beta_1=\beta_3=0.22$ at the turning points on the staircase regions.
- The number of cells (cell stations) per floor is 9.

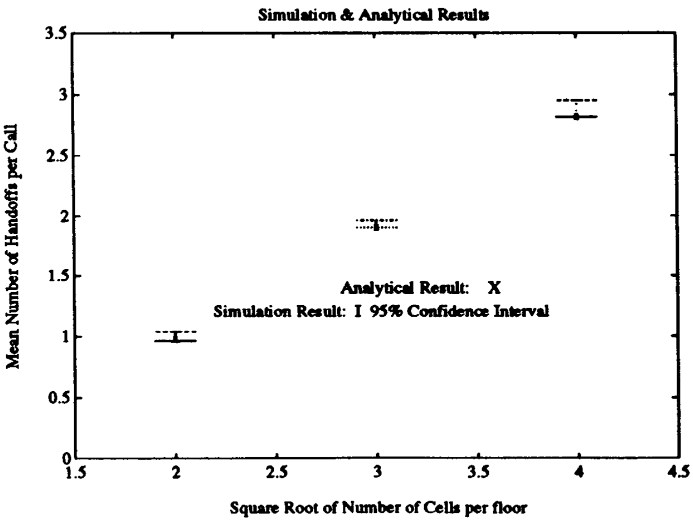

Fig. 6 The mean number of handoffs according to changing the number of cells per floor ($\beta_2=0.3$ and $\beta_1=\beta_3=0.22$).

The effect of changing the number of cell stations per floor on the mean number of handoffs is shown in Fig. 6. Smaller cells yield more frequent handoffs. The computer simulation results agree very well with the analytical ones.

Figure 7 shows the mean number of handoffs versus the change of the area of each staircase region. We can infer that the mean number of handoffs increases as the area of each staircase region increases and this analytical model describes the vertical motions well.

In Fig. 8, we can see the effect of the mean speed of users. Staying users do not create handoffs, while the mean number of handoffs of moving users increases as their mean speed increases.

Figure 9 illustrates the mean number of handoffs versus the number of cells per floor in case of $\alpha_2=0.5$, $\beta_2=0.5$, and $\alpha_1=\alpha_3=0.508$, $\beta_1=\beta_3=0.492$. This analytical model represents the effect of vertical motions fairly well in this case.

4. Conclusions

For the efficient PCS network plannings, it is essential to analyze the 3-dimensional indoor environments as well as 2-dimensional environments. However, there has been no proper mobility model describing the users' motions in 3-dimensional in-

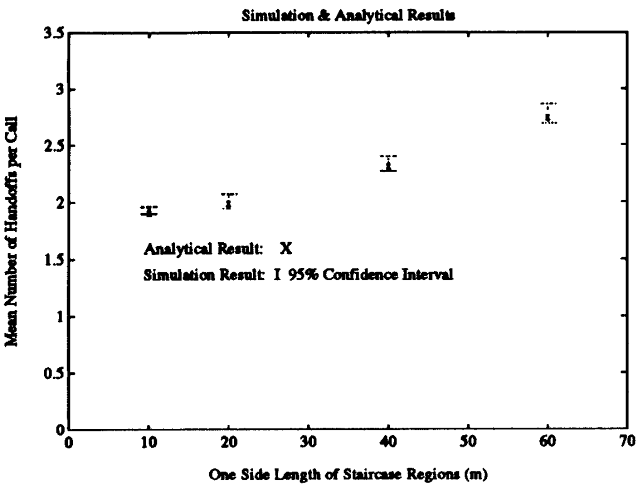

Fig. 7 The mean number of handoffs according to changing the area of each staircase region.

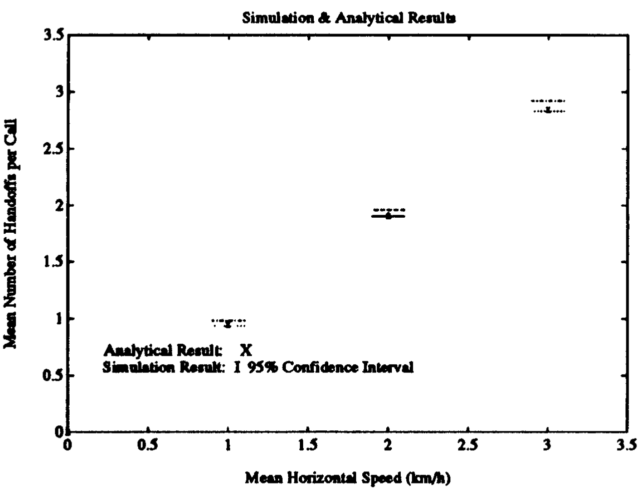

Fig. 8 The mean number of handoffs versus the mean user speed.

door PCS environments with proper boundary conditions on each floor.

We propose a personal mobility model in 3-dimensional environments by considering proper boundary conditions on each floor and horizontal/vertical movements from our 2-dimensional model suggested in [7]. We here assume that users move horizontally or vertically on the staircase region and they move horizontally on the floor. In this paper, we can model the user mobility more realistically, with these boundary conditions and horizontal/vertical motions. The simulation results of the proposed mobility model are nearly close to the analytical ones, regardless of the change of the user speed, the number of cells per floor, and the direction selection ratio.

The 3-dimensional model combined with the pre-

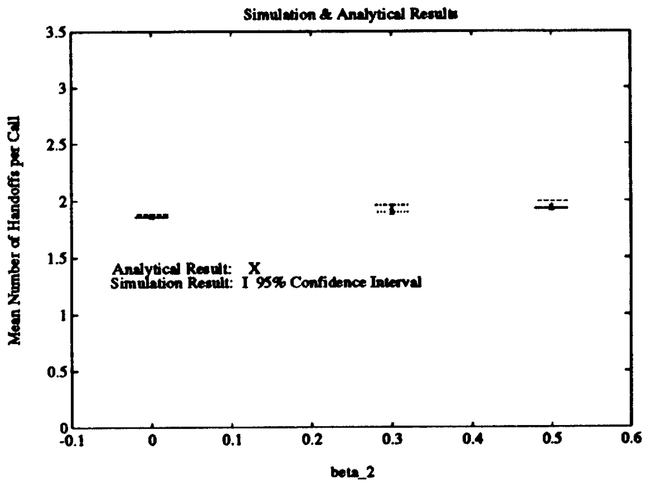

Fig. 9 The mean number of handoffs according to changing the number of cells per floor ($\beta_2=0.5$ and $\beta_1=\beta_3=0.492$).

viously proposed 2-dimensional model can be utilized in the designs and plannings of the integrated PCS networks of 2- and 3-dimensional PCS environments. Analytical characterization of human mobility in radio propagation environments can be for futher study.

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