Abstract—We consider an urban fiber-optic microcellular system in which a cigar-shaped cell consists of several microzones with their own antenna sites connected to a central station through optical fibers. To increase the efficiency of radio resources and reduce unnecessary handoffs between microzones, we propose a movable safety zone scheme. A safety zone is a virtually guarded area that does not permit cochannel interference. Outside the safety zone, cochannels can be reused. The safety zone can move under the condition that its user does not meet cochannel interference as he moves to an adjacent microzone. Considering user mobility characteristics in the cigar-shaped cell, we analyze and evaluate the proposed system in terms of intracell and intercell handoff rates, blocking probability, intracell call-dropping probability, and channel reuse parameter. The proposed system can handle a traffic capacity of about 12 Erlangs for seven traffic channels under a call blocking probability of 1% and generates a negligible number of intracell handoffs compared with those of intercell handoffs.

Index Terms—Cigar-shaped cell, fiber-optic, intracell handoff, microzone, movable safety zone, urban microcell.

I. INTRODUCTION

RECENTLY, a rapid increase in mobile communication demands has required an increase in the capacity of cellular systems, especially in urban areas. To augment system capacity, microcellular systems with a radius of a several hundred meters have been introduced. However, these microcellular systems require a large number of base stations (BS’s) and may generate frequent handoffs.

Fiber-optic microcellular systems integrated with such technologies as subcarrier multiplexing (SCM) and spectrum delivery switching (SDS) have been extensively proposed and investigated to solve the problems encountered in microcellular systems [1]–[11]. We can implement low-cost small-sized BS’s with easy channel control schemes by installing all channel elements including user data processing functions such as a modulator/demodulator, a channel encoder/decoder, and an interleaver/deinterleaver in a central station (CS) and by sharing them among multiple antenna ports. The CS controls connections between its channel elements and antenna ports by utilizing SDS and dynamically assigns traffic channels according to traffic demands. Ichikawa et al. [8] and Morita et al. [11] showed that the centralized channel control with SDS improves system performance in terms of blocking probability, handoff failure probability, and so on.

In conventional systems, CS can assign a traffic channel to only one user, even if there are some users beyond the channel interference, because it has one channel element per traffic channel. Low transmitter power from low-height antenna ports makes cochannel distances shorter in urban microcellular environments. Therefore, CS coverage may include several cochannel distances. In order to increase the efficiency of radio resources, we need to reuse traffic channels in CS coverage. We can consider a CS with multiple channel elements per traffic channel for the reuse of channels. However, this channel reuse may inherently generate internal handoffs in the CS coverage [12].

In this paper, we propose a movable safety zone scheme with which a CS can concurrently assign a traffic channel to multiple users having no cochannel interference each other and can reduce internal handoffs among its antenna ports. The safety zone is a virtually guarded area that does not permit cochannel interference. In other words, cochannels can be reused outside the safety zone. If a user moves to an adjacent antenna port area without causing cochannel interference, he can continue to use his current channel through a new antenna port switched by an SDS, as shown in [13]. At that time, his safety zone is newly formed from his new antenna port area, which means his safety zone follows him. This scheme reduces internal handoffs among CS antenna ports.

In the urban fiber-optic microcellular system considered in this paper, simplified antenna ports called micro-base stations (M-BS’s) are set up along streets, and a cigar-shaped cell is formed with a group of M-BS’s. This is because radio signals propagate along the line-of-sight (LOS) path and sharply attenuate in other directions due to the shadows of neighboring tall buildings [14]–[21]. In the urban microcellular environment, we consider mobility characteristics of pedestrians, such as walking along the street and turning or crossing over to an adjoining street at intersections. We obtain channel holding time in the urban cell and then describe our proposed system using a continuous time Markov chain model. Based on the model, we evaluate the performance of the proposed system in terms of intercell and intracell handoff rates, call blocking probability, intracell call-dropping probability, and channel capacity.
The rest of this paper is organized as follows. In Section II, an urban fiber-optic microcellular network is introduced, and the movable safety zone concept is proposed. In Section III, the proposed system is analyzed using a continuous Markov chain model. In Section IV, some numerical results are taken. Finally, conclusions are drawn in Section V.

II. SYSTEM DESCRIPTION AND MOVABLE SAFETY ZONE CONCEPT

In this section, we introduce an urban fiber-optic microcellular system, as shown in Fig. 1. We consider a grid-structured urban area with horizontal and vertical streets. M-BS’s are set up in the middle of every street block, and the coverage of M-BS is called a microzone. A group of rectilinear M-BS’s forms a cigar-shaped cell. M-BS’s are connected to their CS with optical fibers. The CS controls intracell handoffs between M-BS’s as well as intercell handoffs, and dynamically assigns traffic channels with SDS.

The basic concept of the proposed movable safety zone scheme is as follows. Each communicating user has his own safety zone consisting of a group of microzones within a range of cochannel interferences from his current microzone. Occupied channels in a safety zone can be reused outside the safety zone. If a separation of \( n \) microzones on a line is required to avoid cochannel interference, the safety zone is maximally composed of \( 2n + 1 \) microzones, as shown in Fig. 2(a). In this case, we call the value of \( n + 1 \) the minimum cochannel distance. Fig. 2(b) and (c) shows some safety zones limited by the cigar-shaped cell. We assume that the size of a cigar-shaped cell \( (M) \) is much larger than the maximum size of the safety zone \( (2n + 1) \).

Fig. 3 illustrates the operation of the movable safety zone scheme. Let a mobile user initiate a call with channel \( c \) at \( t = t_0 \). Then, his safety zone is formed to include all microzones within a cochannel interference from microzone \( j \). If he moves to an adjacent microzone \( j + 1 \) at \( t_1 = t_0 + T \), then microzone \( j - n \) becomes free from the cochannel interference of channel \( i \) and microzone \( j + n + 1 \) belongs to the range of the cochannel interference. At that time, if channel \( i \) is not yet occupied at microzone \( j + n + 1 \), then he can continue to use channel \( i \) through the antenna port of microzone \( j + 1 \). His safety zone boundary also moves by one microzone in the direction in which he is moving, as shown in Fig. 3(a). On the other hand, if channel \( i \) has already been occupied at microzone \( j + n + 1 \) at \( t_1 = t_0 + T \), the user can no longer use channel \( i \) because of cochannel interference. If an available channel exists within a new safety zone centering at microzone \( j + 1 \), an intracell handoff is initiated, as shown in Fig. 3(b). If there is no available channel, the call is terminated.

Fig. 4 shows a block diagram of the proposed system to support the movable safety zone scheme. A CS needs several channel elements per traffic channel in order to assign the same channel concurrently to multiple users having no cochannel interference each other. When user \( A \) calls user \( B \), user \( A \)’s messages are routed from his channel element to the designated E/O converter connected to his destination (user \( B \)’s microzone) by SDS. At the M-BS of user \( B \), the optical signal transmitted from the CS is converted into an electrical signal by an O/E converter and then is radiated from the antenna of the M-BS. Conversely, the radio signal received at the M-BS of user \( B \) can be processed in the reverse direction. User \( C \) can concurrently communicate with user \( D \) with another channel element of the same traffic channel if this communication does not yield cochannel interference to user \( A \) or user \( B \).

III. SYSTEM ANALYSIS

In order to analyze the proposed movable safety zone scheme, we make the following assumptions.

- Users make new calls at uniformly distributed random points in the cigar-shaped cell.
- New call generations follow a Poisson process with rate \( \lambda_n \).
- Call holding time \( T_{ch} \) is exponentially distributed with mean \( 1/\mu_{ch} \).
- For both new calls and handoff calls, dwelling time in one microzone, \( T_{dw}^{(i)} \), has a \( r \)-stage Erlang distribution with mean \( 1/\mu_{dw} \). Then, the total dwelling time in \( i \) microzones, \( T_{dw}^{(i)} \), is another Erlang-distributed random variable, and its probability density function \( f_{T_{dw}^{(i)}}(t) \) is given by

\[
 f_{T_{dw}^{(i)}}(t) = \frac{\gamma T_{dw}^{(i)} \mu_{dw} \mu_{ch} t^{r-1}}{(r-1)!} \exp(-\gamma T_{dw}^{(i)} \mu_{ch} t). \quad (1)
\]

- The distributions of \( T_{dw}^{(i)} \) in all microzones are independent and identical.
- No priority is given to intercell handoff calls.
- Minimum cochannel distance is equal to two for mathematical simplicity.
Fig. 2. Shapes of the safety zone: (a) $1 + n \leq j \leq M - n$, (b) $j > M - n$, and (c) $j < 1 + n$.

Fig. 3. Movable safety zone concept: (a) the current channel can be used at microzone $j + 1$ because the channel is not occupied at microzone $j + n + 1$ and (b) an intracell handoff is required because the current channel is occupied by someone at microzone $j + n + 1$.

In this analysis, $M$ and $N$ denote the number of microzones and channels of a cigar-shaped cell, respectively.

A. Channel Holding Time $T_{cho}$

Channel holding time $T_{cho}$ is the time duration between a channel occupancy and its channel release. Fig. 5 shows four cases of channel release: (a) a user completes his call; (b) a user turns at the intersection (a turning handoff); (c) a user moves straight to an adjacent cell (a straight handoff); and (d) a user needs an intracell handoff. Let $T_{dh}$, $T_{sh}$, and $T_{th}$ be the dwelling times from a channel occupancy to a turning handoff, a straight handoff, and an intracell handoff, respectively. Then we can express $T_{cho}$ as

$$ T_{cho} = \min(T_{ch}, T_{dh}, T_{sh}, T_{th}). $$

Since in our proposed system, $T_{dh}$ is expected to be much larger than other variables $T_{ch}, T_{dh},$ and $T_{sh}$, we approximate
This approximation will be justified by simulation later in this section.

Let $m_t$ and $m_s$ be the number of microzones that a user passes before a turning handoff and a straight handoff, respectively. Then the cumulative distribution function of $T_{th}$, $F_{T_{th}}(t)$, is obtained as

$$F_{T_{th}}(t) = 1 - \Pr(T_{th} > t) = 1 - \sum_{i=1}^{\infty} \Pr(T_{th} > t|m_t = i) \Pr(m_t = i)$$

$$= 1 - \sum_{i=1}^{\infty} \Pr(T_{th}^{(i)} > t) P_s^{i-1}(1 - P_s)$$

$$= 1 - \sum_{i=1}^{\infty} \Pr(T_{th}^{(i)} > t) P_s^{i-1}(1 - P_s)$$

where $P_s$ the probability of straight movement without turning at intersections. From (1)

$$F_{T_{th}}(t) = 1 - \exp(-\mu_{d\rightarrow t}) (1 - P_s)$$

$$= 1 - \exp(-\mu_{d\rightarrow t}) \sum_{i=1}^{\infty} \frac{(\mu_{d\rightarrow t})^i}{i!}$$

Similarly, the cumulative distribution function of $T_{sh}$ is

$$F_{T_{sh}}(t) = 1 - \Pr(T_{sh} > t)$$

$$= 1 - \sum_{i=1}^{M} \Pr(T_{sh} > t|m_s = i) \Pr(m_s = i)$$

$$= 1 - \exp(-\mu_{d\rightarrow t}) \sum_{i=1}^{M} \sum_{n=0}^{M} \frac{(\mu_{d\rightarrow t})^n}{n!}.$$

From the three cumulative distribution functions of $T_{ch}$, $T_{th}$, and $T_{sh}$, the cumulative distribution function of $T_{cho}$, $F_{T_{cho}}(t)$.
is obtained by

\[ F_{T_{\text{ch}}} = \Pr(T_{\text{ch}} \leq t) = \int_0^{\infty} \int_0^{\infty} \Pr(T_{\text{ch}} \leq t | T_{\text{th}} = \tau_2, T_{\text{sh}} = \tau_1) \, dF_{T_{\text{th}}}(\tau_1) \times dF_{T_{\text{sh}}}(\tau_2) \]

\[ = F_{T_{\text{ch}}}(t) + F_{T_{\text{th}}}(t) + F_{T_{\text{sh}}}(t) - F_{T_{\text{th}}}(t)F_{T_{\text{sh}}}(t) - F_{T_{\text{ch}}}(t)F_{T_{\text{sh}}}(t) - F_{T_{\text{ch}}}(t)F_{T_{\text{th}}}(t) + F_{T_{\text{ch}}}(t)F_{T_{\text{th}}}(t)F_{T_{\text{sh}}}(t). \] (7)

Finally, the mean channel holding time can be expressed as

\[ E[T_{\text{ch}}] = \int_0^{\infty} (1 - F_{T_{\text{ch}}}(t)) \, dt. \] (8)

Fig. 6 shows good agreements in expected channel holding times between approximation results from (3) and simulation results. Therefore, the approximation of (3) is acceptable.

### B. Probabilities

Let the system state \( S \) represent the number of users being served in a cigar-shaped cell. Then the maximum value of \( S \), \( S_{\text{max}} \), is given by

\[ S_{\text{max}} = \lceil M/2 \rceil \cdot N \] (9)

where \( \lceil x \rceil \) means the smallest integer larger than or equal to \( x \).

Let \( \eta_k \) be the reuse factor of channel \( k \), representing the number of users using channel \( k \). We consider a channel assignment policy that keeps the difference of reuse factors \( \eta_k - \eta_j \) for \( i, j \in \{1, 2, \cdots, N\} \) as small as possible. Under this policy, we assume that

\[ \eta_k - \eta_j \leq 1, \quad \forall i, j \in \{1, 2, \cdots, N\}. \] (10)

From (10), when \( S = aN + b, (0 \leq b < N) \), the channels of the cigar-shaped cell are classified into two sets \( G_a \) and \( G_{a+1} \) according to their reuse factor

\[
\begin{cases}
\text{channel } k \in G_a, & \text{if } \eta_k = \alpha \\
\text{channel } k \in G_{a+1}, & \text{if } \eta_k = \alpha + 1
\end{cases}
\] (11)

for all \( k \in \{1, 2, \cdots, N\} \). Therefore, the number of channels in \( G_a \) and \( G_{a+1} \) is given by

\[
\#(G_a) = N - b \\
\#(G_{a+1}) = b.
\] (12)

The cigar-shaped cell has symmetry with respect to its center. From this property, we can assign a position number to each microzone with the following position function \( \pi(p) \)

\[
\pi(p) = \begin{cases} 
p, & p \leq \lceil M/2 \rceil \\
M - p + 1, & p > \lceil M/2 \rceil
\end{cases}
\] (13)

where \( p \) is the microzone number \((1 \leq p \leq M)\). For microzone \( p \), we name the neighboring microzones \( \alpha\text{-zone}, \beta\text{-zone}, \) and \( \gamma\text{-zone}, \) as shown in Fig. 7. Under the condition that the minimum cochannel distance is equal to two, the number of cases that a given channel is being used in \( m \) microzones among \( M \) microzones at an arbitrary instant, denoted by \( C[M, m] \), is obtained as

\[ C[M, m] = \binom{M - m + 1}{m}. \] (14)

Let \( \eta^{(a)}_\alpha, \eta^{(a)}_\beta, \) and \( \eta^{(a)}_\gamma \) be the number of cases that a given channel belonging to \( G_a \) is used in \( \alpha\text{-zone}, \beta\text{-zone}, \) and \( \gamma\text{-zone} \) among all the cases that the channel is used at \( a \) microzones, and \( \eta^{(a)}_\alpha \) is the number of the cases that the
channel is used in both $\alpha$-zone and $\gamma$-zone. Then, the values of $n_{\alpha}(a)$, $n_{\beta}(a)$, $n_{\gamma}(a)$, and $n_{\gamma'}(a)$ at each microzone are given by (15)–(17), with (17) given at the bottom of the page.

1) $\pi(p) = 1$

$$n_{\alpha}(a) = n_{\alpha}(a) = \begin{cases} 0 & \text{if } 1 \leq \pi(p) \leq \frac{M}{2} \\ C[M - 2, a - 1] & \text{if } \pi(p) > \frac{M}{2} \end{cases}$$

$$(15)$$

2) $\pi(p) = 2$

$$n_{\alpha}(a) = C[M - 2, a - 1]$$

$$n_{\beta}(a) = C[M - 3, a - 1]$$

$$n_{\gamma}(a) = C[M - 2, a - 1] - C[M - 5, a - 2]$$

$$n_{\gamma'}(a) = C[M - 4, a - 2].$$

$$(16)$$

3) $2 < \pi(p) \leq \frac{M}{2}$, see (17).

In the proposed system, a new call generated at microzone $p$ is blocked if each of $\alpha$-zone, $\beta$-zone, or $\gamma$-zone of microzone $p$. From the inequality condition of (10), we can obtain the probability that a new call generated at microzone $p$ is blocked at $s = aN + b$

$$P_{b,p}^{(a)} = \left[ \frac{n_{\alpha}(a) + n_{\beta}(a) + n_{\gamma}(a) - n_{\gamma'}(a)}{C[M, a]} \right]^{N-b} \times \left[ \frac{n_{\alpha}(a+1) + n_{\beta}(a+1) + n_{\gamma}(a+1) - n_{\gamma'}(a+1)}{C[M, a+1]} \right]^{b}.$$

$$(18)$$

Even if a new call occupies a channel successfully, it may experience a forced termination or forced channel changing within the cigar-shaped cell because available channels in its moving safety zone change over time. For example, when a call moves from microzone $p - 1$ to microzone $p$, if its current channel is being used in microzone $p + 1$, the moving call cannot keep its channel because of cochannel interference. In this case, if there is any other channel available in the safety zone composed of microzone $p - 1$, microzone $p$, and microzone $p + 1$, the channel is switched to the available channel; this is called an intracell handoff. If there is no available channel in the safety zone, the call is dropped; this is called an intracell call dropping.

Let $P_{d,p}^{(a)}$ and $P_{d,p}^{(a)}$ be the intracell call-dropping probabilities when a user using channel $k (1 \leq k \leq N)$ moves to microzone $p$ from its $\gamma$-zone and $\alpha$-zone at $s = aN + b$, respectively. Then $P_{d,p}^{(a)}$ and $P_{d,p}^{(a)}$ can be derived as (19) and (20), given at the bottom of the next page, where

$$P_{b,p}^{(a)} = \left[ \frac{n_{\alpha}(a) + n_{\beta}(a) + n_{\gamma}(a) - n_{\gamma'}(a)}{C[M, a]} \right]^{N-b} \times \left[ \frac{n_{\alpha}(a+1) + n_{\beta}(a+1) + n_{\gamma}(a+1) - n_{\gamma'}(a+1)}{C[M, a+1]} \right]^{b}.$$

$$(17)$$
In (19) and (20), $P(s)$ represents the steady-state probability. Similarly, let $P^1_{h,p}$ and $P^1_{h,p}$ be the intracell handoff probabilities when a user using channel $k$ ($1 \leq k \leq N$) moves to microzone $p$ from its $\alpha$-zone and $\gamma$-zone at $s = \alpha N + b$, respectively. Then $P^1_{h,p}$ and $P^1_{h,p}$ can be derived as (21) and (22), given at the bottom of the next page.

We can obtain the probability (23) that a call generated in microzone $p$ is eventually dropped within the cell

$$P_{d,p} = P_{short} \sum_{k=1}^{\pi(p)-1} \Pr(T_{ch} > T_{dw}^{(k)}) P_{s}^{k} \prod_{i=1}^{M-\pi(p)} (1 - P^1_{d,i})$$

and

$$\Pr(T_{ch} > T_{dw}^{(k)}) = \int_{0}^{\infty} (1 - F_{T_{ch}}(t)) f_{T_{dw}^{(k)}}(t) dt$$

$$= \int_{0}^{\infty} \exp(-\mu_{ch} t) \frac{T_{dw}^{(k)} \mu_{ch}^{(k)} t^{\pi(p)-1}}{(\pi(p) - 1)!} \exp(-\mu_{dw} t) dt$$

$$= \left[ \frac{T_{dw}^{(k)} \mu_{ch} + \mu_{dw}}{\mu_{ch} + \mu_{dw}} \right]^{\pi(p)}$$

and $P_{short}$ and $P_{short}$ are the probabilities of moving toward the nearer and farther cell boundaries at the channel occupancy point, respectively.

Similarly, the probability that a call generated in microzone $p$ experiences at least one intracell handoff ($P_{h,p}$) is given by

$$P_{h,p} = P_{short} \sum_{k=1}^{\pi(p)-1} \Pr(T_{ch} > T_{dw}^{(k)}) P_{s}^{k} \prod_{i=1}^{M-\pi(p)} (1 - P^1_{h,i})$$

$$\times \Pr(T_{ch} > T_{dw}^{(k)}) P_{s}^{k} \prod_{i=1}^{M-\pi(p)} (1 - P^1_{h,i})$$

$$= \left[ \frac{T_{dw}^{(k)} \mu_{ch} + \mu_{dw}}{\mu_{ch} + \mu_{dw}} \right]^{\pi(p)}$$

where $P^1_{m,p}$, $P^1_{m,p}$, $P^1_{m,p}$, and $P^1_{m,p}$ are shown in (25) and (26), given at the bottom of the next page.

C. Call Arrival Rate

Let $P_{h,p}$ and $P_{sh,p}$ be the probabilities that a call generated in microzone $p$ tries a turning handoff and a straight handoff, respectively. Then $P_{h,p}$ and $P_{sh,p}$ can be derived by (27) and (28), given at the bottom of the next page.

New call rate and turning-handoff call rate are identical over all microzones. However, straight-handoff calls are generated only at the ends of the cigar-shaped cell, i.e., microzone 1 and microzone $M$. Therefore, the call arrival rate of each microzone is written as

$$\lambda_p = \begin{cases} \lambda_h + \lambda_{th}, & p = 1 \text{ or } M \\ \frac{\lambda_h}{2}, & 2 \leq p \leq M - 1. \end{cases}$$

We assume that straight-handoff calls and turning-handoff calls occur according to Poisson processes with rates $\lambda_{sh}$ and $\lambda_{th}$, respectively. The $\lambda_{th}$ and $\lambda_{sh}$ can be given by

$$\lambda_{th} = \sum_{p=1}^{M} \lambda_p (1 - P_{sh,p}) P_{h,p}$$

$$\lambda_{sh} = \sum_{p=1}^{M} \lambda_p (1 - P_{sh,p}) P_{sh,p}$$

Finally, the total arrival rate of new calls, turning-handoff calls, and straight-handoff calls is approximated by a Poisson
process with the following rate:

$$\lambda = \lambda_n + \lambda_s + \lambda_{sh}. \quad (31)$$

**D. Limiting Distribution of System State**

Considering Poisson call arrivals, generally distributed service time, and a finite system capacity $S_{\text{max}}$, we can represent

$$P_{n,p}^\dagger = \frac{\sum_{s=1}^{S_{\text{max}}} P(s) \left\{ P_a \cdot \frac{n_{\gamma}^{(a)}}{C[M, a]} \cdot \left( 1 - P_{b_{\gamma}^{(a)}}^{(a)} \right) + P_{a+1} \cdot \frac{n_{\gamma}^{(a+1)}}{C[M, a+1]} \cdot \left( 1 - P_{b_{a+1}}^{(a+1)} \right) \right\}}{\sum_{s=1}^{S_{\text{max}}} P(s) \left\{ P_a \cdot \frac{n_{\gamma}^{(a)}}{C[M, a]} + P_{a+1} \cdot \frac{n_{\gamma}^{(a+1)}}{C[M, a+1]} \right\}} \quad (21)$$

$$P_{m,p}^\dagger = \frac{\sum_{s=1}^{S_{\text{max}}} P(s) \left\{ P_a \cdot \frac{n_{\gamma}^{(a)}}{C[M, a]} \cdot \left( 1 - P_{b_{\gamma}^{(a)}}^{(a)} \right) + P_{a+1} \cdot \frac{n_{\gamma}^{(a+1)}}{C[M, a+1]} \cdot \left( 1 - P_{b_{a+1}}^{(a+1)} \right) \right\}}{\sum_{s=1}^{S_{\text{max}}} P(s) \left\{ P_a \cdot \frac{n_{\gamma}^{(a)}}{C[M, a]} + P_{a+1} \cdot \frac{n_{\gamma}^{(a+1)}}{C[M, a+1]} \right\}} \quad (22)$$

$$P_{m-i}^\dagger = \left\{ \begin{array}{ll} P_{m-j}^\dagger, & i \leq [M/2] \\ P_{m-j}^\dagger, & i > [M/2] \end{array} \right.$$  

$$P_{h-i}^\dagger = \left\{ \begin{array}{ll} P_{h-j}^\dagger, & i \leq [M/2] \\ P_{h-j}^\dagger, & i > [M/2] \end{array} \right.$$  

$$P_{n-p} = P_{\text{short}} \sum_{k=1}^{\pi(p)} \Pr(T_{ch} > T_{\text{dwo}}^{(k)}) P_{k-1}^{s} \left( 1 - P_{b_{\gamma}^{(p)}}^{(p)} \right) + P_{\text{aug}} \sum_{k=1}^{M - \pi(p)+1} \Pr(T_{ch} > T_{\text{dwo}}^{(k)}) P_{k-1}^{s} \left( 1 - P_{b_{\gamma}^{(p)}}^{(p)} \right) \times \prod_{i=\pi(p)+1}^{\pi(p)+k-1} \left( 1 - P_{d_{i}}^{(p)} \right) \quad (27)$$

$$P_{n-h} = P_{\text{short}} \Pr(T_{ch} > T_{\text{dwo}}^{(p)}) P_{\text{aug}} \prod_{i=\pi(p)+1}^{\pi(p)-1} \left( 1 - P_{b_{\gamma}^{(p)}}^{(p)} \right) + P_{\text{aug}} \Pr(T_{ch} > T_{\text{dwo}}^{(M - \pi(p)+1)}) P_{M - \pi(p)+1}^{s} \times \prod_{i=\pi(p)+1}^{M} \left( 1 - P_{d_{i}}^{(p)} \right) \quad (28)$$


The proposed system as an \( M/G/S_{\text{max}} \) loss system. The limiting distribution of the system state is identical to that of an \( M/M/S_{\text{max}} \) loss system due to the insensitivity property \[22\]. The state transition diagram for the \( M/M/S_{\text{max}} \) loss model representing the proposed system is shown in Fig. 8. In this figure, \( P_b^s \) denotes the conditional blocking probability at state \( s \). Solving the balance equations, we can obtain the steady-state probability

\[
P(s) = \begin{cases} 
\frac{1}{s!} \left( \frac{\lambda}{\mu} \right)^s P(0), & 0 \leq s \leq N \\
\frac{1}{s!} \left( \frac{\lambda}{\mu} \right)^s \prod_{k=N}^{s-1} (1 - P_b^k) P(0), & N < s \leq S_{\text{max}} 
\end{cases}
\]

The blocking probability in microzone \( p \) \( (P_{b,p}) \) can be obtained as

\[
P_{b,p} = \sum_{s=N}^{S_{\text{max}}-1} P_{b,p}^s P(s) \quad \text{for} \quad S_{\text{max}} \quad \text{(33)}
\]

where

\[
P(0) = \frac{1}{E[T_{\text{cho}}]}.
\]

The blocking probability in microzone \( p \) \( (P_{b,p}) \) can be obtained as

\[
P_{b,p} = \sum_{s=N}^{S_{\text{max}}-1} P_{b,p}^s P(s) + P(S_{\text{max}})
\]

where \( P_{b,p}^s \) is the blocking probability in microzone \( p \) at state \( s \).

IV. NUMERICAL EXAMPLES

We now evaluate the proposed system in terms of blocking probability, intracell call-dropping probability, and cell capacity. We use a numerical method to calculate the system state probability. The parameters used in our analysis are listed in Table I.

### Table I: List of System Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average call holding time, ( E[T_{\text{c}}] )</td>
<td>100 s</td>
</tr>
<tr>
<td>Average dwelling time in a microzone, ( E[T_{\text{d}}] )</td>
<td>500 s</td>
</tr>
<tr>
<td>Stage of Erlang distribution, ( r )</td>
<td>5</td>
</tr>
<tr>
<td>( P_{\text{short}}, P_{\text{long}} ) and ( P_b )</td>
<td>0.3</td>
</tr>
<tr>
<td>Number of microzones in a cigar-shaped cell, ( M )</td>
<td>10</td>
</tr>
<tr>
<td>Number of channels per cigar-shaped cell, ( N )</td>
<td>7</td>
</tr>
</tbody>
</table>

---

**Fig. 9.** Blocking probability at each state.

**Fig. 10.** Handoff call rates.

**Fig. 11.** Blocking probability and the probability that a call is eventually dropped within a cell.

**Fig. 12.** Channel reuse parameter.

---

Authorized licensed use limited to: Korea Advanced Institute of Science and Technology. Downloaded on May 10, 2009 at 23:27 from IEEE Xplore. Restrictions apply.
Fig. 9 shows the blocking probability of new call at each state. When a cell has seven channels, i.e., \( N = 7 \), the conventional cellular systems without channel reuse within the cell usually have the blocking probability of one at \( S = 7 \), while the proposed system yields the blocking probability about \( 10^{-4} \) at the same state. Even if the system state increases up to 13, we can keep the blocking probability below 1%.

The proposed system may generate intracell handoff calls. Fig. 10 shows the handoff call rate versus the new call rate \( \lambda_n \) for three different types of handoff calls. We can observe that the intracell handoffs rarely occur. For example, the intracell handoff call rate is about 0.0004 for \( \lambda_n = 0.2 \) which corresponds to only one intracell handoff among 500 new calls. In addition, the intracell handoff call rate is much lower than turning-handoff call rate which is dominant in total intercell handoff call rate of turning-handoff and straight-handoff calls. From this result, we can infer that the effect of intracell handoffs is negligible.

Fig. 11 shows the blocking probability \( P_b \) and the probability that a call is eventually dropped within a cell \( P_d \) for varying the offered traffic load. \( P_b \) is given by \( (1/M) \sum_{m=1}^{M} P_{b,m} \) and \( P_d \) is similarly written as \( (1/M) \sum_{m=1}^{M} P_{d,m} \). The proposed system can accommodate about 12 Erlangs under a blocking probability of 1% for \( N = 7 \), while under the same condition, the conventional cellular systems handle about 2.64 Erlangs. This means that system capacity increases by \( 12/2.64 \approx 45 \% \). The probability \( P_d \) is smaller than \( 10^{-2} \cdot P_b \). In the analysis of quality of service (QOS), the weight on forced terminations may be ten times larger than that on new call blockings [23]. The effect of the intracell call dropping on QOS in the proposed system is negligible because \( P_b + 10P_d \approx P_b \).

We define a channel reuse parameter \( f_r \) at \( s = aN + b \), as

\[
f_r = \sum_{s=0}^{S_{\text{max}}} \frac{a(N-b)+(a+1)b}{N} P(s).
\]

(34)

The channel reuse parameter \( f_r \) represents the average number of channel reuses in a cell. Fig. 12 shows the channel reuse parameter for varying the offered traffic load. We can see that \( f_r \) increases as the offered traffic load increases. This implies that the system capacity is expandable up to \( \lceil M/2 \rceil \cdot N \) due to channel reuse as the offered traffic load increases. For example, the channel reuse parameter is about 1.6 at an offered load of about 11.6 Erlangs, corresponding to the acceptable blocking probability level of 1%, as shown in Fig. 11. This implies that the system can handle \( 1.6 \times 7 \) channels.

No movable safety zone means no channel reuses like conventional systems. In other words, the channels of CS can be used only one time in a CS coverage (a cigar-shaped cell in this paper) consisting of multiple microzones. On the other hand, however, it guarantees no intracell handoff resulting in no intracell call dropping. The blocking probability of the system without the movable safety zone scheme is definitely higher than that of channel reuse system with the movable safety zone scheme. In order to evaluate the two systems, we use the weighted sum \( P_b + 10P_d \). As shown in Fig. 13, simulation results are higher than analytical results for the movable safety zone scheme because (10) underestimates the blocking and call-dropping probabilities. Although we take into account the difference between simulation and analytical results, we can improve of QOS with the movable safety zone scheme.

V. CONCLUSIONS

We proposed a movable safety zone scheme in urban fiber-optic microcellular systems and described a new CS
architecture for managing the scheme. We also evaluated the proposed urban fiber-optic microcellular system in terms of the intra and intercell handoff rate, the blocking probability, the intracell call-dropping probability, and the channel reuse parameter by considering user mobility characteristics and cell shapes in urban areas.

Utilizing the movable safety zone, we can reuse traffic channels within a cell and reduce unnecessary intracell handoffs among microzones. Therefore, we can significantly increase the efficiency of radio resources, thus yielding a considerable improvement in system traffic capacity. For example, the proposed system can handle 12 Erlangs under the blocking probability of 1% for seven channels. These results can be utilized in implementing urban microcellular systems.

REFERENCES