Technical Research Report

Channel Holding Time Distribution in A Hybrid Satellite and Cellular Communication System

by T-H. Wu and E. Geraniotis

CSHCN TR 93-8/ISR TR 93-96

Center for Satellite & Hybrid Communication Networks

A NASA Center for the Commercial Development of Space

University of Maryland Institute for Systems Research

CHANNEL HOLDING TIME DISTRIBUTION IN A HYBRID SATELLITE AND CELLULAR COMMUNICATION SYSTEM

T.-H. Wu and E. Geraniotis

Department of Electrical Engineering
and Institute for Systems Research
University of Maryland
College Park, MD 20742

Abstract

This paper evaluates the distribution of channel holding time in a hybrid satellite and cellular communication system. The channel holding time is defined as the time duration between the instant that a channel is assigned to a call and the instant it is released either upon the completion of a call or a upon the completion of a cell (or satellite footprint) boundary crossing by a mobile. Our hybrid system consists of three levels of cells - microcell, macrocell, and satellite footprint. The distribution of channel holding time for each cell level is analyzed by using a distinct system model. The results show that a negative exponential distribution is an appropriate approximation of the channel holding time in our system. This provides a very useful system parameter in multi-layer cellular systems.

This research was supported in part by the Center for Satellite and Hybrid Communication Networks (NASA CCDS) and in part by the Institute for Systems Research at the University of Maryland, College Park, through the National Science Foundation's Engineering Research Centers Program, NSF CDR 8803012.

1 INTRODUCTION

The distribution of channel holding time is an important parameter in cellular systems. Most of the issues in cellular systems (such as systems design, channel assignment, and handoff procedures) relate strongly to this parameter. In the previous work analyzing cellular systems (see [1], [2]), the distribution of channel holding time was approximated to a negative exponential distribution. By using this approximation, the performance analysis of cellular system becomes easier. The suitability of this approximation has been proved by both computer simulation [3] and analytical approach [1], [3]. But all these works are based on a traditional cell structure (Figure 1), which cannot be applied to our hybrid system.

The structure of our hybrid system is shown in Figure 2. A satellite footprint contains some macrocellular systems, while each microcellular system has an overlaying macrocellular system. The cell size of a macrocell is about that of the traditional cellular system. Because of the increasing demand for cellular radio service in urban areas and hand-portable cellular terminals, there is an increased interest in making the cells smaller. This small cell is called a "microcell". On the other hand, in order to build a system that can provide flexible, wireless, and person-to-person communication services on a worldwide basis, communication satellites have to be incorporated into the system, so that the whole system can become a hybrid satellite and cellular communication system, which includes microcells, macrocells, and satellite footprints. Normally, a microcellular system is located in urban areas and has cell radius smaller than several hundred meters. A macrocellular system covers both urban and suburban areas. It not only overlays a microcellular system in a city, but also provides services in the suburbs of the city. The radius of a macrocell ranges from 1 to 10 kilometers. A satellite footprint covers a radius of a few hundred kilometers and, as such, it overlays both microcellular and macrocellular systems. This hybrid structure is much more complicated than the simple structure of the traditional cellular system shown in Figure 1. Therefore, the analysis results based on the simple structure [1], [3] are not applicable to our hybrid system.

In this paper, we analyze the distribution of channel holding time in three levels - the microcell, the macrocell, and the satellite footprint level. As usual, the call duration (or message duration) is assumed to have an exponential distribution. If a mobile stays in a cell all the time, the channel holding time is the call duration. But in fact, a mobile can move through several cells while involved in a single call. In this case, the channel holding time equals the fraction of the total call duration, during which the mobile is located in the associated cell. Intuitively, a mobile tends to stay in a large cell (such as the satellite footprint) for a long period of time. So the channel holding time in a satellite footprint tends to be exponentially distributed. On the contrary, a mobile can move through several small cells in a short period of time. So the channel holding time in a small cell need not be exponentially distributed. Accordingly, we put more emphasis on the analysis of microcellular systems in this paper.

This paper is organized as follows. In Section 2, the method of analyzing the channel holding time is described. Section 3 presents the system model and the analysis of channel holding time at each level of the cell. In Section 4, numerical analysis results of some specific parameters of the system are presented. Conclusions are drawn in Section 5.

2 Derivation of Channel Holding Time

We use an analytical approach to analyze the channel holding time. This approach is described in detail in [1]. The channel holding time T_H is defined as the time duration between the instant that a channel is assigned to a call and the instant it is released upon either completion of the call or a cell (or satellite footprint) boundary crossing by a mobile. To derive the distribution of T_H, the following random variables are defined:

- D_n: a mobile's travel distance in a cell between the instants of call initiation and the mobile's exiting the cell.
- D_h: a mobile's travel distance in a cell (between the instants of its entering and exiting the cell).
- V : the average speed of a mobile.
- T_n: the time duration between call initiation and the mobile's exiting the cell.
- T_h: the time duration between the mobile's entering the cell and the mobile's exiting the cell.
- T_L: the time a mobile waits at the traffic lights.
- T_M: the unencumbered message duration (i.e., the time an assigned channel would be held, if no handoff is required.)

In addition, two deterministic variables are necessary :

- Λ_n: the average rate (calls/sec/cell) at which new calls are carried.
- Λ_h: the average rate (calls/sec/cell) at which handoff calls are carried.

The random variable T_M is assumed to be exponentially distributed with mean value $1/\mu_M$ and with probability density function

$$f_{T_M}(t) = \begin{cases} \mu_M e^{-\mu_M t} & \text{for } t \geq 0 \\ 0 & \text{otherwise} \end{cases} \tag{1}$$

A channel of a cell can be occupied by two types of calls. One encompasses the calls that originate in the cell and get the channel; we define them as Type I calls. The other involves calls that are handed off successfully to the cell and get the channel. We define them as Type II calls. For a Type I call, it occupies the channel from the time of its initiation until the call terminates or until a cell boundary crossing by the mobile takes place. Therefore, the channel holding time of a type I call T_{H1} is either T_M or T_n, whichever is less; i.e.,

$$T_{H1} = \min(T_M, T_n) \tag{2}$$

For a Type II call, the channel is occupied, since the mobile enters the cell till the call is completed in the cell or the mobile again crosses the cell boundary. So the channel holding time of a type II call T_{H2} is either the remaining message duration of a call after handoff, or T_h, whichever is less. Because of the memoryless property of the exponential distributions, the remaining message duration has the same distribution as the unencumbered message duration. Therefore, T_{H2} is given by

$$T_{H2} = \min(T_M, T_h) \tag{3}$$

With the average call rates Λ_n and Λ_h, the distribution of T_H is

$$f_{T_H}(t) = \frac{\Lambda_n}{\Lambda_n + \Lambda_h} f_{T_{H1}}(t) + \frac{\Lambda_h}{\Lambda_n + \Lambda_h} f_{T_{H2}}(t) \tag{4}$$

Since the distribution of $Z = min(X, Y)$ is

$$f_z(z) = f_x(z)[1 - F_y(z)] + f_y(z)[1 - F_x(z)] \tag{5}$$

where f_x, f_y, f_z are pdfs of X, Y, and Z, respectively; F_x, F_y are cdfs of X, and Y, respectively.

Equation (4) can be written as

$$f_{T_H}(t) = e^{-\mu_M t}[\mu_M(1 - F_{T'_H}(t)) + f_{T'_H}(t)] \tag{6}$$

where

$$\begin{aligned} f_{T'_H}(t) &= \frac{\Lambda_n}{\Lambda_n + \Lambda_h} f_{T_n}(t) + \frac{\Lambda_h}{\Lambda_n + \Lambda_h} f_{T_h}(t) \\ &\triangleq P_I f_{T_n}(t) + P_{II} f_{T_h}(t) \end{aligned} \tag{7}$$

$$F_{T'_H}(t) = \int_0^t f_{T'_H}(x)dx \tag{8}$$

Random variables T_n and T_h are given by

$$T_n = \frac{D_n}{V} + T_L \tag{9}$$

$$T_h = \frac{D_h}{V} + T_L \tag{10}$$

Note that the average speed V is measured under the condition that the time a mobile spends at the traffic lights is ignored. In the above two equations, D_n and D_h depend on the structure of the cell, V depends on the traffic, while T_L depends on both. To get the distribution of channel holding time in the microcell, macrocell, and at the satellite footprint, we build one model for each of the three cell levels. The next section presents these models. And the random variables T_n, T_h, and T_H are analyzed.

3 SYSTEM MODELS AND ANALYSIS

3.1 Microcell Systems

The geometry of our microcellular system, which is adopted from [4], consists of a rectangular layout of avenues intersecting with streets (Figure 3). The streets and avenues have approximately the same width, which equals A meters and delimit city blocks that are fairly constant in size and roughly equal to $B \times B$ meters. The range of microcells and the location of base stations are shown in Figure 4. The vertical and horizontal lines respectively denote the city avenues and city streets. The small dots and squares denote the base stations on avenues and streets. The bold line section covers the range of a city microcell. Here we assume that a microcell covers a range of even number (N) of intersections (and blocks), so that the base station locates at the middle of a block. The base station antennas are installed at elevations well below the city skyline with a minuscule base station transmit power (e.g. on a telephone post or a street lamp.) So the received pilot signal level on the mobile terminal becomes suddenly low whenever the mobile turns out of the main street in which the base station is located. By using this property, the handoff criteria of our microcellular system is the following: if the current pilot signal is not the highest one, then the handover procedure begins. But we can see from Figure 4 that there are always two strong enough and compatible pilot signals in each intersection. To avoid unnecessary handoffs caused by the competition of these two pilot signals, when a mobile goes through an intersection, the handoff criteria of our microcellular system is modified as follows: if the strength of the current pilot signal is not the highest one and is lower than some threshold, then the handover procedure begins. On the basis of this criterion, a single microcell is actually a section of avenue (or street) consisting of N intersections and N blocks. Figure 5 shows a typical microcell consisting of 4 intersections and 4 blocks.

Let us begin the analysis of the distribution of channel holding time in the microcellular system. Assuming that the traffic patterns in each direction of a street (or avenue) are statistically symmetric, we need only consider traffic movement toward one direction (say north in Figure 5). To analyze T_n for Type I calls, the whole cell is segmented into $2N+1$ contiguous regions, from region 1 to region $2N+1$. In Figure 5, the south edge of the cell is set to be the origin of the coordinate. Let $E_i (1 \leq i \leq 2N+1)$ denote the coordinate of the edge between region i and region $i+1$; then

$$E_i = \begin{cases} \frac{i-1}{2}A + \frac{i}{2}B & i = odd\ ;\ i \neq 2N+1 \\ \frac{i-1}{2}(A+B) & i = even \\ N(A+B) & i = 2N+1 \end{cases} \qquad (11)$$

Assume that a mobile can initiate a call at any location (or coordinate) of the cell with equal probability; then the probability of a call initiation in region i ($1 \leq i \leq 2N+1$) is

$$p_i = \begin{cases} \frac{B}{2N(A+B)} & i = 1 \\ \frac{A}{2N(A+B)} & i = even \\ \frac{A+2B}{2N(A+B)} & i = odd \; ; \; i \neq 1, 2N+1 \\ \frac{1}{2N} & i = 2N+1 \end{cases} \tag{12}$$

Assume that there is a traffic light in each intersection. These traffic lights are located at the edge between region $2i-1$ and $2i$ $(1 \leq i \leq N)$ and are denoted by $S_1, \ldots, S_N$ in Figure 5. A mobile in region $2i-1(1 \leq i \leq N)$ may wait at traffic light S_i before entering region $2i$ or just enter region $2i$ without waiting at S_i. We assume that the probability a mobile in region $2i-1$ has to wait at light S_i is p_w, for $i = 1, \ldots, N$. The routing behavior of a mobile in the cell is described in the following. When a mobile is in an odd region, it can go straight to the next region only. When a mobile is in an even region $2i$, it can either go straight to region $2i+1$ with probability p_s, or make a left (or right) turn at the boundary of region $2i$ and $2i+1$ with probability $1-p_s$. Thus, after a call initiation, a mobile can take several possible paths before leaving the cell. The number of paths depends only on where the call is originated. Let $m_i(1 \leq i \leq 2N+1)$ be the number of different paths a mobile may use, given the call is originated in region i; then m_i is

$$m_i = N + 2 - \lceil \frac{i}{2} \rceil \tag{13}$$

For each i, we sort the m_i paths by length in ascending order. That is, for a given i, the length of path j is shorter than that of path $j+1$, for $j = 1, \ldots, m_i - 1$. Figure 6 shows the 15 different paths a mobile may take when the call is originated in region 1 and $N = 4$. Let $q_{ij}(1 \leq i \leq 2N+1, 1 \leq j \leq m_i)$ denote the probability that a mobile uses path j, given that the call is originated in region i; then

$$\begin{aligned} q_{ij} &= P_r\{ \text{ a mobile uses path } j | \text{ the call is originated in region } i\} \\ &= p_s^{j-1}(1-p_s)^{I_{ij}} \end{aligned} \tag{14}$$

where

$$I_{ij} = \begin{cases} 1 & \text{if } j < m_i \\ 0 & \text{if } j = m_i \end{cases} \tag{15}$$

Let $L_{ij}(i \leq 1 \leq 2N+1, 1 \leq j \leq m_i)$ be the number of traffic lights a mobile need to pass, given that the call originates in region i and that the mobile uses path j; then L_{ij} is

$$L_{ij} = \begin{cases} j - [(i+1) \bmod 2] & \text{for } j < m_i \\ j - 1 - [(i+1) \bmod 2] & \text{for } j = m_i \end{cases} \tag{16}$$

Let $\beta_{ijk}(1 \leq i \leq 2N+1, 1 \leq j \leq m_i, 0 \leq k \leq L_{ij})$ be the probability that a mobile waits at k traffic lights, given that the call originates in region i and that path j is used by the mobile; then

$$\begin{aligned} \beta_{ijk} &= \{ \text{ a mobile waits at } k \text{ signals} | \begin{matrix} \text{call initiation in region } i, \\ \text{path } j \text{ used} \end{matrix} \} \\ &= \binom{L_{ij}}{k} {p_w}^k (1-p_w)^{L_{ij}-k} \end{aligned} \tag{17}$$

Define random variable $D_{nij}(1 \leq i \leq 2N+1, 1 \leq j \leq m_i)$ as the distance a mobile travels in a cell from the time the call is initiated until the mobile exits the cell, given that the call is originated in region i and that the mobile uses path j. For a given i, the coordinate at which a call is originated is uniformly distributed over region i and the coordinate at which the mobile leaves the cell depends only on j. D_{nij} is the distance between the deterministic exit point of path j (denoted by Z_{ij}) and the random call initiation point in region i. So D_{nij} is uniformly distributed over a range $R_i = E_i - E_{i-1}(1 \leq i \leq 2N+1, E_0 = 0)$, which is independent of i. For given i,j, the lower bound of range R_i (denoted by L_{nij}) is $Z_{ij} - E_i$. The variables Z_{ij}, R_i, and L_{nij} are presented below.

$$Z_{ij} = \begin{cases} [\frac{2N-1}{2} - (m_i - j - 1)](A+B) & j < m_i \\ N(A+B) & j = m_i \end{cases} \tag{18}$$

$$R_i = \begin{cases} \frac{B}{2} & i = 1 \\ \frac{A}{2} & i = \text{even} \\ \frac{A+2B}{2} & i = \text{odd}, i \neq 1, 2N+1 \\ \frac{A+B}{2} & i = 2N+1 \end{cases} \tag{19}$$

$$L_{nij} = \begin{cases} \frac{1}{2}A(i \bmod 2) + (j-1)(A+B) & i \neq 2N+1, j < m_j \\ \frac{1}{2}A(i \bmod 2) + \frac{2j-3}{2}(A+B) & i \neq 2N+1, j = m_i \\ 0 & i = 2N+1 \end{cases} \tag{20}$$

By using these variables, the distribution of D_{nij} is

$$f_{D_{nij}}(d) = \begin{cases} \frac{1}{U_{nij}-L_{nij}} & L_{nij} < d < U_{nij} \\ 0 & \text{otherwise} \end{cases} \tag{21}$$

where

$$U_{nij} = L_{nij} + R_i \tag{22}$$

To derive the distribution of T_n, we still have to know the distribution of the average speed of a mobile and that of the time a mobile spends at the traffic lights. As mentioned in Section II, the average speed V is measured under the condition that the time a mobile spends at the traffic lights is ignored. That is, we pause the average speed measuring instrument, while a mobile waits at a traffic light, and resume it when the mobile gets going again. Since there is always a speed limit in a city street and the traffic in the city tends to keep every single mobile driving in a fairly constant speed, the average speed V of a mobile in a microcell ordinarily takes some specific values. These values are decided by a few factors. For instance, in a multi-lane street, the mobiles in different lanes usually drive at different speeds. In addition, different kinds of mobiles generally do not move in the same speed range. So, in our model, the distribution of the average speed of a mobile in a microcell V is assumed to be discrete with pmf given by

$$P(V = v_l) = \alpha_l, \qquad l = 1, 2, \ldots, M \tag{23}$$

where the v_ls and M are parameters which may vary from cell to cell and from one time period to another (e.g. in rush hour, the average speed becomes slower.)

Let $T_{L_{ijk}} (1 \leq i \leq 2N+1, 1 \leq j \leq m_i, 0 \leq k \leq L_{ij})$ be the total time a mobile waits at traffic lights from the time of the call initiation until the mobile exits the cell, given that the call is originated in region i, the mobile takes path j and waits at k traffic lights in path j. Evidently, $T_{L_{ijk}}$ depends only on the value of k. Assume that the time a mobile spends at a single traffic light is uniformly distributed over $[0, T_w]$ and that the time a mobile spends at different traffic lights are independent; then $T_{L_{ijk}}$ is the sum of k i.i.d. uniform distributions. For $k = 0$ to 2, the distribution of $T_{L_{ijk}}$ is

$$f_{T_{L_{ijk}}}(t) = \begin{cases} \delta_0(t) & k = 0 \\ U[0, T_w](t) & k = 1 \\ Tri[0, 2T_w](t) & k = 2 \end{cases} \tag{24}$$

where $U[a,b]$ denotes a uniform distribution over $[a,b]$, and $Tri[a,b]$ denotes a triangular distribution over $[a,b]$, i.e.,

$$Tri[a,b](t) = \begin{cases} \frac{4}{(b-a)^2}(t-a) & a \le t < \frac{a+b}{2} \\ \frac{-4}{(b-a)^2}(t-b) & \frac{a+b}{2} \le t \le b \end{cases} \tag{25}$$

For $k \ge 3$, $T_{L_{ijk}}$ can be well approximated by a Gaussian distribution with mean $\frac{kT_w}{2}$ and variance $\frac{kT_w{}^2}{12}$ [5]. Therefore,

$$T_{L_{ijk}} \sim N(\frac{kT_w}{2}, \sqrt{\frac{kT_w{}^2}{12}}), \qquad k \ge 3 \tag{26}$$

Let $T_{n_{ijk}} (1 \le i \le 2N+1, 1 \le j \le m_i, 0 \le k \le L_{ij})$ denote the time a mobile spends in a cell from the time of call initiation until the mobile exits the cell, given that the call is originated in region i, the mobile takes path j and waits at k traffic lights; then $T_{n_{ijk}}$ is given by

$$T_{n_{ijk}} = \frac{D_{nij}}{V} + T_{L_{ijk}} \tag{27}$$

The distribution of $T_{n_{ijk}}$ is

$$\begin{aligned} f_{T_{n_{ijk}}}(t) &= \sum_{l=1}^{M} f_{T_{n_{ijk}}|V}(t|V = v_l)\alpha_l \\ &\triangleq \sum_{l=1}^{M} f_{T_{n_{ijkl}}}(t)\alpha_l \end{aligned} \tag{28}$$

where

$$T_{n_{ijkl}} = \frac{D_{nij}}{v_l} + T_{L_{ijk}} \tag{29}$$

From (24), (26), and (29), the distribution of $T_{n_{ijkl}}$ can be obtained as

$$T_{n_{ijkl}}(t) = \begin{cases} U[\frac{L_{nij}}{v_l}, \frac{U_{nij}}{v_l}] & k = 0 \\ U[\frac{L_{nij}}{v_l}, \frac{U_{nij}}{v_l}] * U[0, T_w] & k = 1 \\ U[\frac{L_{nij}}{v_l}, \frac{U_{nij}}{v_l}] * Tri[0, 2T_w] & k = 2 \\ U[\frac{L_{nij}}{v_l}, \frac{U_{nij}}{v_l}] * N(\frac{kT_w}{2}, \sqrt{\frac{kT_w{}^2}{12}}) & k \ge 3 \end{cases} \tag{30}$$

where $*$ denotes the convolution operation. To get a closed form for the above equation we need to derive the following distributions:

- $U[a,b] * U[0,T]$
- $U[a,b] * Tri[0,2T]$
- $U[a,b] * N(\eta,\sigma)$

The first distribution is

$$U[a,b] * U[0,T] = \begin{cases} \frac{t-a}{(b-a)T} & a \le t \le \min(b, a+T) \\ \frac{1}{T} & b = \min(b, a+T) \le t \le \max(b, a+T) \\ \frac{1}{b-a} & \min(b, a+T) \le t \le \max(b, a+T) = b \\ \frac{b-t+T}{(b-a)T} & \max(b, a+T) \le t \le b+T \end{cases} \tag{31}$$

The distribution of $U[a,b] * Tri[0,2T]$ can be evaluated in a similar way and

$$U[a.b] * N(\eta,\sigma) = Q(\frac{t-a-\eta}{\sigma}) - Q(\frac{t-b-\eta}{\sigma}) \tag{32}$$

where

$$Q(\alpha) = \int_{-\infty}^{\alpha} \frac{1}{\sqrt{2\pi}} e^{-\frac{x^2}{2}} dx \tag{33}$$

Finally, the distribution of T_n can be presented as

$$f_{T_n}(t) = \sum_{i=1}^{2N+1} \sum_{j=1}^{m_i} \sum_{k=0}^{L_{ij}} \sum_{l=1}^{M} f_{T_{n_{ijkl}}}(t) \alpha_l \beta_{ijk} q_{ij} p_i \tag{34}$$

This equation can be evaluated by substituting the associated terms with (12), (14), (17), (23), and (30).

Next we evaluate the distribution of T_h for Type II calls. As we defined in Section II, T_h is the time duration between the instants a mobile enters and exits a cell. It is necessary to identify the points at which a mobile can enter a cell first, the so-called "entry points." A mobile can enter a cell through $N+1$ entry points. Figure 7 shows the 5 entry points of a cell with cell size parameter $N = 4$. One is at the South edge of the cell. The other four entry points are located at the four intersections of the main avenue and the four streets. Since traffic in the two directions of a street is considered symmetric, we assume that there is only one entry point at each road intersection. If we use the same coordinate system as before, the coordinate of entry point i, denoted by $E'_i(1 \le i \le N+1)$, is given by

$$E'_i = \begin{cases} 0 & i = 1 \\ \frac{2i-3}{2}(A+B) & i = 2, \ldots N+1 \end{cases} \tag{35}$$

Imitating the analyzing process of Type I calls we define the following variables:

- $p'_i(1 \le i \le N+1)$: the probability that a call is handed off to a cell through entry point i.
- $m'_i(1 \le i \le N+1)$: the number of different paths a mobile may use, given that the call is handed off through entry point i.
- $q'_{ij}(1 \le i \le N+1, 1 \le j \le m'_i)$: the probability that a mobile uses path j, given that the call is handed off through entry point i.
- $Z'_{ij}(1 \le i \le N+1, 1 \le j \le m'_i)$: the coordinate of the exit point of path j, given that the mobile enters the cell through entry point i.
- $L'_{ij}(1 \le i \le N+1, 1 \le j \le m'_i)$: the number of traffic lights a mobile need to pass, given that the call is handed off through entry point i and that the mobile uses path j.
- $\beta'_{ijk}(1 \le i \le N+1, 1 \le j \le m'_i, 0 \le k \le L'_{ij})$: the probability that a mobile waits at k traffic lights, given that the call is handed off through entry point i and path j is used by the mobile.
- $D_{h_{ij}}(1 \le i \le N+1, 1 \le j \le m'_i)$: the distance a mobile travels in a cell from the time it enters the cell till it exits the cell, given that the mobile enters the cell through entry point i and that it uses path j.
- $T'_{L_{ijk}}(1 \le i \le N+1, 1 \le j \le m'_i, 0 \le k \le L'_{ij})$: the total time a mobile waits at traffic lights between the instants it enters and exits the cell, given that it enters the cell through entry point i, takes path j, and waits at k traffic lights in path j.
- $T_{h_{ijk}}(1 \le i \le N+1, 1 \le j \le m'_i, 0 \le k \le L'_{ij})$: the time a mobile spends in a cell from the time it enters the cell until it exits the cell given that the mobile enters the cell through entry point i, takes path j, and waits at k traffic lights in path j.

According to the symmetric traffic assumption, we consider the traffic in one direction only. So, after a mobile enters a cell, it moves in the direction which we considered (say north in Figure 7.) m'_i is then given by

$$m'_i = N + 2 - i \qquad , i = 1, 2, \ldots, N + 1 \tag{36}$$

Again, we sort the m'_i paths by length in ascending order. Then q'_{ij} and Z'_{ij} are given by

$$q'_{ij} = p_s{}^{j-1}(1 - p_s)^{I'_{ij}} \tag{37}$$

where

$$I'_{ij} = \begin{cases} 1 & j < m'_i \\ 0 & j = m'_i \end{cases} \tag{38}$$

$$Z'_{ij} = \begin{cases} (i + j - \frac{3}{2})(A + B) & j < m'_i \\ N(A + B) & j = m'_i \end{cases} \tag{39}$$

Traffic lights are installed in the same way we stated earlier (see Figure 7 also); then L'_{ij} and β'_{ijk} are given by

$$L'_{ij} = \begin{cases} j & j < m'_i \\ j - 1 & j = m'_i \end{cases} \tag{40}$$

$$\beta'_{ijk} = \binom{L'_{ij}}{k} p_w^k (1 - p_w)^{L'_{ij} - k} \tag{41}$$

$D_{hij} = Z'_{ij} - E'_i$ is given by

$$D_{hij} = \begin{cases} \frac{2j-1}{2}(A + B) & j < m'_i, i = 1 \\ (j - 1)(A + B) & j = m'_i, i = 1 \\ j(A + B) & j < m'_i, i = 2, \ldots, N + 1 \\ \frac{2j-1}{2}(A + B) & j = m'_i, i = 2, \ldots, N + 1 \end{cases} \tag{42}$$

$T_{L_{ijk}}$, $T'_{L_{ijk}}$ also depends on k only. For the same k, the distribution of $T'_{L_{ijk}}$ is the same as that of $T_{L_{ijk}}$ and is given by (24) and (26).

$T_{h_{ijk}}$ and its distribution are given by

$$T_{h_{ijk}} = \frac{D_{hij}}{V} + T'_{L_{ijk}} \tag{43}$$

$$f_{T_{h_{ijk}}}(t) = \sum_{l=1}^{M} f_{T_{h_{ijk}}|V}(t|V = v_l)\alpha_l$$
$$\triangleq \sum_{l=1}^{M} f_{T_{h_{ijkl}}}(t)\alpha_l \tag{44}$$

where

$$f_{T_{h_{ijkl}}}(t) = \begin{cases} \delta_{\frac{D_{h_{ij}}}{v_l}}(t) & k = 0 \\ U[\frac{D_{h_{ij}}}{v_l}, \frac{D_{h_{ij}}}{v_l} + T_w] & k = 1 \\ Tri[\frac{D_{h_{ij}}}{v_l}, \frac{D_{h_{ij}}}{v_l} + 2T_w] & k = 2 \\ N(\frac{kT_w}{2} + \frac{D_{h_{ij}}}{v_l}, \sqrt{\frac{kT_w{}^2}{12}}) & k \geq 3 \end{cases} \tag{45}$$

Finally, the distribution of T_h can be presented as

$$f_{T_h}(t) = \sum_{i=1}^{N+1} \sum_{j=1}^{m'_i} \sum_{k=0}^{L'_{ij}} \sum_{l=1}^{M} f_{T_{h_{ijkl}}}(t)\alpha_l \beta'_{ijk} q'_{ij} p'_i \tag{46}$$

Given the system parameters p'_i, this equation can be evaluated by substituting the associated terms with (23), (37), (41), and (45).

3.2 Macrocell Systems

Because suburban traffic is not as heavy as the urban traffic, suburban areas are normally configured into macrocells, rather than as microcells, whose capacity would not be utilized adequately in suburban areas. To evaluate the distribution of channel holding time in a macrocellular system, we have to model the road systems in a cell first. In general, suburban road systems are less regular than urban road systems. Thus, one cannot model the road systems within a macrocell with the systematic configurations that we have used for microcells. Since the cell size of the traditional cellular system is comparable to that of our macrocellular system, we briefly describe the system model in [1]. The authors use a simple cell structure like the one shown in Figure 1. They analyzed the distribution of channel holding time on the basis of the following assumptions:

- the mobiles are spread evenly over the area of the cell

- the direction a mobile travels in a cell is uniformly distributed over $[0, 2\pi]$, and remains constant during the mobile's travel in the cell
- a handoff can occur at any point of the cell boundary (which is assumed to be a circle) with equal probability.

These assumptions are simple but may not reflect the nature of mobile behavior inside a cell. Clearly, most traffic in a suburban area is on the main routes leading to either highways or neighbor cells. The travel direction follows the route direction. The place a handover can occur also depends on how neighboring cells are connected by major routes. Therefore, the assumptions in [1] are not realistic. In this paper, we use a different model to analyze the channel holding time in a macrocell.

We categorize the mobiles in a macrocell into two types: one type covers those which stay in the same macrocell all the time (i.e., drives within the cell only); we call it Type A traffic. The second type (Type B traffic) includes traffic which leaves the cell by crossing cell boundaries. A mobile belongs to Type A as long as it does not leave the cell, belongs to Type B as long as it does leave the cell, no matter it is in the cell originally or it enters the cell from some neighboring cell. For Type A traffic, since the mobile only moves within the same cell, the channel holding time equals the message duration (i.e., $T_H = T_M$). For Type B traffic, we need to consider the road configuration of the cell. Here we categorize the roads in a macrocell into three types: highways, main routes, and secondary routes. Figure 8 shows a specific road structure in a suburban macrocell. We assume that highways always have their own highway microcellular systems. If a main route is equipped with its own microcellular system, we consider it as a highway. Besides, a secondary route is assumed to always merge into a main route. A mobile is considered leaving a cell when it enters a neighboring macrocell or microcell (which could be a highway section). We also assume that a mobile can only leave a cell through main routes. This means that the traffic from a secondary routes will have to enter a main route before leaving a cell. In the following discussion, a cell into which a mobile moves is referred to as a target cell; a cell that a mobile is leaving is referred to as a source cell; and the point on a main route between two cells is called a "junction point". Junction points are the only points at which handoffs can occur. A main route connects two of the junction points of a cell. Figure 8 shows a macrocell with 7 junction points and all possible main routes.

The channel holding time of Type B traffic is analyzed in the following. Let N be the number of main routes in a macrocell (from route 1 to route

N). $p_i(1 \leq i \leq N)$ denotes the probability that a mobile uses route i in the cell. Here "uses route i" means a mobile moves on route i or starts from one of the secondary routes of route i and then enters route i. Let X_i be the length of route i and M_i the number of secondary routes which merge into main route i. Figure 9 shows a typical main route with 3 secondary routes ($M_i = 3$). Let $Y_{ij}(1 \leq i \leq N, 1 \leq j \leq M_i)$ be the distance between secondary route j and arbitrary one of the two Junction points of main route i. The selected junction point is called the "origin" of main route i. Let $q_i(1 \leq i \leq N)$ be the probability that a mobile on main route i moves in the direction from origin to the other junction point. We call this direction "positive direction" and the other direction "negative direction." Let $r_{ij}(1 \leq 1 \leq N, 1 \leq j \leq M_i)$ be the probability that a mobile merged to main route i comes from secondary route j. Let $s_i(1 \leq i \leq N)$ denote the probability that a mobile on main route i comes directly from main route i, then

$$s_i + \sum_{j=1}^{M_i} r_{ij} = 1, \qquad for\ all\ i$$

Type B traffic belongs to either one of two types. One initiates calls before entering the main route (i.e., the call is originated in some secondary route) and is called Type $B1$ traffic. The other type covers the mobiles which initiate calls on main routes and is called Type $B2$ traffic. Let $b1$ be the proportion of Type $B1$ traffic; then $b2 = 1 - b1$ is the proportion of Type $B2$ traffic.

We define the following variables:

- $D_{1ij}(1 \leq i \leq N, 1 \leq j \leq M_i)$: the distance a Type $B1$ mobile travels on main route i from the time the call is initiated until the mobile exits the cell, given that the mobile comes from secondary route j of main route i.

- $D_{2ij}(1 \leq i \leq N, 1 \leq j \leq M_i)$: the distance a Type $B2$ mobile travels on main route i from the time the call is initiated until the mobile exits the cell, given that the mobile comes from secondary route j of main route i.

- $D_{3i}(1 \leq i \leq N)$: the distance a Type $B2$ travels on main route i from the time the call is initiated until the mobile exits the cell, given that the mobile comes directly from main route i.

- $T_{n1ij}(1 \le i \le N, 1 \le j \le M_i)$: the time a Type $B1$ mobile spends in a cell from the time the call is initiated until the mobile exits the cell, given that the mobile uses main route i and it comes from a secondary route j of main route i.

- $T_{n2i}(1 \le i \le N)$: the time a Type $B2$ mobile spends in a cell from the time the call is initiated until the mobile exits the cell, given that the mobile uses main route i.

- $T_{s1ij}(1 \le i \le N, 1 \le j \le M_i)$: the time a Type $B1$ mobile spends in secondary route j of main route i from the time the call is initiated until the mobile enters main route i.

Evidently, D_{1ij} is the distance between the junction point at which the mobile leaves the cell and the location the mobile enters main route i. For positive and negative direction traffic, D_{1ij} is given by

$$D_{1ij} = \begin{cases} X_i - Y_{ij} & \text{Positive direction} \\ Y_{ij} & \text{Negative direction} \end{cases} \tag{47}$$

Assume that the location at which a Type $B2$ mobile on a certain main route initiates a call is uniformly distributed between the locations it enters and exits the route, then D_{2ij} is also uniformly distributed and is given by

$$D_{2ij} \sim \begin{cases} U[0, X_i - Y_{ij}] & \text{Positive direction} \\ U[0, Y_{ij}] & \text{Negative direction} \end{cases} \tag{48}$$

D_{3i} is also assumed to be uniformly distributed

$$D_{3i} \sim U[0, X_i] \tag{49}$$

Assume T_{s1ij} is uniformly distributed between 0 and some upper bound, then

$$T_{s1ij} \sim U[0, T_{maxij}] \tag{50}$$

For the speed of a mobile in the macrocell, we adopt the model used in microcell systems [see (23)]. Random variables T_{n1ij} and T_{n2i} are given by

$$T_{n1ij} = \frac{D_{1ij}}{V} + T_{s1ij} \tag{51}$$

$$T_{n2i} = \begin{cases} \frac{D_{2ij}}{V} & \text{for mobiles from secondary route } j \\ \frac{D_{3i}}{V} & \text{for mobiles from main route } i \end{cases} \tag{52}$$

Let $R_i = \sum_{l=1}^{M_i} r_{il}$; then the distribution of T_n is given by

$$f_{T_n}(t) = \sum_{i=1}^{N}\{b1\sum_{j=1}^{M_i}[\frac{r_{ij}}{R_i}f_{T_{n1_{ij}}}(t)] + b2 f_{T_{n2_i}}(t)\}p_i \tag{53}$$

where

$$f_{T_{n2_i}}(t) = s_i f_{\frac{D_{3_i}}{V}}(t) + \sum_{j=1}^{M_i} r_{ij} f_{\frac{D_{2_{ij}}}{V}}(t) \tag{54}$$

$$f_{\frac{D_{3_i}}{V}}(t) = \sum_{k=1}^{M} f_{\frac{D_{3_i}}{v_k}}(t)\alpha_k \tag{55}$$

$$f_{\frac{D_{2_{ij}}}{V}}(t) = \sum_{k=1}^{M} f_{\frac{D_{2_{ij}}}{v_k}}(t)\alpha_k \tag{56}$$

$$\frac{D_{3i}}{v_k} \sim U[0, \frac{X_i}{v_k}] \tag{57}$$

$$\frac{D_{2ij}}{v_k} \sim q_i U[0, \frac{X_i - Y_{ij}}{v_k}] + (1 - q_i)U[0, \frac{Y_{ij}}{v_k}] \tag{58}$$

The distribution of $T_{n1_{ij}}$ is

$$f_{T_{n1_{ij}}}(t) \triangleq \sum_{k=1}^{M} f_{T_{n1_{ijk}}}(t)\alpha_k \tag{59}$$

where

$$T_{n1_{ijk}} = \frac{D_{1_{ij}}}{v_k} + T_{s1_{ij}}$$

and has distribution

$$T_{n1ijk} \sim q_i U[\frac{X_i - Y_{ij}}{v_k}, \frac{X_i - Y_{ij}}{v_k} + T_{s1ij}] + (1 - q_i)U[\frac{Y_{ij}}{v_k}, \frac{Y_{ij}}{v_k} + T_{s1ij}] \tag{60}$$

Apply equations (54)-(56) and (59) to (53); then $f_{T_n}(t)$ is

$$\begin{aligned} f_{T_n}(t) = \quad & b1 \quad \sum_{i=1}^{N}\sum_{j=1}^{M_i}\sum_{k=1}^{M} f_{T_{n1_{ijk}}}(t)\frac{r_{ij}}{R_i}\alpha_k p_i + \\ & b2 \quad \sum_{i=1}^{N}\sum_{j=1}^{M_i}\sum_{k=1}^{M}[f_{\frac{D_{3_i}}{v_k}}(t)\frac{s_i p_i \alpha_k}{M_i} + f_{\frac{D_{2_{ij}}}{v_k}}(t) r_{ij}\alpha_k p_i] \end{aligned} \tag{61}$$

This equation can be evaluated by substituting the associated terms with equations (57),(58), and (60).

Let D_h denote the distance a mobile travels from the time it enters the cell until it leaves the cell. Then D_h exists only for those Type $B2$ traffic patterns that enter the cell through one of the two junction points on a main route and leaves the cell through the other. So D_h is just the length of the main route that the mobile uses. The distribution of D_h is given by

$$P(D_h = X_i) = p_i \tag{62}$$

T_h for these traffic pattern equals $T_h = \frac{D_h}{V}$ and has distribution

$$P(T_h = t_{ik}) = p_i \alpha_k \qquad , 1 \leq i \leq N, 1 \leq k \leq M \tag{63}$$

where

$$t_{ik} = \frac{X_i}{v_j} \qquad , 1 \leq i \leq N, 1 \leq k \leq M$$

If we apply equations (61) and (63) to (7), and then apply the result to (6), we can get the channel holding time of Type B traffic in a macrocell (denoted by T_{HB}). If the proportion of Type B traffic is p_B, the channel holding time in macrocell level is given by

$$f_{T_H} = (1 - p_B) f_{T_M}(t) + p_B f_{T_{HB}}(t) \tag{64}$$

3.3 Satellite Footprint System

In this section, we discuss the channel holding time in satellite footprint level. Since the radius of a satellite footprint is in a few hundred kilometers, the speed of a mobile is relatively slow, T_n and T_h are both longer than a message duration most of the time. Intuitively, the distribution of T_H at a satellite footprint tends to be similar to that of the message duration, which is exponentially distributed. We describe the cell structure briefly. At a satellite footprint, there are some cities with their own macrocellular and microcellular systems. There are also highways and local roads connecting these cities and leading to neighboring footprints. We use the same model like the one used in macrocell systems. But here a junction point could be on boundaries between two footprints, between a footprint and a macrocell, or between a footprint and a microcell. In addition, no secondary routes are considered in our own footprint model. Figure 10 shows a typical footprint structure. A mobile is considered leaving a footprint when it enters a macrocell inside the footprint, a highway microcell inside the footprint, or a neighboring satellite footprint.

Employing the analyzing process used in the macrocell systems, we define the following variables:

- N: the number of main routes at the footprint.
- $X'_i (1 \leq i \leq N)$: the length of main route i.
- $p'_i (1 \leq i \leq N)$: the probability that a mobile uses route i in the footprint.
- $V_i (1 \leq i \leq N)$: the average speed of mobiles on main route i.
- $D'_{ni} (1 \leq i \leq N)$: the distance a mobile travels on route i from the time the call is initiated till it exits the footprint.
- $T'_{ni} (1 \leq i \leq N)$: the time a mobile spends on route i from the time the call is initiated until it exits the footprint.
- $T'_{hi} (1 \leq i \leq N)$: the time a mobile spends on route i from the time the call is handed off to route i of the footprint until the mobile exits the footprint.

Here we assume V_i to be a random variable with uniform distribution,

$$V_i \sim [V_{imin}, V_{imax}] \tag{65}$$

where V_{imin} and V_{imax} are system parameters. If we assume that a mobile on route i may initiate a call at any location on the route with equal probability, then D'_{ni} is uniformly distributed over $[0, X'_i]$. T'_{ni} and its distribution are given by

$$T'_{ni} = \frac{D'_{ni}}{V_i} \tag{66}$$

$$\begin{aligned} f_{T'_{ni}}(t) &= \int_{V_{imin}}^{V_{imax}} V_i f_{D'_{ni}V_i}(tV_i, V_i) dV_i \\ &= \begin{cases} \frac{V_{imax}+V_{imin}}{2X'_i} & 0 \leq t \leq \frac{X'_i}{V_{imax}} \\ \frac{1}{2X'_i(V_{imax}-V_{imin})}[(\frac{X'_i}{t})^2 - V_{imin}{}^2] & \frac{X'_i}{V_{imax}} \leq t \leq \frac{X'_i}{V_{imin}} \end{cases} \end{aligned} \tag{67}$$

Finally, the distribution of T_n is

$$f_{T_n}(t) = \sum_{i=1}^{N} f_{T'_{ni}}(t) p'_i \tag{68}$$

The distance a mobile travels on route i from the time the call is handed off to the footprint (or since the mobile enters the footprint) until the mobile exits the footprint is just the length of route i (X'_i), so T'_{hi} and its distribution are given by

$$T'_{hi} = \frac{X'_i}{V_i} \tag{69}$$

$$f_{T'_{hi}}(t) = \frac{X'_i}{(V_{imax} - V_{imin})t^2} \qquad \frac{X'_i}{V_{imax}} \le t \le \frac{X'_i}{V_{imin}} \tag{70}$$

Finally, the distribution of T_h is

$$f_{T_h}(t) = \sum_{i=1}^{N} f_{T'_{hi}}(t) p'_i \tag{71}$$

If we apply equations (68) and (71) to (7) and then apply the result to (6), we can get the channel holding time of Type B traffic at a footprint (denoted by T'_{HB}). Given the proportion of Type B traffic p'_B, the channel holding time at the footprint level is given by

$$f_{T_H}(t) = (1 - p'_B) f_{T_M}(t) + p'_B f_{T'_{HB}}(t) \tag{72}$$

4 NUMERICAL RESULTS

The average of the unencumbered message duration $\overline{T}_M = 120\ s$ (*i.e.*, $\mu_M = 1/120$) is used for our calculations. Figure 11 shows the distribution of channel holding time in a microcell with the following parameters: the proportion of new calls and handoff calls a microcell carries are $P_I = 0.6$ and $P_{II} = 0.4$, respectively. The number of blocks N in a cell equals 4. The width of the street and block are $A = 25\ m$ and $B = 62\ m$, respectively. The probability that a mobile goes straight in an intersection $p_s = 0.6$, that a mobile waits a traffic light $p_w = 0.5$. The maximum time duration that a mobile waits at a traffic light $T_w = 60\ s$. The average speed V is assumed to be uniformly distributed with pmf and is given by

$$P(V = v_k = V_{min} + (l-1)\frac{V_{max} - V_{min}}{M-1}) = \alpha_l = \frac{1}{M}, \qquad l = 1, 2, \ldots, M \tag{73}$$

where $M = 6$, $V_{min} = 7$ (m/s), and $V_{max} = 18$ (m/s). For type II traffic, the probability that a call is handed off to a cell through entry point i is $p'_i = \frac{1}{N+1}$, for all i.

Figure 12 shows the distribution of channel holding time in a macrocell with the following parameters: The probability that a mobile belongs to Type B traffic is $p_B = 0.75$. In Type B traffics, the proportion of Type B1 traffics is $b1 = 0.5$. In Type B1 and B2 traffic, the proportion of Type I and Type II traffic is $P_I = 0.9$ and $P_{II} = 0.1$, respectively. The number of main routes $N = 16$. $p_i = \frac{1}{N}$, for all i. The length and the number of secondary routes of main route i are

$$X_i = X_{min} + (i-1)\frac{X_{max} - X_{min}}{N-1} \tag{74}$$

$$M_i = \lceil (i)(rate) \rceil$$

for all i, where $X_{min} = 500$ (m), $X_{max} = 5000$ (m), and the rate equals 0.4. We assume that the distances between the origin junction point and the first secondary route, the other junction point and the last secondary route, and each pair of adjacent secondary routes are equal; then

$$Y_{ij} = \frac{j}{M_i + 1} X_i$$

The traffic movements in the two directions of a main route are symmetric; so $q_i = 0.5$, for all i. The probability that a mobile enters main route i directly from main route i is $s_i = 0.6$, for all i. All secondary routes in a main route are equally utilized, so $r_{ij} = (1 - s_i)/(M_i)$, for all j. The maximum time a channel is occupied, when a mobile is in a secondary route, is $T_{s1ij} = 45$ s, for all i, j. Equation (73) is used again for the average speed of mobiles in a macrocell, but $M = 4$, $V_{min} = 16$ (m/s), and $V_{max} = 28$ (m/s).

Figure 13 shows the distribution of channel holding time in a satellite footprint with the following parameters. The probability that a mobile belongs to Type B traffic is $p'_B = 0.6$. In Type B traffic, the proportion of Type I and Type II traffic is $P_I = 0.95$ and $P_{II} = 0.05$, respectively. The number of routes in the footprint $N = 16$. Equation (74) is used again for the length of main route i, but $X'_{max} = 200$ (mi), $X'_{min} = 50$ (mi). $p'_i = \frac{1}{N}$. $V_{imin} = \frac{45}{60}$ (mi/min) and $V_{imax} = \frac{65}{60}$ (mi/min) for all i.

5 CONCLUSIONS

In this paper we have presented new models for analyzing the distribution of channel holding time in a hybrid satellite and cellular communication system. We have proved that exponential distribution can be used as an approximation to the distribution of channel holding at all the three cell levels of our system. Because of the very high handoff rate and the complicated geometry of a city microcell system, the channel holding time in a microcell is hard to predict. We use a detailed model to solve this problem. The appropriateness of using an exponential distribution as an approximation to the channel holding time in a microcell has been affirmed within the range of normal system parameters. A cell-shaped independent model for macrocell system is used to analyzing the channel holding time of such systems. Exponential distribution is again a suitable approximation. Since the size of a satellite footprint is very large, the channel holding time is very close to the message duration, which is exponentially distributed.

References

[1] D. Hong and S. S. Rappaport, "Traffic model and performance analysis for cellular mobile radio telephone systems with prioritized and non-prioritized hand-off procedures," *IEEE Trans. Vehic. Technol.,* Vol. VT-3, pp.77-92, Aug. 1986.

[2] Sami A. El-Dolil and Wai C. Wong and Raymond Steele, "Teletraffic Performance of Highway Microcells with Overlay Macrocell," *IEEE Journal on Selected Areas in Communications.*, Vol. 7, No. 1, pp.71-78, Jan. 1989.

[3] Roch A. Guerin, "Channel Occupancy Time Distribution in a Cellular Radio System," *IEEE Trans. Vehic. Technol.*, Vol. VT-35, No. 3, pp.89-99, Aug. 1987.

[4] Jean-Frederic Wagen, "SIP simulation of UHF propagation in Urban Microcells," *IEEE* 41st Vehicular Technology Conference pp.301-306, 1991.

[5] Athanasios Papoulis, "Probability, Random Variables, and Stochastic Processes," McGraw-Hill, pp.194-197, 1984.

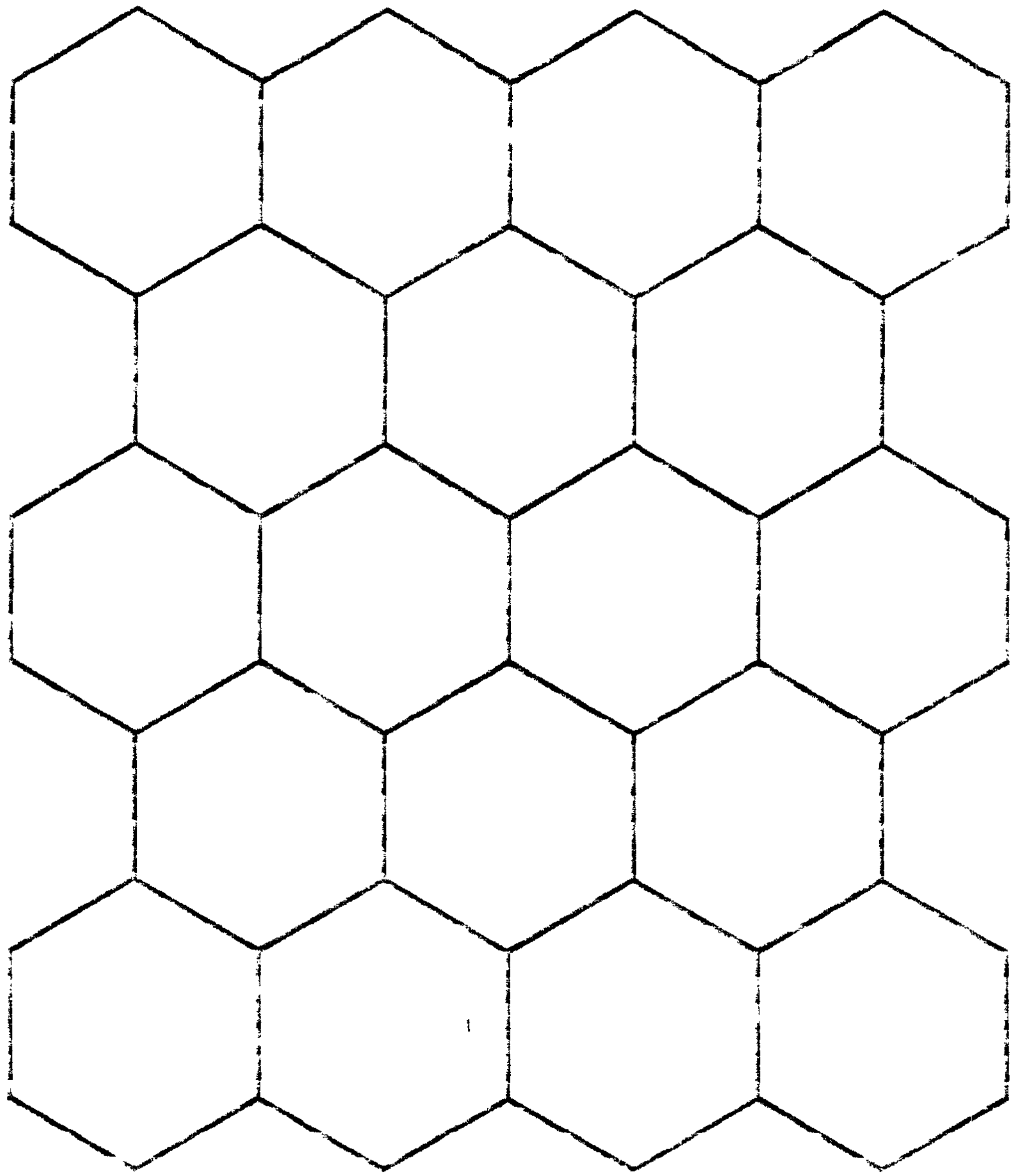


figure 1. cell structure of the traditional cellular system

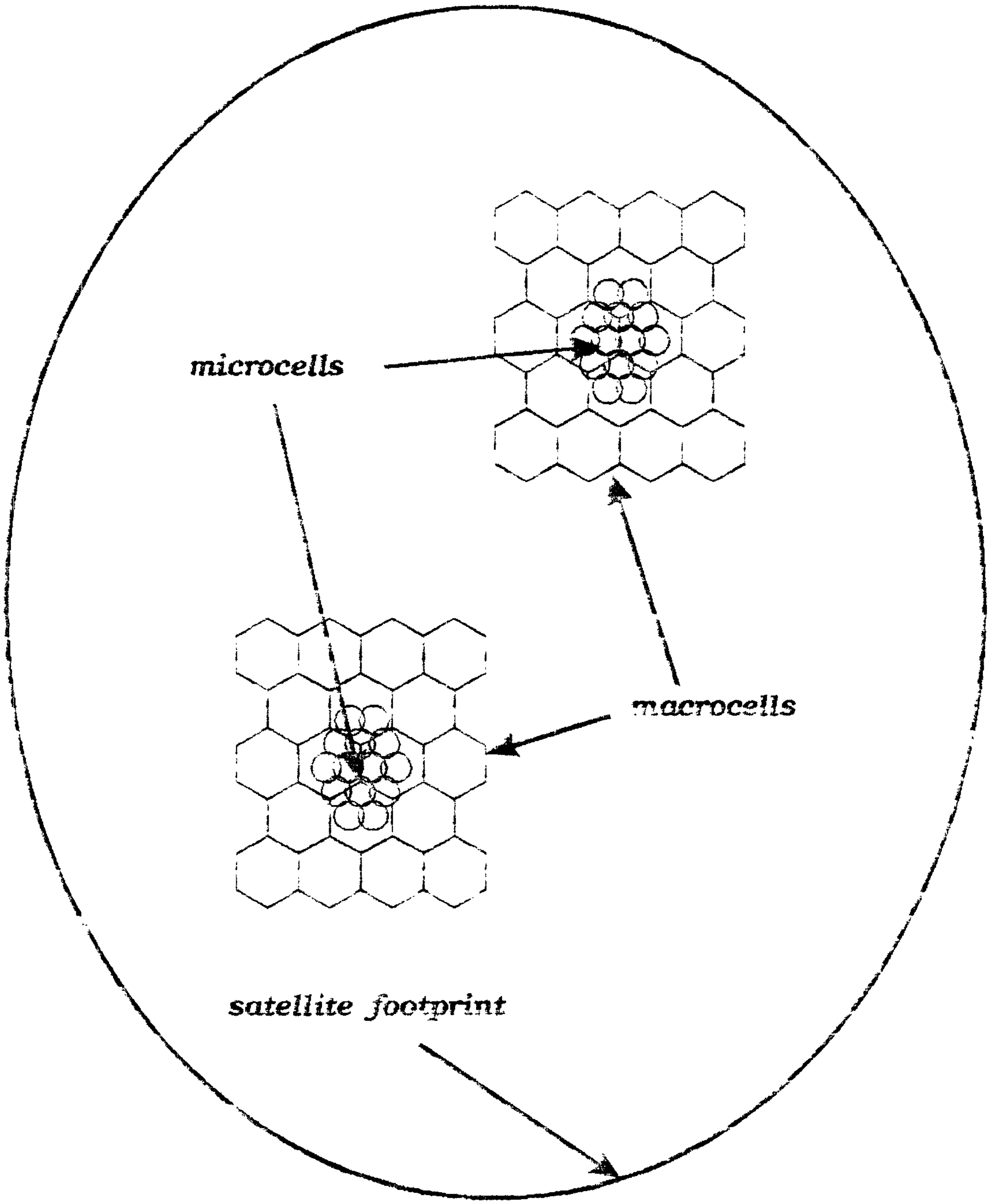
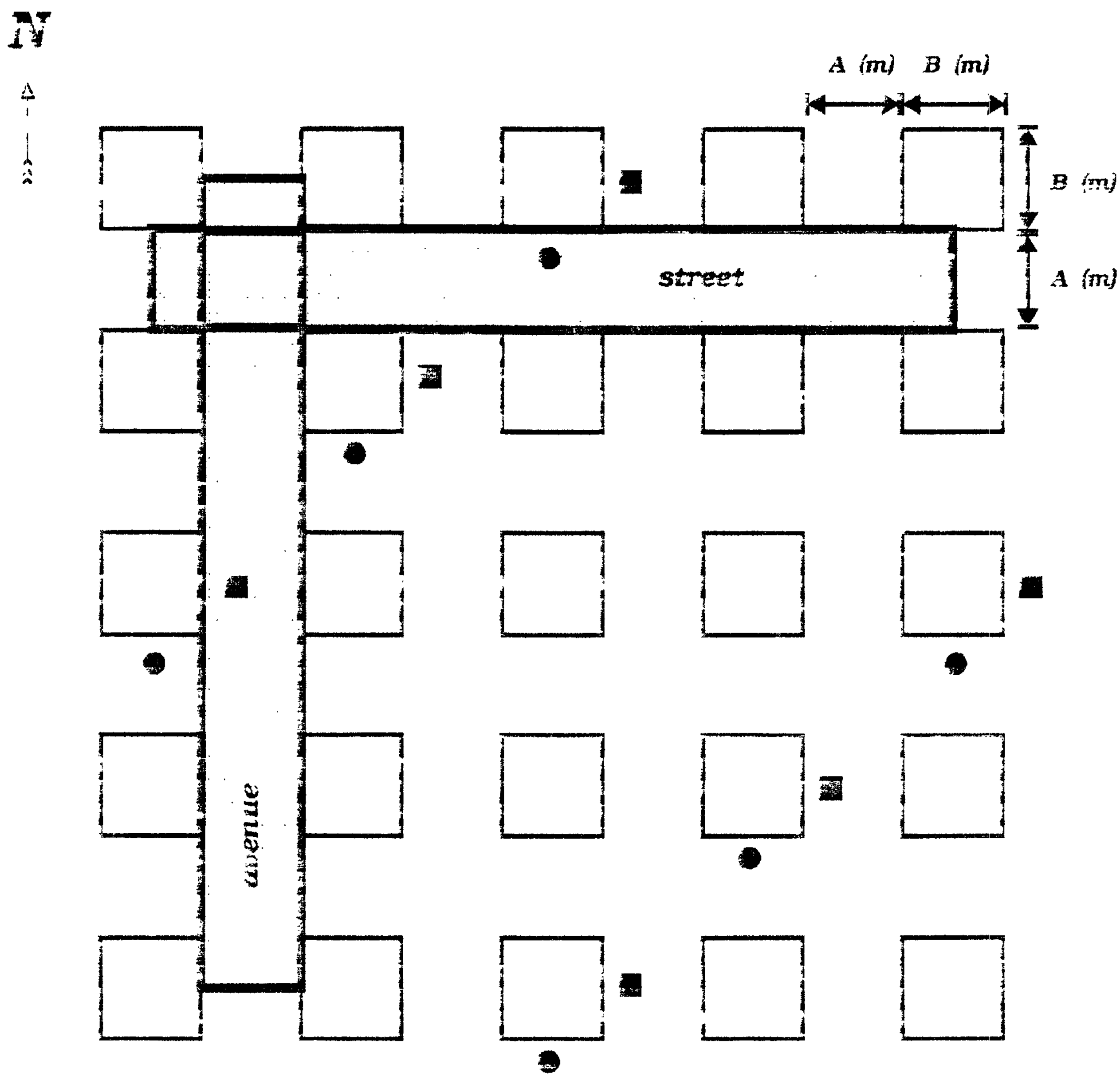


figure 2. cell structure of the hybrid satellite and cellular system



● ■ denote the location of base stations

Each shaded area covers a cell area

figure 3. geometry of the urban microcell

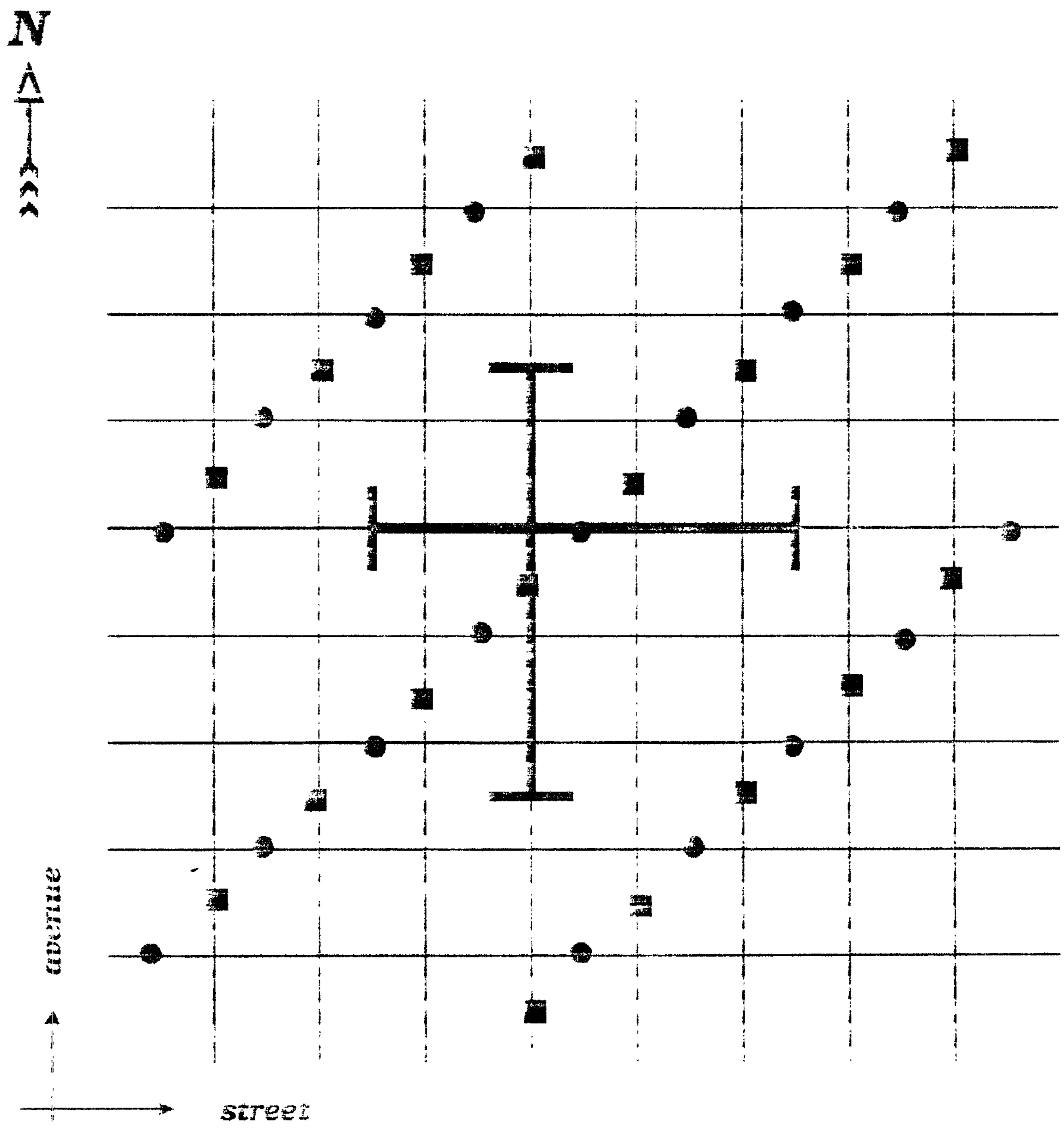


figure 4. the range of microcells and the location of base stations

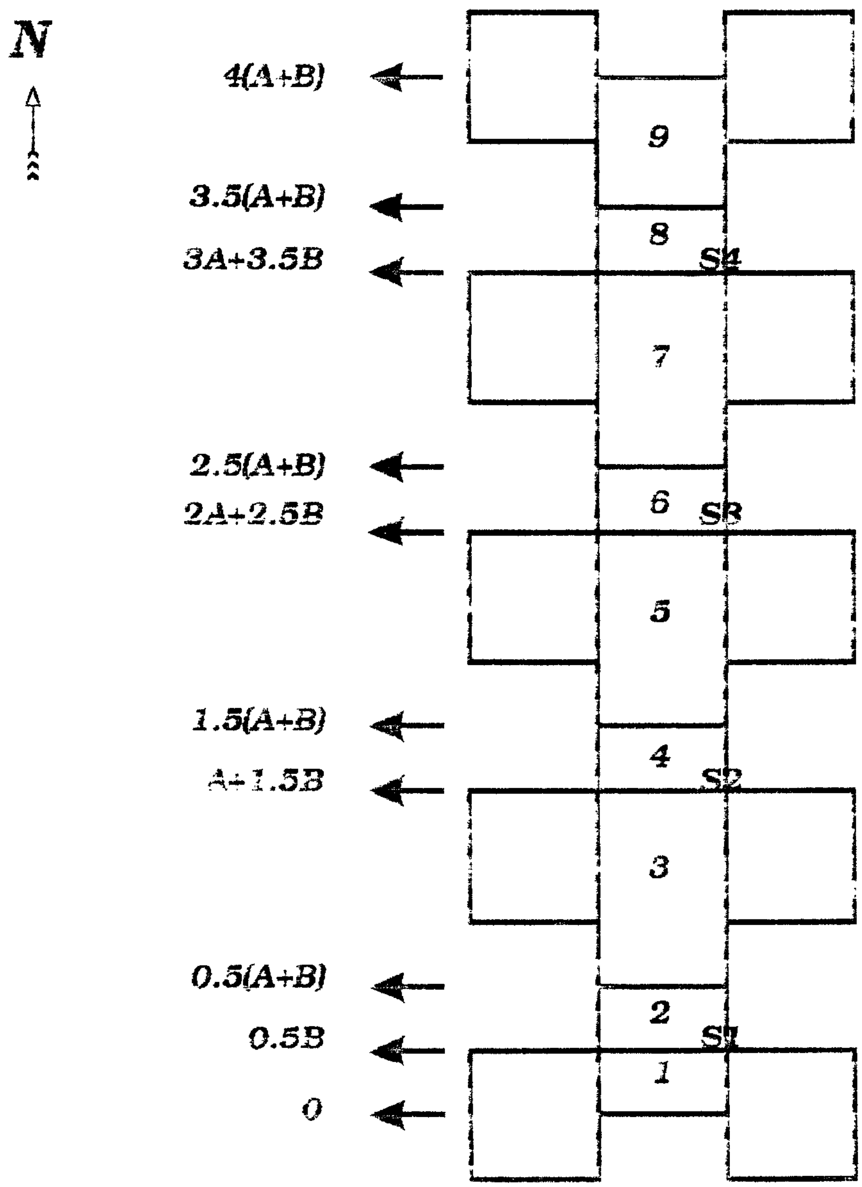


figure 5. a city microcell for N=4

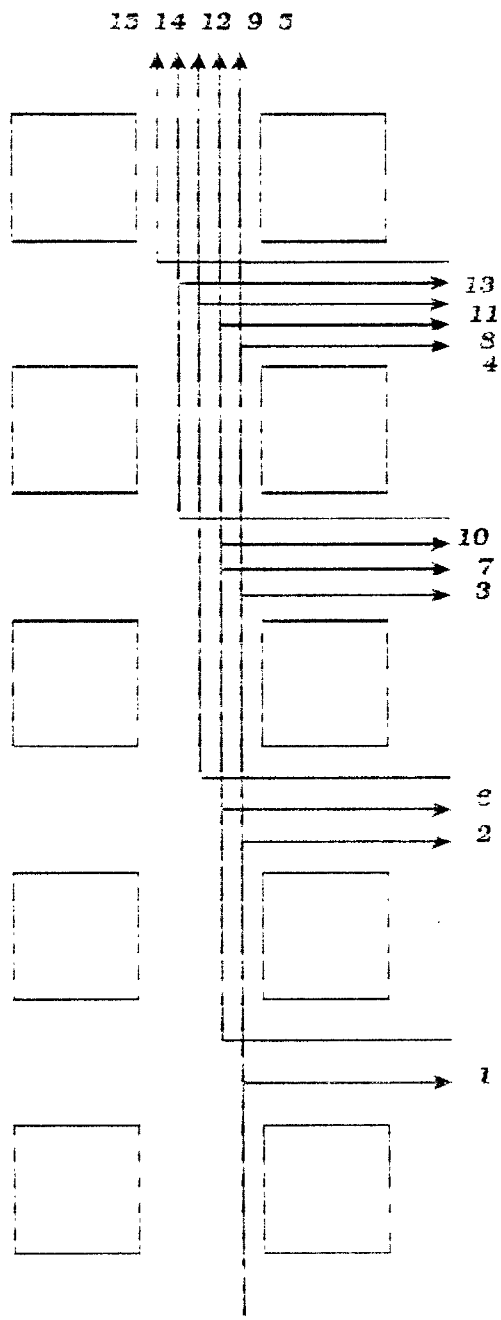


figure 6. different paths a mobile may take
N=4

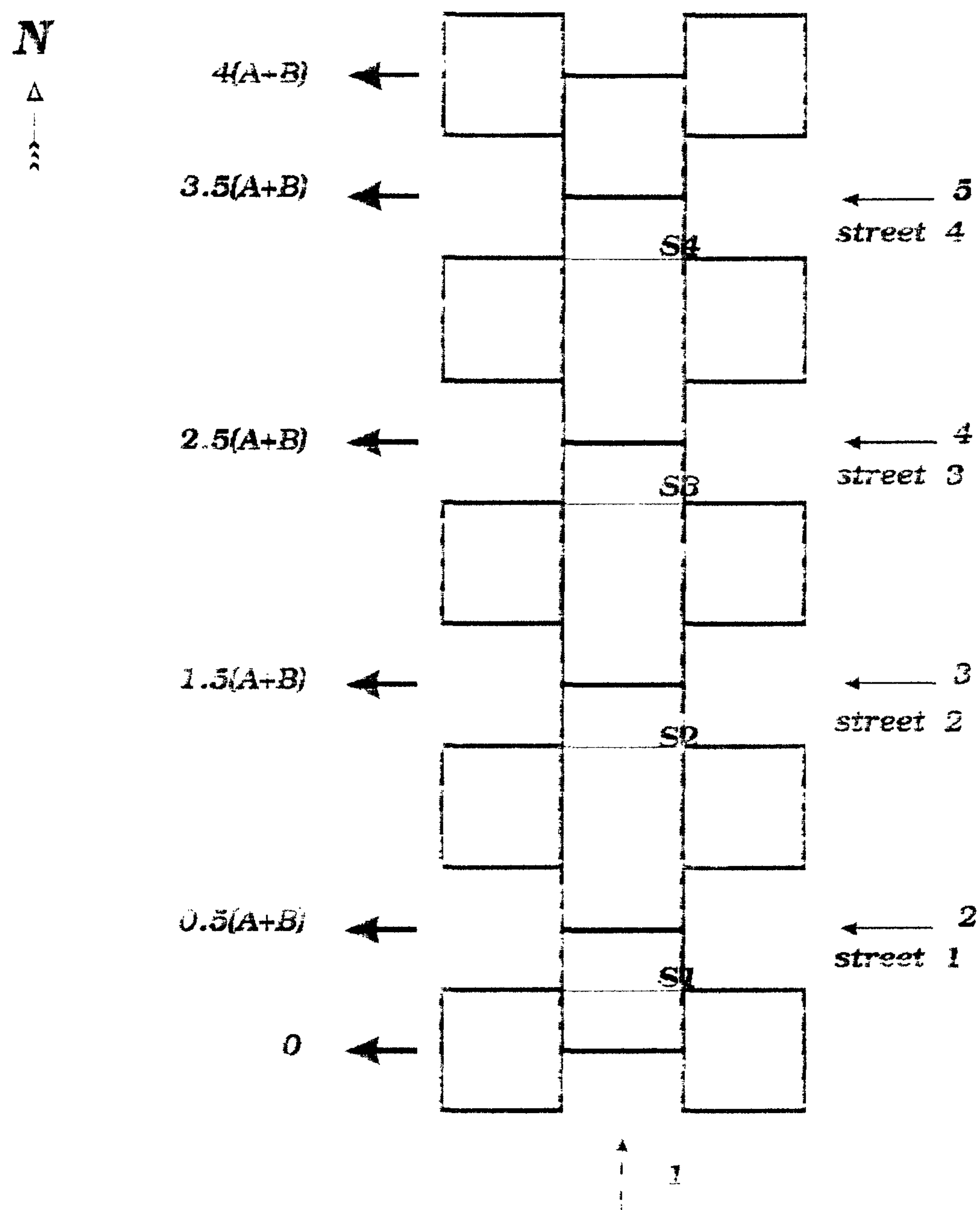
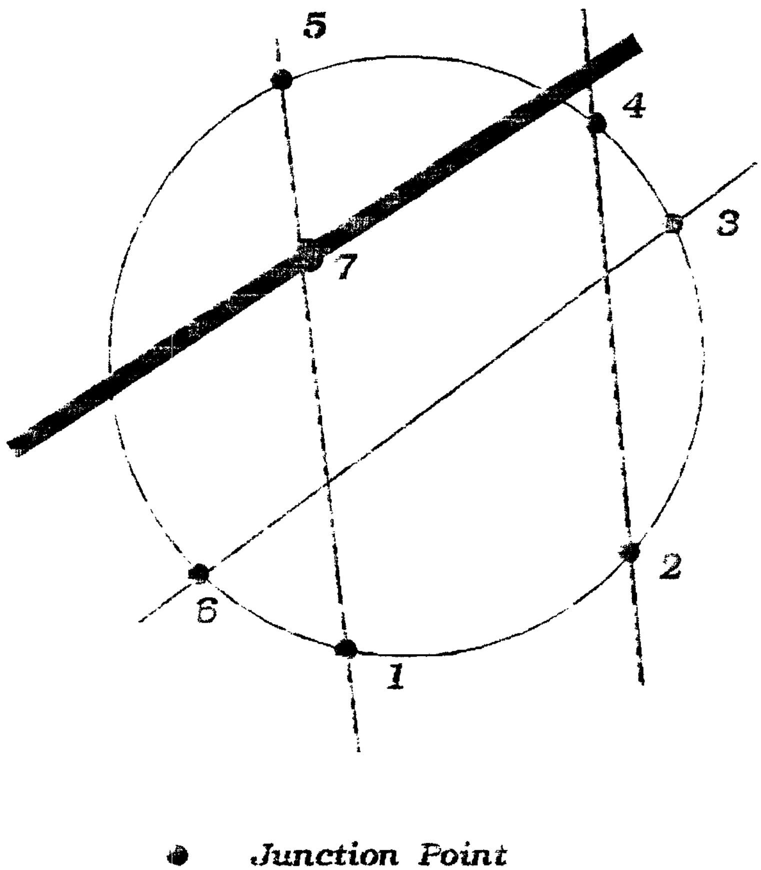


figure 7. the entry points of a microcell



possible main routes :

1 - 3	1 - 4	1 - 5	1 - 7
2 - 3	2 - 4		
3 - 6	3 - 7		
4 - 6	4 - 7		
5 - 6	5 - 7		
6 - 7			

figure 8. suburban macrocell structure

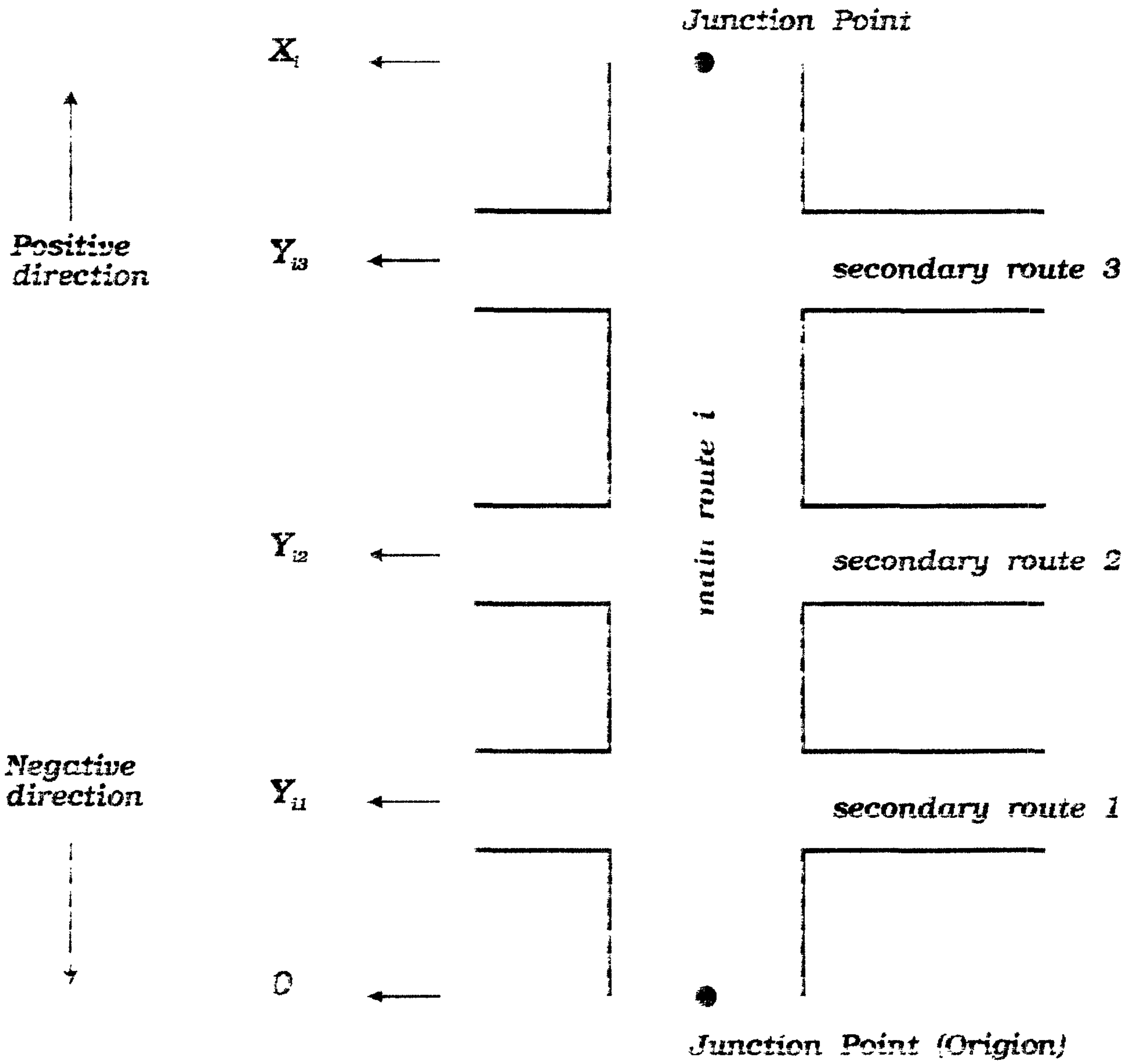


figure 9. a main route i with 3 secondary routes

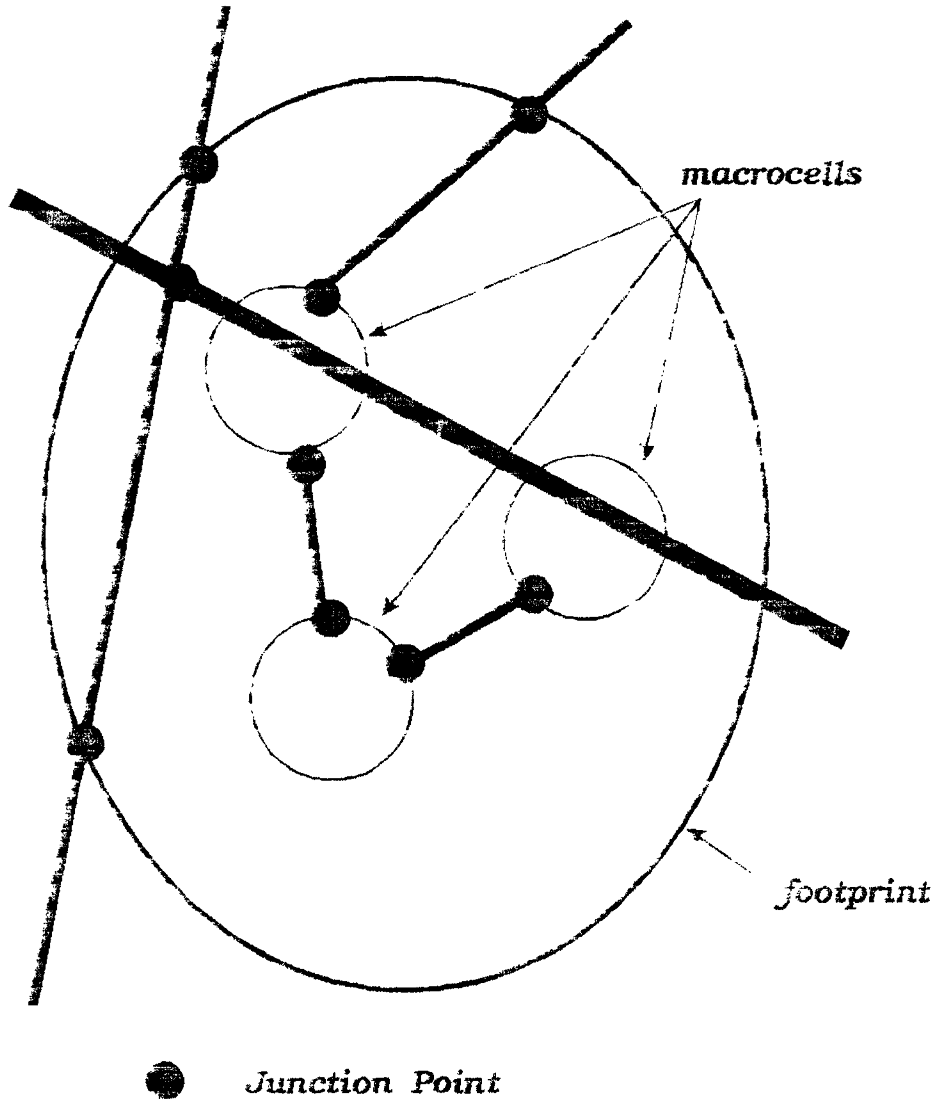


figure 10. satellite footprint structure

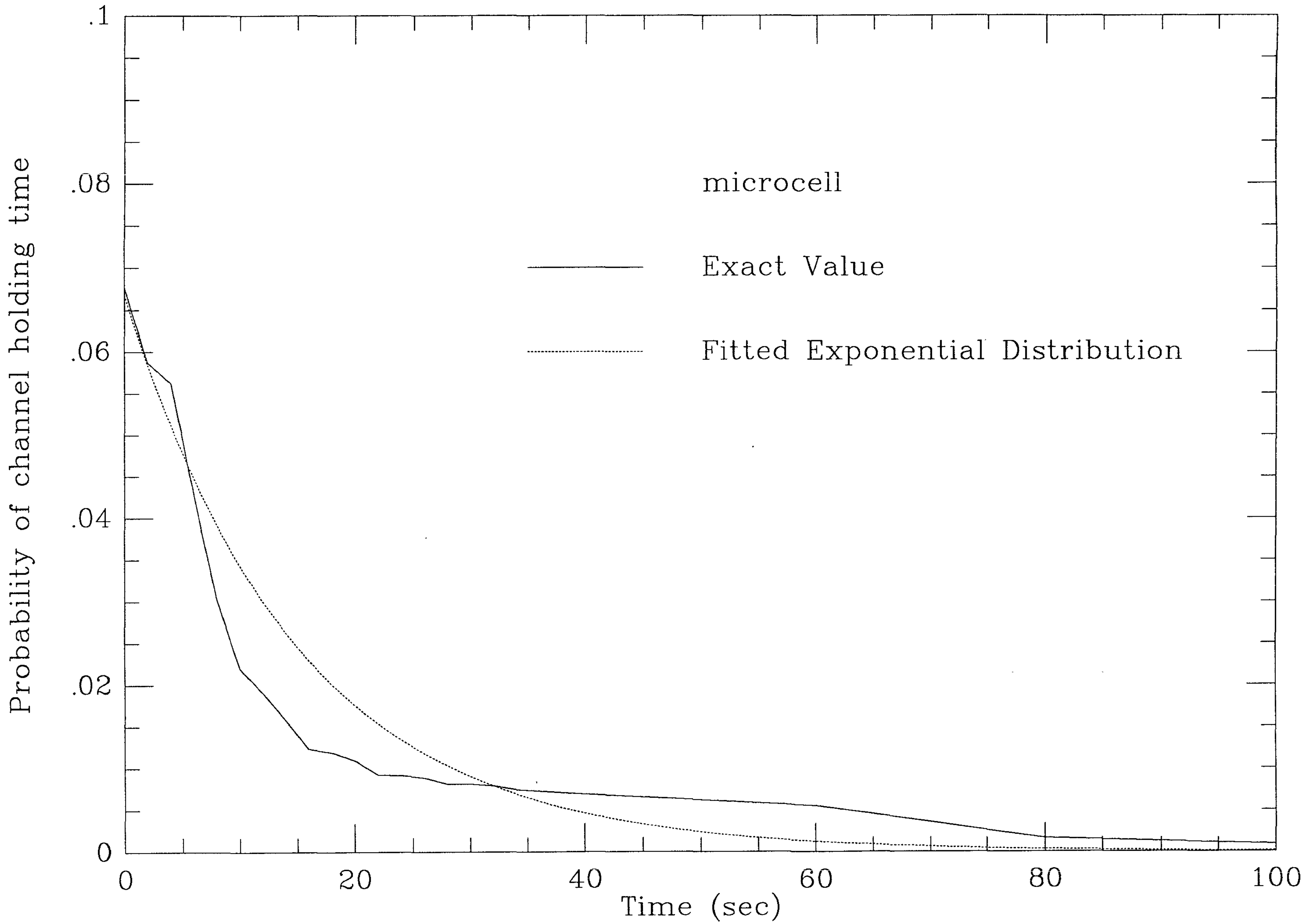


Figure 11. Probability density function of channel holding time for microcell.

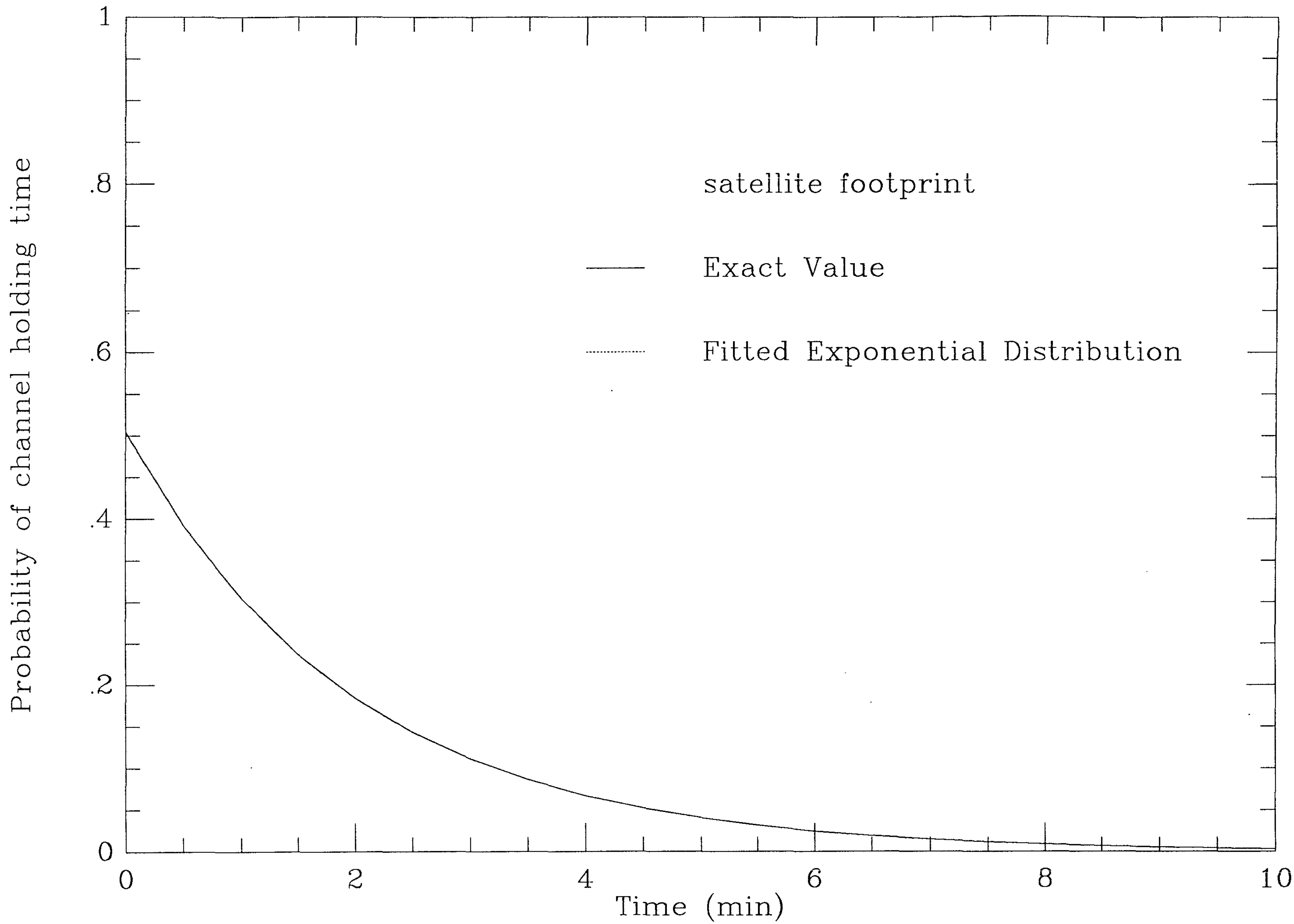


Figure 13. Probability density function of channel holding time for satellite footprint.