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Analytical Bounds on Quality of Service for an Indoor Personal Communication System with General Distributed Handoff Traffic and Dynamic Channel Allocation

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Abstract—**In this paper, we propose an indoor mobility model consisting of asymmetric pico-cells for a typical personal communication system. Cell-wise mobility characteristics and the overall mobility characteristic of the system are obtained. The proposed model utilises Dynamic Channel Allocation (DCA) for effective load balancing and General distributed handoff traffic for accurate Quality of Service (QoS) estimates. Various QoS parameters have been computed for the typical indoor cellular structure. Results are compared with existing classes of models viz. Timid DCA, Aggressive DCA and Fixed Channel Allocation (FCA), which does not use load balancing. The proposed model is useful in designing indoor cellular system as it allocates channel resources effectively with fairly accurate QoS estimates.**

Key Words—**Cellular system, channel allocation, handoff traffic, mobility, pico-cell, quality of service, wireless personal communication.**

I. INTRODUCTION

In a Personal Communication Network (PCN), the mobility of a mobile user plays an important role in network performance and Quality of Service (QoS). Thus it is important to accurately model the user movement in a particular scenario together with a suitable traffic model. Several mobility models have been developed and investigated in the literature [1]–[5]. Most of the work dealt with outdoor scenario (urban or suburban) considering vehicle-borne mobile users in street layouts. Kim *et al.* [6], [7] first showed the importance of modeling an indoor environment with pico-sized cells considering turning motions of walking users in horizontal plane, vertical motion in elevators and staircases. However, no specific traffic model was developed for indoor mobility. Therefore, the application of the available outdoor traffic models, where the cell sizes are usually not pico-cells, can be investigated for indoor application. Traditionally, majority of the outdoor traffic models assumed both fresh call and handoff traffic streams to be Poisson distributed. Traffic models developed by Foschini *et al.* [8] and Re *et al.* [9] are also based on Poisson traffic but use Fixed Channel Allocation (FCA) and Dynamic Channel Allocation (DCA), respectively. It has been noticed that the assumption of Poisson traffic in general is not valid for handoff traffic regardless of the use of FCA or DCA [10]–[12], as users in micro and pico-cells undergo frequent handoffs. In such cases, the analysis using single-moment approach is not accurate and two-moment approach is needed for General distributed traffic streams [13], [14].

Therefore, the modeling of an indoor environment with General distributed traffic streams using DCA merits investigation. In this paper, we develop an indoor mobility model of a typical airport building that has several floors and elevators. Thus a user undergoes both vertical and horizontal handoffs. We use a traffic model [15] that takes General distributed handoff traffic into account and also investigate the effectiveness of DCA to achieve better QoS. We evaluate the QoS parameters using the proposed model and compare them with the bounds given by Cimini *et al.* [16] and Foschini *et al.* [8].

This paper is organized as follows. In Section II, we develop the mobility model of an airport building with some necessary assumptions. Different cell types based on the mobility factor and handoff characteristics are also classified. Finally, we obtain the expressions for system mobility and individual cell mobilities. Section III uses General distributed handoff traffic model for DCA [15], Poisson distributed traffic model for FCA [8], and Poisson distributed traffic model for DCA using Ad-Hoc Erlang approximation of Cimini *et al.* [16] in the mobility model to evaluate different types of congestion. In Section IV, various other QoS parameters are computed and their contextual effectiveness is determined. Finally, in Section V, we compare the numerical results obtained using the proposed model with those computed using an FCA model [8], and the models suggested by Cimini *et al.* [16]. We also discuss the effects of using various models on QoS parameters. Finally, we conclude with observations on how the more accurate results of the proposed model enable a system designer to achieve a specified QoS effectively.

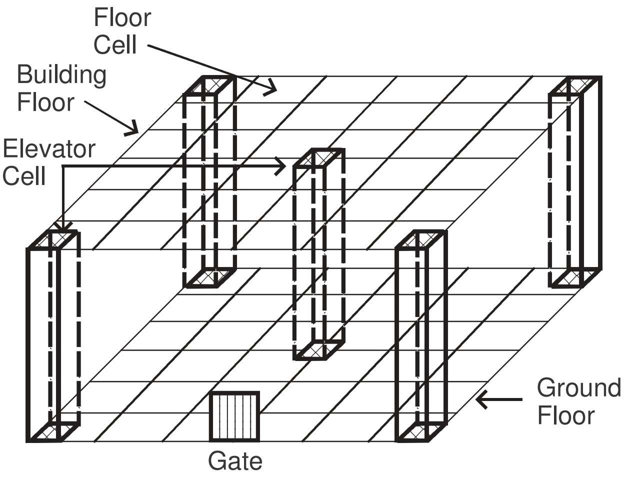


Fig. 1. Multi-level airport building.

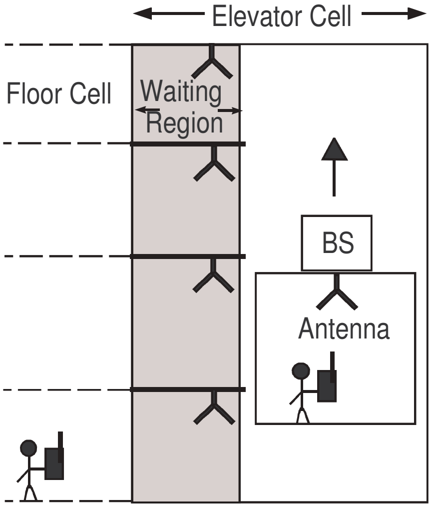


Fig. 2. Moving elevator-cell system.

II. MOBILITY MODEL OF AN AIRPORT BUILDING

We propose a mobility model for a multilevel airport building based on the mobility model of Kim *et al.* [7]. The cellular structure of a typical airport building is shown in Fig. 1. It has several floors and each floor has square shaped cells called *floor cell.* There are altogether five elevators of which one is placed at the center and others in the four corners of the building. The placement leads to the minimum average distance traveled by any user to reach the nearest elevator. Assumptions and notations used in this model are stated below.

G : Number of cell visited during a call
H : Number of handoffs during a call
V : Horizontal speed of a user
T : Call duration of a user
K : Number of floors in the building
X : Distance between two successive turning points of a horizontally moving user (exponentially distributed)
J : Journey time from waiting for an elevator until getting off the elevator (elevator cell residence time)
d : Width of a square shaped cell
u : Width of the gate
A : Area of a cell on a floor
a : Square root of the number of floor cells per floor
b : Area of an elevator region on a floor
c : Area of a floor
β_i : Vertical direction selection ratio of a user after turning in an elevator region on the i^{th} floor

We assume that the users move vertically using elevators and horizontally on the floors. We consider a *moving elevator-cell system* [17] to represent each of the elevators in the proposed model. An elevator cell includes an elevator and its waiting region on each floor as shown in Fig. 2.

Here an user does not experience the undesirable inter-floor handoffs as the elevator moves up and down. A waiting region is defined as the region immediately in front of the door of the elevator. It consists of passages excluding the elevator. The remaining region on each floor is called the floor region. An elevator cell covers both users waiting for the elevator in the elevator region and users inside the elevator. Each floor has elevator region and floor region. The users move on square-shaped floor cells, wait for elevators, or stay inside elevators. Horizontally moving users move straight until they change direction, i.e. turn right, left, or back, and then continue to move straight again. When users touch any wall, they go back to the incoming direction without delay and this is not regarded as a turning point. A user cannot handoff from any corner of a cell. There is a gate at the center of one side of the wall on the ground floor. Users in the building can enter or exit through it (Fig. 1). As soon as users choose the vertical direction in an elevator region, they handoff to the corresponding elevator cell, where they begin to wait for the elevator or enter the elevator without waiting. User density in the floor cells on each floor is identical for all floors. A horizontal handoff occurs when a user crosses a floor cell boundary or enters an elevator cell. A vertical handoff occurs when a user leaves an elevator cell. The idle duration (I) and the call duration (B) of a static user is exponentially distributed with mean $E[I] = 1/\lambda_f$ and $E[B] = E[T]$ respectively, where λ_f denotes the mean arrival rate of fresh calls (Poisson distributed). The offered load of fresh call traffic (ρ) is obtained as $\rho = \frac{E[B]}{E[I]}$.

A. Estimation of Mobility

With the above scenario, we proceed to calculate the user mobility. The cells can be classified on the basis of handoff traffic characteristics and mobility. Therefore, we first calculate the mobility specific to the type of a cell, then the mobility for the whole system. The probability of releasing an occupied channel in a cell due to handoff, ζ (also called the mobility factor), is evaluated as follows. In an infinite resource (non-blocking) system the expected number of cells visited during a call, E[G], is given by

$$\begin{aligned} E[G] &= 1(1-\zeta) + 2\zeta(1-\zeta) + 3\zeta^2(1-\zeta) + \dots \\ &= (1-\zeta)^{-1} \end{aligned} \tag{1}$$

In the above equation, the first term denotes one cell visit multiplied by the probability of one cell visit till call completion, the second term denotes two cell visits multiplied by the probability of two cell visits till call completion and so on. Hence, the mean number of handoffs during a call in a nonblocking system [8] is given by

$$E[H] = E[G] - 1 = \frac{1}{1-\zeta} - 1 \tag{2}$$

Thus, the mobility factor is expressed as

$$\zeta = 1 - \frac{1}{E[H]+1} \tag{3}$$

We now use Eqn. (29) of [7] (which is rewritten below) to obtain the probabilities of finding a user in a floor and in an elevator cell. This equation gives the probabilities of finding a user in the floor cell and the elevator cell respectively in a K storied building that contains nine floor cells per floor and one elevator cell as

$$p = \begin{cases} \dfrac{1/9}{K + \frac{B}{C}\frac{E[J]}{E[\frac{X}{V}]}\sum_{i=1}^{K}\beta_i} & \text{(floor cell)} \\[2ex] \dfrac{\frac{B}{C}\frac{E[J]}{E[\frac{X}{V}]}\sum_{i=1}^{K}\beta_i}{K + \frac{B}{C}\frac{E[J]}{E[\frac{X}{V}]}\sum_{i=1}^{K}\beta_i} & \text{(elevator cell)} \end{cases} \tag{4}$$

Modifying Eqn. (4) in the current context, we obtain the probabilities of finding a user in a floor (P_{FC}) and in an elevator cell (P_{EC}) for the proposed model as

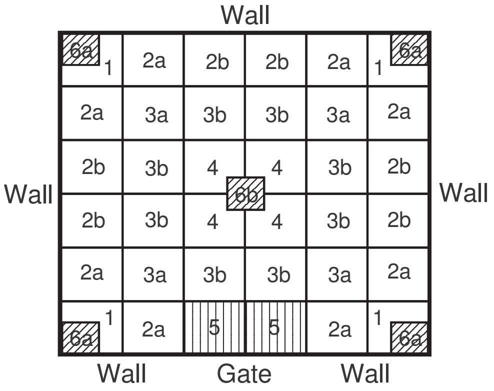
$$P_{FC} = \frac{K}{K + \frac{5b\cdot E[J]\cdot\sum_{i=1}^{K}\beta_i\cdot E[V]}{c\cdot E[X]}} \tag{5a}$$

$$P_{EC} = \frac{\frac{5b\cdot E[J]\cdot\sum_{i=1}^{K}\beta_i\cdot E[V]}{c\cdot E[X]}}{K + \frac{5b\cdot E[J]\cdot\sum_{i=1}^{K}\beta_i\cdot E[V]}{c\cdot E[X]}} \tag{5b}$$

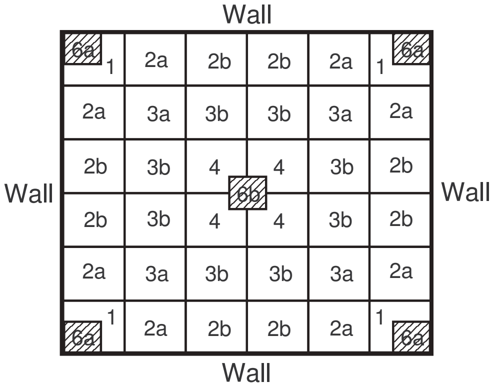
As shown in Fig. 3, the cells in this model are classified in six types (1,2,…,6). Further, a type 2 cell is subclassified as type 2a (side cell), 2b (intermediate cell) depending upon their positions among themselves. Similarly, a type 3 cell is subclassified as type 3a (corner cell), 3b (intermediate cell). Finally, type 6 cell is subclassified as 6a (corner), 6b (central).

Let us define the mobility factor of a user in type j ($j \in \{1, 2a, 2b, 3a, 3b, 4, 5, 6a, 6b\}$) cell as ζ_j and the probability of the user residing in any cell of type j as p_j. When handoffs take place from any side of a square shaped micro-cell, the mean number of handoffs during a call is expressed [18] as

$$E[H] = \frac{E[V]\cdot E[T]}{d} \tag{6}$$



(a) Ground floor.



(b) Any other floor.

Fig. 3. Types of cells.

Type 1 cell has two sides surrounded by walls, and thus, probabilistically, half the users arriving at cell sides return without a handoff. Hence, $E[H]$ is multiplied by a factor 0.5 in Eqn. (6) while computing the mean number of handoffs in type 1 cell. Since, an elevator cell also exists in type 1 cell, the additional handoffs will also occur from the type 1 cell. These are accounted for by adding a term $\frac{b}{A}\frac{\beta_i E[V]E[T]}{E[X]}$ in $E[H]$. Thus, the expressions for ζ_1 and p_1 are written as

$$\zeta_1 = 1 - \frac{1}{1 + 0.5\frac{E[V]\cdot E[T]}{d} + \frac{b}{A}\cdot\frac{\beta_i E[V]\cdot E[T]}{E[X]}} \tag{7a}$$

$$p_1 = P_{FC}\cdot\frac{4\,(1-b/A)}{a^2 - 5b/A} \tag{7b}$$

Type 2 cell has one of its four sides as wall. So $E[H]$ is multiplied with a factor of 0.75. Thus the expressions for ζ_2 and p_2 are written as

$$\zeta_2 = 1 - \frac{1}{1 + 0.75\frac{E[V]\cdot E[T]}{d}} \tag{8a}$$

$$p_2 = P_{FC}\cdot\frac{(a-2)4K - 2}{(a^2 - 5b/A)K} \tag{8b}$$

Since there are no walls in a type 3 cell, the corresponding

TABLE I
CELL TYPES WITH THEIR COUNTS AND NEIGHBORS

Cell Type	*Cell Count*	*Neighbor Count*
1	4K	3
2a,2b	$(a-2)4K-2$	3
3a,3b	$[(a-2)4-4]K$	4
4	4K	5
5	2	4
6a	4	1
6b	1	4
Average		*3.514*

expressions for a type 3 cell become

$$\zeta_3 = 1 - \frac{1}{1+\frac{E[V]\cdot E[T]}{d}} \tag{9a}$$

$$p_3 = P_{FC}\cdot\frac{4a-12}{a^2-5b/A} \tag{9b}$$

A type 4 cell includes a quarter of an elevator waiting region, hence

$$\zeta_4 = 1 - \frac{1}{1+\left(1-\frac{\sqrt{b}}{4d}\right)\frac{E[V]\cdot E[T]}{d}+\frac{0.25b}{A}\cdot\frac{\beta_i\cdot E[V]\cdot E[T]}{E[X]}} \tag{10a}$$

$$p_4 = P_{FC}\cdot\frac{2^2-b/A}{a^2-5b/A} \tag{10b}$$

A type 5 cell includes the effect of handoffs through the gate on the ground floor, giving ζ_5 and p_5 as

$$\zeta_5 = 1 - \frac{1}{1+\left(0.75+\frac{u}{8d}\right)\frac{E[V]\cdot E[T]}{d}} \tag{11a}$$

$$p_5 = P_{FC}\cdot\frac{2}{(a^2-5b/A)K} \tag{11b}$$

And finally for the type 6 (elevator) cell,

$$\zeta_6 = 1 - \frac{1}{1+\frac{E[T]}{E[J]}} \tag{12a}$$

$$p_6 = P_{EC} \tag{12b}$$

Hence, the expected mobility ζ for the system is given by

$$\zeta = \sum_{\forall j}(\zeta_j\cdot p_j) \tag{13}$$

The number of different types of cells (cell count) in the K storied airport building along with number of their neighbors (neighbor count) are given in Table I.

III. TRAFFIC MODELS

Let us consider each square shaped cell to be fitted with a base station at its center such that no two adjacent cells overlap each other. The arrangement is shown in Fig. 4, which leaves some corner spaces in cells. Since a user in the proposed mobility model cannot handoff from any corner, we assume that the probability of a user staying in such spaces is negligible. We also consider that each cell interferes with the first tier of its adjacent cells. However, both first and second tiers of adjacent cells would interfere with the elevator cells. The number of interfering cells for different types of cells classified earlier are shown in Table II.

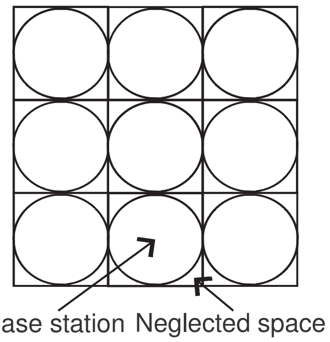


Fig. 4. Square shaped cells with base stations.

TABLE II
CELL TYPES WITH NUMBER OF INTERFERING CELLS

Cell Type	*Interfering Cell Count*
1	4
2a	6
2b	5
3a	10
3b	9
4	9
5	5
6a	4
6b	16
Average	*7*

A. General distributed Handoff Traffic with DCA

It has been shown in [10]–[14] that handoff traffic is more accurately modeled as General distributed process. The assumptions in Section II lead to the use of a traffic model [15] that allocates a channel dynamically and assumes General distributed handoff traffic. Various kinds of congestion can therefore be estimated for indoor mobile communication with DCA using the above traffic model. In order to do that, we now obtain the input parameters needed for the specified traffic model from the proposed mobility model.

Let M channels be available in the system for allocation and L denote the number of cells in a reuse group for DCA [16]. The offered load without mobility, ρ, is obtained in Section II. Mobility factors for the system and different types of cells in the proposed model have already been determined in Section II-A. The service time without mobility in a cell is considered to be Negative Exponential distributed with mean $1/\mu$, where $\mu = 1/E[T]$. Therefore, the number of cells visited per unit time, n, is obtained from Eqn. (1) as

$$n = \frac{\mu}{1-\zeta} \tag{14}$$

and the mean duration of stay in a cell, τ, is given by

$$\tau = \frac{1}{n} = \frac{1-\zeta}{\mu} \tag{15}$$

Hence, the service rate with mobility, μ', for serving a call in a cell is the reciprocal of τ, which can be written as

$$\mu' = \frac{\mu}{1-\zeta} \tag{16}$$

The mean call termination rate, μ_t, and the mean call handoff rate, μ_h, of [15] in the present context can be expressed as $\mu_t = \zeta\mu'$ and $\mu_t = (1-\zeta)\mu'$ respectively. The number of neighboring cells (W) for each of the types of cells and for the system as an average are given in Table I. The number of interfering cells (W_I) for each of the types of cells and for the system as an average are given in Table II. Using the parameters $M, \rho, \zeta, W,$ and W_I in the above traffic model we estimate the congestion of fresh call offered traffic (P_F), congestion of handoff offered traffic (P_H), and traffic congestion (P_{TC}).

B. Poisson distributed Traffic with FCA

We now briefly describe the model proposed by Foschini *et al.* [8] for Poisson distributed traffic streams with FCA. Let λ_f be the mean arrival rate of fresh call traffic (Poisson distributed) and $\bar{\Lambda}$ be the mean arrival rate of handoff traffic (Poisson distributed) in a cell. Using cellular call flow conservation [8], i.e. equating incoming and outgoing offered traffic, we obtain

$$W\bar{\Lambda} = (\lambda_f + W\bar{\Lambda})(1-P_T)\zeta Sec \tag{17}$$

where P_T is the time congestion of the combined traffic stream (which is also the call congestion of the fresh call offered traffic as well as handoff traffic). Solving Eqn. (17) for $\bar{\Lambda}$, we obtain

$$\bar{\Lambda} = \frac{\lambda_f\zeta(1-P_T)}{W[1-(1-P_T)\zeta]} \tag{18}$$

Thus, the offered traffic load with mobility, ρ', is expressed as

$$\rho' = \frac{\lambda_f + W\bar{\nabla}\Lambda}{\mu'} = \frac{1-\zeta}{1-\zeta+P_T\zeta}\rho \tag{19}$$

The congestion is obtained by using Erlang B formula and ρ' from Eqn. (19) as

$$P_T = \frac{(\rho')^C/C!}{\sum_{i=0}^{C}(\rho')^i/i!} \tag{20}$$

where $C = M/L$.

Under nonblocking condition ($P_T = 0$), $\rho' = \rho$. In such a scenario, channel occupancy distribution of the offered load does not depend on mobility. Under mobile and blocking environment ρ' depends on both congestion and mobility. As such ρ is not defined as offered traffic intensity in case of non-Poisson traffic. However, we can loosely call the mean of the traffic offered as ρ, though it does not reflect the effect of the variance of the traffic distribution.

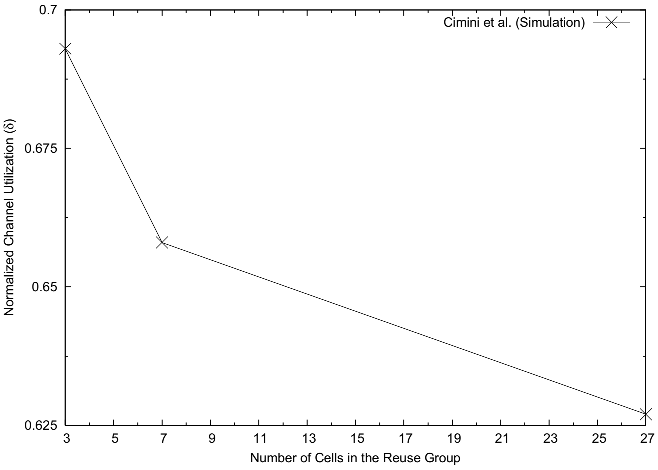


Fig. 5. Normalized channel utilization for Timid DCA model.

C. Poisson distributed Traffic with Timid DCA and Aggressive DCA

Numerous DCA models are available in literature [9], [19]–[23]. Rather than comparing with a specific DCA model, we compare the proposed model with two broad classes of homogeneous and memoryless DCA models [16], viz. *Timid DCA* and *Aggressive DCA*. The Timid DCA model proposes a mobile user to acquire a channel only if there are no nearby interferers on that channel. On the contrary, the Aggressive DCA model proposes a mobile user to take a channel even if there is interference present on that channel at the expense of additional reconfigurations (or *intra-cell handoffs*). Cimini *et al.* [16] have defined a few terms and measures related to traffic study of these models. The term *saturated array* implies that no additional cell in that cellular array can use a channel without violating the interference constraint. *Saturation density* is defined as the ratio of the number of cells using the channel to the total number of cells in the saturated array. The *normalized channel utilization (δ)* is defined as the ratio of the saturation density achieved by a model relative to the best possible saturation density. The values of δ for Timid DCA model against the number of cells in reuse group (L) are computed and plotted in Fig. 5. The parameter L depends on the cell arrangement and the structure of the mobility model. To compare the congestion using Timid and Aggressive DCA, the Erlang formula is extended to *Ad-Hoc Erlang formula* [16] as

$$P_T = \frac{(\tilde{\rho})^C/C!}{\sum_{i=0}^{C}(\tilde{\rho})^i/i!} \tag{21a}$$

where C is the number of channels available to the reuse group and $\tilde{\rho} = \rho L$. Further, for noninteger value of C, the Ad-Hoc Erlang formula can be rewritten [24] as

$$P_T = \left[\tilde{\rho}\int_0^{\infty} e^{-\tilde{\rho}t}(1+t)^C dt\right]^{-1} \tag{21b}$$

The above expressions are valid for Poisson distributed traffic streams without mobility. These are now modified to introduce the effect of mobility by replacing $\tilde{\rho}$ with $\tilde{\rho}'$ in Eqn. (22) where $\tilde{\rho}' = \rho' L$. The value of ρ' is obtained from Eqn. (19). The value of C is dependent on the number of channels available in the system (M) and is given by $C = \delta M$. For Timid DCA model, δ is determined from the plot in Fig. 5, and for Aggressive DCA model, δ is 1.

IV. DETERMINATION OF QOS PARAMETERS

In this section, few QoS parameters to quantify the performance of the system are defined. These are: i) *Forced Termination Probability* (P_{FT}), ii) *Call Completion Probability* given that the call is initiated (P_{CC}), and iii) *Mean Number of Handoffs per Call* ($E[H']$). Different types of congestion have already been discussed earlier. Table III shows the probability of a call being terminated or completed in n^{th} cell ($n = 1, 2, \dots \infty$).

The parameter P_{FT} is the probability that a call is terminated before its due completion. The first row of Table III shows the probability that a call is terminated in n^{th} cell. Summing the entries of the first row, we obtain P_{FT} as

$$\begin{aligned} P_{FT} &= P_F + (1 - P_F)P_H \sum_{n=1}^{\infty} (1 - P_H)^{n-1} \zeta^n \\ &= P_F + \frac{(1 - P_F)P_H \zeta}{1 - (1 - P_H)\zeta} \qquad (22) \end{aligned}$$

The parameter P_{CC} is a measure of how often a call which is initiated successfully is completed successfully (without being terminated due to channel unavailability). The second row of Table III shows the probability that a call is completed successfully in n^{th} cell. Summing the entries of the second row, we obtain the probability of call initiation and completion as

$$\begin{aligned} &Pr[\text{Call Initiation} \bigcap \text{Call Completion}] \\ &\quad = 0 + (1 - P_F)(1 - \zeta) \sum_{n=1}^{\infty} [(1 - P_H)\zeta]^n \\ &\quad = \frac{(1 - P_F)(1 - \zeta)}{1 - (1 - P_H)\zeta} \\ \therefore P_{CC} &= Pr[\text{Call Completion / Call Initiation}] \\ &= \frac{Pr[\text{Call Completion} \bigcap \text{Call Initiation}]}{Pr[\text{Call Initiation}]} \\ &= \frac{1 - \zeta}{1 - (1 - P_H)\zeta} \qquad (23) \end{aligned}$$

Here P_{FT} includes the chance of call blocking at the time of initiation (i.e. fresh call congestion). To find $E[H']$, we determine the expected number of cells visited, $E[G']$, as

$$\begin{aligned} E[G'] &= \sum_{n=1}^{\infty} n \big[(1 - P_F)P_H(1 - P_H)^{n-1}\zeta^n \\ &\quad + (1 - P_F)(1 - \zeta)(1 - P_H)^{n-1}\zeta^{n-1} \big] \\ &= \frac{1 - P_F}{1 - \zeta + P_H\zeta} \qquad (24) \\ \therefore E[H'] &= E[G'] - 1 \\ &= \frac{\zeta(1 - P_H) - P_F}{1 - (1 - P_H)\zeta} \qquad (25) \end{aligned}$$

A. Relative merits and demerits of the QoS parameters

Designing a micro-cellular system needs some QoS parameters to be kept under desired bounds. For a few of the QoS parameters discussed in this context, it is important to choose those which provide maximum behavioral information of the cellular model. Congestion or blocking is a good choice as this clearly indicates the failed calls or call attempts. In general, there can be three types of congestion as mentioned in Section III-A. In a non-prioritized design, traffic congestion (P_{TC}) is a more effective choice, as it directly indicates the proportion of the lost traffic, be it fresh calls or handoff calls. In a prioritized design, call congestion of the handoff traffic (P_H) is a more effective choice, because it indicates the chance of call dropping, which is more significant as it is annoying to the user.

The Mean Number of Handoffs per Call ($E[H']$) cannot be a strong choice because it does not get affected appreciably by call blocking or dropping. Since the numerator increases with mobility and the denominator decreases with mobility in Eqn. (25), $E[H']$ monotonically increases with mobility, and vice versa. We note that none of the other QoS parameters defined in this section has this drawback. Call Completion Probability (P_{CC}) predicts the probability of a call failure after being initiated and is unaffected by the probability of call initiation. If we take the call initiation probability into account, P_{CC} becomes the complement of forced termination probability (P_{FT}). Hence, P_{FT} contains the information about mobility of the users as well as the traffic characteristics of the system in terms of mobility, call initiation chance (call congestion of the fresh call traffic), and call dropping chance (call congestion of the handoff traffic). Thus, P_{TC} and P_{FT} represent the most effective choice of QoS parameters for the proposed model.

V. RESULTS AND DISCUSSIONS

We compute performance parameters for the proposed model and also for the traffic models specified in Section III when they are applied to the mobility model of Section II. The performance parameters under investigation are (i) call congestion of fresh call offered traffic, (ii) call congestion of handoff offered traffic, (iii) traffic congestion, (iv) forced termination probability, (v) probability of call completion given that the call is initiated, and (vi) mean number of handoffs per call in presence of congestion. The parameters (i), (ii), and (iii) are

TABLE III

PROBABILITY OF VISITING n NUMBER OF CELLS, $n = 0, 1, \ldots \infty$

Call Status	*0 cell*	*1 cell*	*2 cell*	...	*n cell*	...
Termination	P_F	$(1-P_F)\zeta P_H$	$(1-P_F)(1-P_H)\zeta^2 P_H$	...	$(1-P_F)(1-P_H)^{n-1}\zeta^n P_H$	...
Completion	0	$(1-P_F)(1-\zeta)$	$(1-P_F)(1-P_H)\zeta(1-\zeta)$	...	$(1-P_F)(1-P_H)^{n-1}\zeta^{n-1}(1-\zeta)$	...

equal for Poisson distributed traffic streams. These parameters are computed for various (a) types of cells, (b) offered load of fresh call traffic, (c) user speed, and (d) mean residence time of a user in an elevator cell. Unlike Poisson distributed traffic streams, in the proposed model, the call congestion experienced by fresh calls, handoff calls, and traffic congestion are not the same. These are shown distinctly in subsequent plots. The model parameters and assumptions used for computation are stated below.

- A 5-level airport building of 300 m × 300 m × 20 m is considered.
- An elevator region consists of passages excluding the elevator, includes the elevator waiting region, and its size is 10 m × 10 m × 4 m.
- There are 5 elevators placed in the building as shown in Fig. 1.
- The number of floor cells per floor is 36. This includes all types of cells that are categorized in Section II-A.
- Width of the gate is 10 m [7].
- Mean distance between successive turning points of a user is 10 m [6], [7].
- Horizontally moving users at turning points in the elevator region chooses vertical motion with probabilities 0.5 and 0.3 [7] on the ground floor and other floors, respectively.
- Mean call duration of a static user is 500 s [6], [7].
- 30 channels are available in a reuse group.
- Number of cells in reuse group is 5 in the proposed mobility model (Section II).
- The corresponding δ for Timid DCA model is found out from Fig. 5, which is equal to 0.675.

The model of Section III-A requires mean (ϵ) and standard deviation (σ) of threshold *Interference to Signal Ratio* as specified in [25]. In the mobility model of Section II, we have two tiers of interfering cells in case of the five elevator cells. In order to maintain the same ϵ, σ as specified in [25], we choose ϵ proportionately to be 4.25 dB and σ to be 4 dB.

A. Effects of Cell Types on Congestion

Congestion predicted by the above mentioned models in each type of cell are shown in Fig. 6. We assume the mean speed of a user to be 2 km/h. during a call, which is reported to be applicable for indoor users [6] and the mean residence time of a user in an elevator cell is assumed to be 60 s. The offered load of fresh call traffic is assumed to be 5 Erlang/cell. The above load can be considered to be moderate and is the same for all types of cells. In the following, we use the parameters mentioned above to investigate the performance of the proposed model, Aggressive and Timid DCA models. Aggressive and Timid DCA consider the number of channels in the system and number of cells in reuse group for estimating congestion. Thus these are insensitive to the number of neighbors, number of interfering cells, and level of interference. They merely give bounds on congestion. FCA model also gives bound on congestion but for fixed number of available channels in the cell, which depends upon the number of cells in the reuse group. These models serve well for regular and symmetric cellular structure but are unsuitable for the cellular structure of the proposed mobility model, where the elevator cells have different dimensions and placed asymmetrically. The proposed model accounts for the number of neighbors, number of interfering cells, and level of interference instead of using fixed reuse group while estimating congestion. Fig. 6 shows that for all type of cells, the call congestion of fresh call traffic and handoff traffic as well as the traffic congestion are equal as predicted by the proposed model. However, these vary from type to type. We infer that the handoff traffic still remains Poisson distributed in the chosen loading condition. We now analyze congestion behavior for different types of cells. Let us first consider type 1 cell. The proposed model predicts lesser congestion than other models for this type of cells. The Aggressive DCA always predicts lower congestion than the Timid DCA and FCA models. This is at the expense of number of reconfigurations i.e. intra-cell handoffs as mentioned in Section III-C. Timid DCA model predicts higher values of congestion than the FCA model. This occurs because congestion is more sensitive to the offered load than the number of channels available. It is to be noted that for the proposed mobility model, the equivalent offered load for the reuse group is much higher than the load offered to the

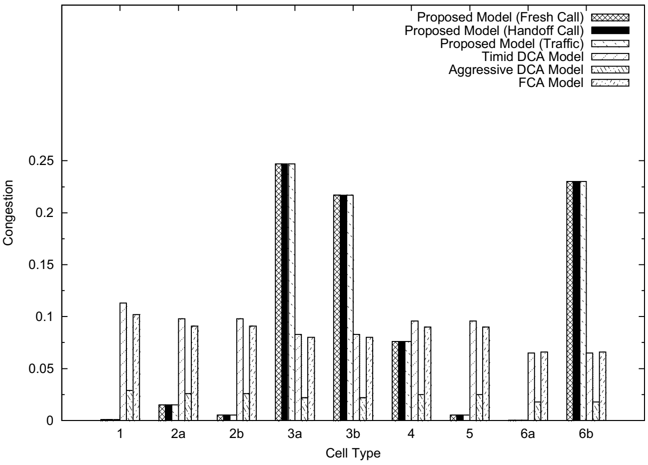


Fig. 6. Comparison of congestion among types of cells.

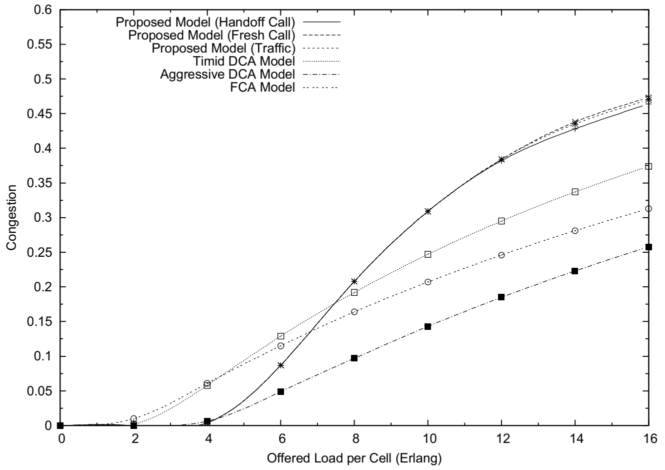


Fig. 7. Effects of offered load on congestion.

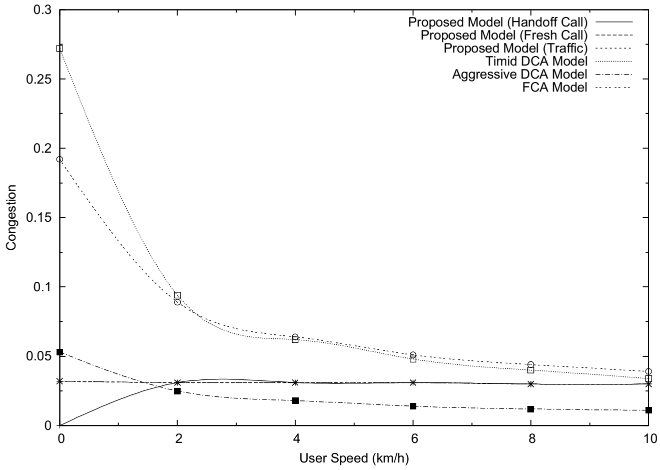


Fig. 8. Effects of user speed on congestion.

individual cells. A type 1 cell has relatively low mobility, thus the reduction in offered load due to mobility is less. A similar behavior is depicted for type 2a, 2b, and 5 cells. Type 3a, 3b, and 6b cells have large number of interferers (Table II) due to the vicinity of two elevator cells (the central and a corner). Thus the proposed model predicts considerably higher congestion than that of the other three models.

Since type 4 cells have moderate number of neighbors (5) and interferers (9), placement of these cells resembles symmetric planar cellular structure. Under this condition, the proposed model predicts higher congestion than the Aggressive DCA, while it predicts lesser congestion as compared with Timid DCA and FCA models. Thus the congestion predicted by the proposed model remains within the bounds predicted by Timid and Aggressive DCA models, which is intuitive.

Type 6a cells have high mobility that reduces the offered load in those cells. Thus Timid DCA model predicts lower congestion than FCA model. Rest of the findings are similar to that for type 1 cells.

B. Effects of Offered Load on Congestion

Next, the offered load of fresh call traffic is varied from 0 to 16 Erlang/cell while other parameters are maintained at the values mentioned in Section V-A. The resulting congestion versus offered load for the respective models is shown in Fig. 7, which depicts a similar trend as that of [15].

We classify *light load* as the offered load through which congestion predicted by the proposed and the Aggressive DCA models are negligible. With the values of the parameters assumed for the proposed model, it corresponds to a load of 4 Erlang/cell. However, at light load, Timid DCA and FCA models predict noticeable congestion ($\sim 5\%$). We consider the loads that generate (8%) congestion in the proposed model as *moderate load.* It ranges from 4 to 6 Erlang/cell. The offered load values above 6 Erlang/cell are considered as *high load.* Under light and moderate loads, all three types of congestion in the proposed model are equal. This is because DCA supports greater Erlang capacity than FCA. Thus the handoff traffic remains Poisson distributed. At high loads (around 8 Erlang/cell) the proposed model predicts higher congestion than that of the Timid DCA and FCA models. At very high loads (greater than 11 Erlang/cell), call congestion of the handoff traffic is found to be less than that of the fresh call traffic. This occurs because handoff traffic stream becomes relatively smoother (non-Poisson). Traffic congestion, in such conditions, has a range of values between the fresh call congestion and handoff call congestion. This is expected because traffic congestion gives the estimate of lost traffic that contains both fresh and handoff call requests.

C. Effects of User Speed on Congestion

Fig. 8 shows the variation of congestion with user speed. The offered load and the mean elevator cell residence time are kept constant at 5 Erlang/cell and 60 s, respectively. It is observed that the congestion decreases with increase in the user speed as expected [7]. However, at higher user speeds the rate of reduction is low. This is because, at higher speeds, most of the incoming handoff calls are blocked, thus contributing little to the call congestion in the target cell. Since the offered load is constant, the congestion tends to stabilize at higher speeds. Further computations show that reduction in the congestion and settled value of the congestion depend on the load. We also note that for a typical indoor user either walking or in horizontal escalator, the proposed model predicts appreciably lower congestion for both fresh and handoff calls compared with Timid DCA and FCA models. However, Aggressive DCA predicts lower congestion compared with the proposed model as expected. The congestion predicted using the proposed model remains unaffected with the change in user speed in this load. This occurs because the decrease in offered load due to increase in user speed is compensated by the incoming handoff traffic. The loading contribution by the incoming handoff traffic stream is more in the proposed model than the other models because it experiences lesser congestion in the former. The increased handoff traffic does not allow the congestion to decrease in the proposed model, which is usual

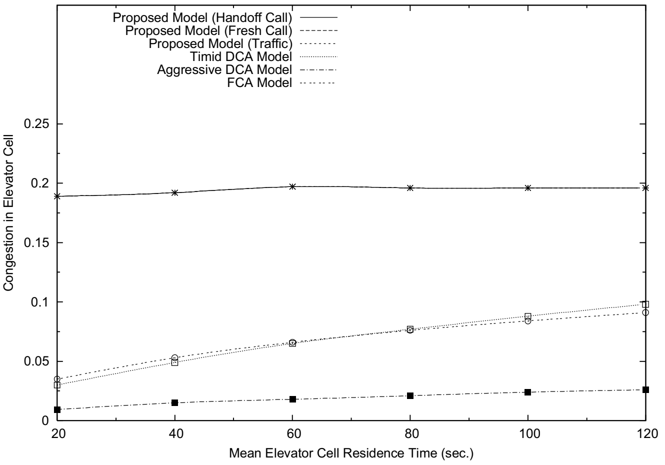
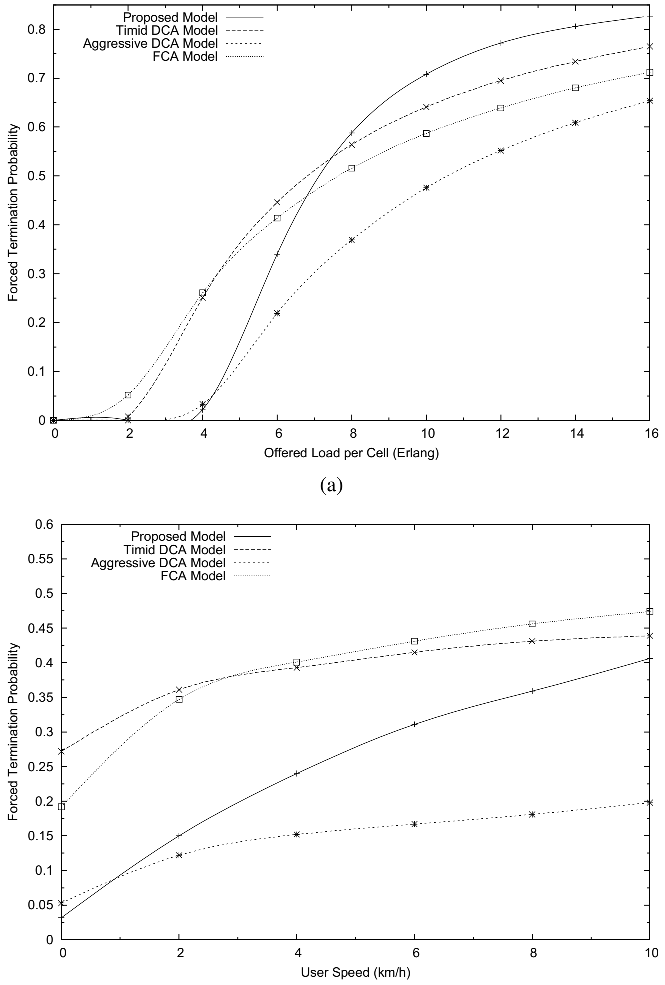


Fig. 9. Effects of elevator cell residence time on congestion.



(a)

(b)

Fig. 10. Effects of (a) offered load and (b) user speed on forced termination probability.

for other models.

D. Effects of Elevator Cell Residence Time on Congestion in an Elevator Cell

We note that the change in elevator cell residence time does not affect congestion in floor cells, because the mobility of the system does not change appreciably with elevator cell residence time. However, the elevator cell residence time affects congestion in an elevator cell.

Fig. 9 shows the variation of congestion in an elevator cell with elevator cell residence time, while keeping offered load and user speed constant at 5 Erlang/cell and 2 km/h, respectively.

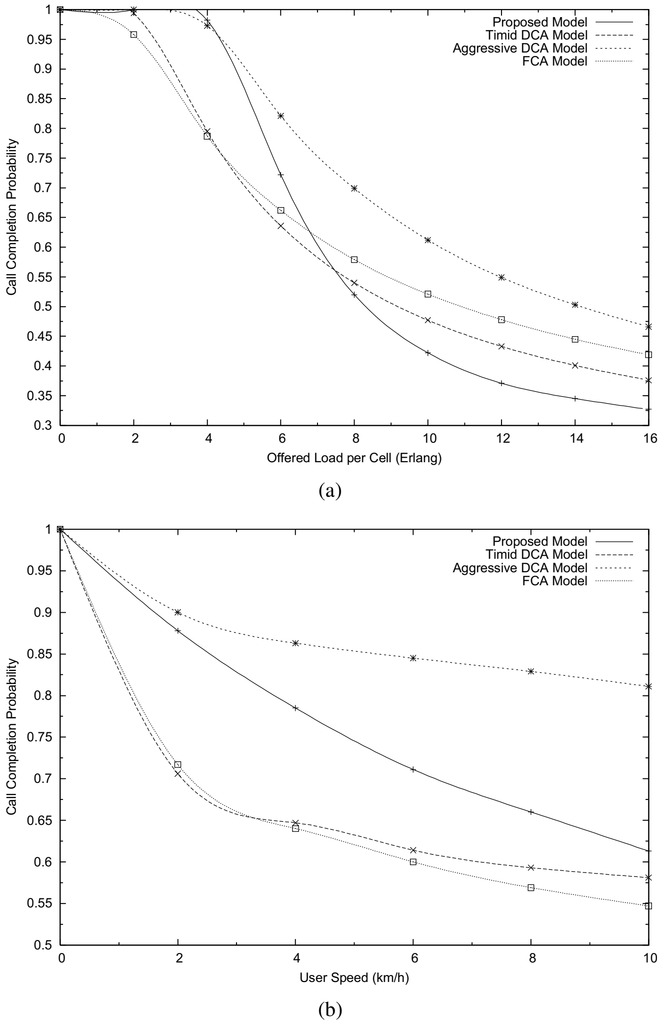
User speed does not affect the mobility in elevator cells as users do not move inside elevator cells. Instead, the duration of stay of users affects the mobility. It is observed that the proposed model predicts much higher congestion than other models because an elevator cell encounters a large number of interfering cells. We further notice an increase in congestion with the increase in elevator cell residence time for Timid DCA, Aggressive DCA, and FCA models.

The proposed model, on the other hand, predicts insignificant increase in congestion with elevator cell residence time. As the users stay more in an elevator cell, they occupy channels for longer duration. This restricts the incoming fresh call and handoff traffic in the elevator cell. Since the offered load is kept constant, the decrease in the effective load due to high rate of call failure does not allow congestion to increase with respect to elevator cell residence time. This is unique to our proposed model as the other models do not account such behaviour.

E. Effects of Offered Load and User Speed on QoS parameters

Fig. V-E shows the variation of forced termination probability (P_{FT}) with the offered load, keeping user speed and mean elevator cell residence time constant at 2 km/h and 60 s, respectively. It follows from Eqn. (22) that P_{FT} is a function of (a) call congestion during handoff, (b) call congestion during call initiation i.e. fresh call congestion, and (c) mobility. Since the congestion during handoff increases with the offered load, the value of P_{FT} increases. It is interesting to observe that at light and moderate loads (till 6 Erlang/cell), the proposed model predicts lower P_{FT} than the Timid DCA and FCA models. At high loads, the proposed model starts to perform poorly and thus predicts higher congestion than the FCA model. The performance deteriorates even more at further high load, when P_{FT} predicted by the proposed model crosses that of the Timid DCA model. This is the manifestation of inherent instability of the DCA models. It limits the accuracy of the proposed model in very high load range.

Fig. 10(b) shows the variation of P_{FT} with user speed, keeping offered load and mean elevator cell residence time constant at 5 Erlang/cell and 60 s, respectively. It is observed that P_{FT} increases with user speed. This occurs because as the user speed increases, the user crosses more cell boundaries. During each handoff, any occurrence of call drop contributes to P_{FT}. Though call congestion during handoff decreases with increase in user speed, the combined effect of all three components, as mentioned in the discussion of Fig. V-E, makes P_{FT} increase with speed. The predicted value of P_{FT} using different models are not the same. Moreover, we notice that for static users i.e. at stale condition, all models predict some non-zero P_{FT}. In such case only the congestion offered to fresh call traffic contributes to P_{FT}.



(a)

(b)

Fig. 11. Effects of (a) offered load and (b) user speed on call completion probability.

Fig. shows the variation of Call Completion Probability given that the call is initiated (P_{CC}) with offered load when we keep user speed constant at 2 km/h and mean elevator cell residence time constant at 60 s. It is observed that P_{CC} decreases with increase in offered load which is expected, because congestion of the handoff traffic reduces P_{CC}. Since P_{CC} and P_{FT} complement each other, it is evident that the characteristics found here will be opposite in nature to that observed in Fig. . Thus the proposed model predicts lower P_{CC} than other models except Aggressive DCA model at light and moderate loads. The condition becomes reversed in high and very high load.

Fig. 11(b) shows the effect of variation of user speed on P_{CC} while we keep the offered load and elevator cell residence time constant at 5 Erlang/cell and 60 s, respectively. With the increase in user speed, the chance of handoff failure increases. Naturally, the chance of call termination during each handoff process increases, which results in a reduction in P_{CC}. We also notice that P_{CC} tends to decrease at a slower rate at high user speeds (greater than 4 km/h). This occurs because the congestion of the handoff traffic attains a high value. As a result, the incoming handoff traffic flow to a cell reduces noticeably. Thus, in equilibrium, load in that cell attains a saturation value that does not increase with further increment in speed. So congestion during handoff process remains unchanged, and only the increment in mobility with speed causes decrement in P_{CC}.

Fig. 12(a) shows the variation of mean number of handoffs per call with offered load, while keeping user speed and mean elevator cell residence time constant at 2 km/h and 60 s, respectively. As congestion during each handoff increases with the increment in offered load, the mean number of handoffs per call decreases. At heavy load, it drops rapidly compared with the light load. At light load i.e. availability of almost infinite resources, the proposed model conforms to the results of the other models as expected.

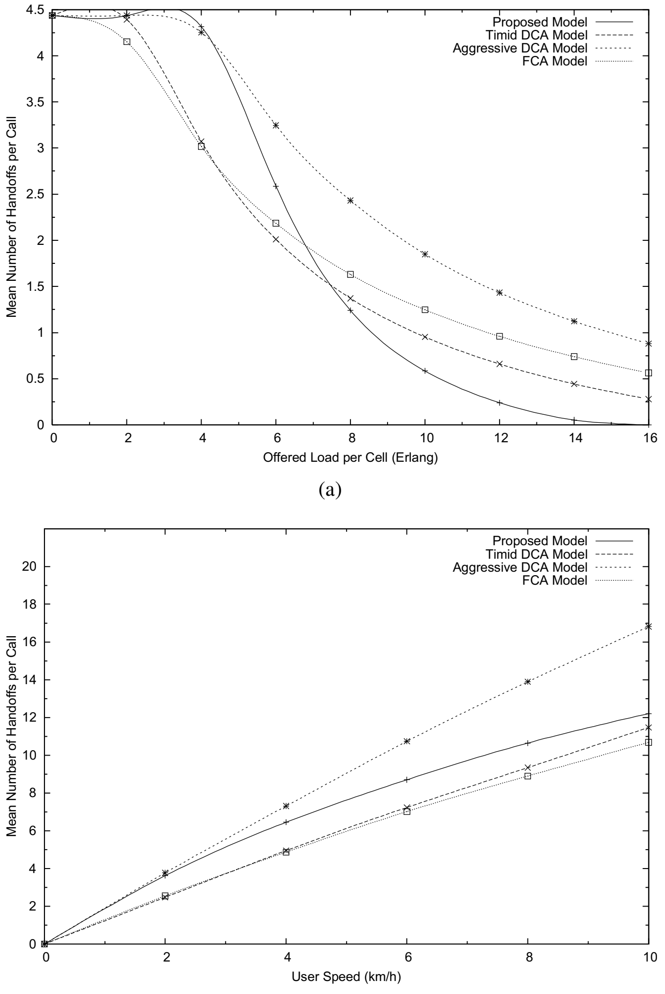
Fig. 12(b) shows the variation of mean number of handoffs per call with user speed while the user speed and mean elevator cell residence time are kept constant at 2 km/h and 60 s, respectively. We note that increase in the user speed causes a user to cross more number of cell boundaries, but mean number of handoffs per call does not increase in that proportion. This is remarkably visible in the proposed model because the congestion predicted by the model increase rapidly at heavy load.

The trends of results obtained in this paper are summarized in Fig. 13.

In the figure, trends for parameters Congestion versus Load, Forced Termination Probability versus Offered Load, and Forced Termination Probability versus Speed are as expected. The same is applicable for Congestion versus Elevator Cell Residence Time in FCA model. The trends for other parameters (viz. Congestion versus Speed, Call Completion Probability versus Speed) have not been reported earlier.

VI. CONCLUSION

In this paper, we developed an indoor mobility model with asymmetric cellular structure at pico-cell level, where both static floor cells and moving elevator cells are considered using both horizontal and vertical handoffs. In view of the established accuracy of General distributed handoff process, we investigated the effects of both symmetric and asymmetric cellular structures on QoS parameters. While the earlier models that are developed for symmetric cellular structure, viz. FCA, Timid DCA, and Aggressive DCA predict congestion bounds, the proposed model predicts accurate results because



(a)

(b)

Fig. 12. Effects of (a) offered load and (b) user speed on mean number of handoffs per call.

it takes number of channels in the system, number of cells in the reuse group, number of neighbors, number of interfering cells, and the level of interference into account. The earlier models consider only number of channels in the system and number of cells in the reuse group. The methodology presented in this work can be used by a system designer to achieve a specified level of QoS by allocating the resources i.e. number of channels effectively. The above is especially applicable when the cellular structure is asymmetric and handoff process is non-Poisson. The less accurate, earlier models can be used for symmetric cellular structure and Poisson distributed handoff process.

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→ **Models** ↓ **Parameters**	**Timid DCA**	**Aggr. DCA**	**FCA**
Congestion in Cell Type			
1,2a,2b,5,6a	<	<	<
3a,3b,6b	>	>	>
4	<	>	<
Elevator Cell Res. Time	>	>	>

(a)

→ **Models** ↓ **Parameters**	**Timid DCA**	**Aggr. DCA**	**FCA**
Congestion and Forced Termination Probability			
Light Load	<	=	<
Moderate Load	<	>	<
Heavy Load	>	>	>
Low Speed	<	<	<
Moderate / High Speed	<	>	<

(b)

→ **Models** ↓ **Parameters**	**Timid DCA**	**Aggr. DCA**	**FCA**
Call Completion Probability given Call Initiated			
Light Load	>	=	>
Moderate Load	>	<	>
Heavy Load	<	<	<
All Speed	>	<	>

(c)

Fig. 13. *The trends of results*: (a) congestion in cell type and elevator cell, (b) congestion and forced termination probability, (c) call completion probability.
Note 1: Here $<, =, >$ respectively denote that the predicted value using the proposed model is lesser, equal, greater than the predicted value using the shown model (Timid DCA/Aggressive DCA/FCA).
Note 2: The corresponding table for mean number of handoffs per Call is obtained by replacing $<, =, >$ with $>, =, <$ respectively in (b).

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