ABSTRACT

Over the past few years there has been rapid growth in the demand for mobile communications that has led to intensive research and development of complex PCS (personal communication services) networks. Capacity planning and performance modeling are necessary to maintain a high quality of service to the PCS subscriber while minimizing costs. Effective and practical performance models for large-scale PCS networks are currently available. Two new performance models are presented in this article which can be solved using analytical techniques. The first is the so-called portable population model, based on the flow equivalent assumption (the rate of portables into a cell equals the rate of portables out of the cell). The model provides the steady-state portable population distribution in a cell that is independent of the portable residual time distribution, which can be used by simulations to reduce the necessary execution time by reaching the steady state more rapidly. Additionally, this model can be used to study the blocking probability of a low (portable) mobility PCS network and the performance of portable deregistration strategies. The second model is the so-called *portable movement model* which can be used to study location tracking and handoff algorithms. The model assumes that the arriving calls to a portable form a Poisson process, and portable residual times have a general distribution. This model can be used to study location-tracking algorithms and handoff algorithms. It is shown that under some assumptions, the analytic techniques are consistent with the simulation model.

Modeling Techniques for Large-Scale PCS Networks

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A personal communications services (PCS) network [1] is a wireless network that provides communication services for *PCS subscribers*. The service area of a PCS network is populated with base stations. The radio coverage of a base station is called a *cell*. The base station locates a subscriber or *portable*, and delivers calls to and from the portable by means of paging within the cell it serves. A registration area (RA) consists of an aggregation of cells, forming a contiguous geographical region. To connect a phone call to a roaming portable, it is necessary to identify the portable's RA. The strategies commonly proposed are two-level hierarchies [2] that maintain a system of home and visited databases (home location registers, or HLRs, and visitor location registers, or VLRs). To order PCS services, a PCS subscriber must "enroll" with a particular PCS provider. When enrolling, the PCS subscriber gives the PCS provider the necessary information, such as credit, service type, and current location, to set up the PCS account. This PCS account information is stored in the HLR of the PCS provider. When the PCS subscriber roams to another RA, which is likely to be owned by another PCS provider, the PCS subscriber becomes a "visitor" of that RA. The VLR of this RA is used to store the visiting PCS subscriber's information. Upon registering with the VLR, the VLR notifies the HLR of the visiting PCS subscriber that "your subscriber is at my place."

General models are needed to understand different aspects of large-scale PCS networks (such as user location strategies [3–5], registration strategies [6–9], handoff or automatic link transfer strategies [10–14], and channel allocation strategies [15–18]) so that the network will provide a high quality of service to mobile subscribers while minimizing the resource cost incurred by the PCS provider.

In this article we are concerned with analytic models for large-scale PCS networks. Analytic models are able to capture the behavior of a system in a concise mathematical formulation without the high computational overheads associated with large simulations. Accordingly, we describe two analytic models that will reduce the effort involved in studying the behavior of large-scale PCS networks. The first model is called the *portable population model*, and is based on the flow equivalent assumption (the rate at which portables move into a cell is equal to the rate at which they move out of the cell). This model enables determination of the steady-state portable population distribution in a cell that is independent of the portable residence time distribution. The model can be used to study the blocking probability of low-mobility (portable) PCS networks and the performance of portable deregistration strategies. The second model is the so-called *portable movement model*. By assuming that the arrival of calls to a portable form a Poisson process, and portable residence times have a general distribution, this model can be used to study location tracking and handoff algorithms.

The main contribution of this article is to illustrate that effective, practical models for large-scale PCS networks are available to provide essential quantitative information to network designers.

PCS NETWORK PLANNING ISSUES

The PCS business has been grown very fast since 1990. Worldwide and U.S. cellular subscribers growth is illustrated in Fig. 1.

The challenge of the PCS business is that customer demand has increased dramatically every year. Thus, sophisticated performance evaluation must be conducted to provide guidelines for PCS network planning. Several network planning issues and the modeling techniques described in this article are listed below.

ISSUE 1

As the subscriber population grows, the capacities of databases (i.e., VLRs) should be upgraded so the probability that the

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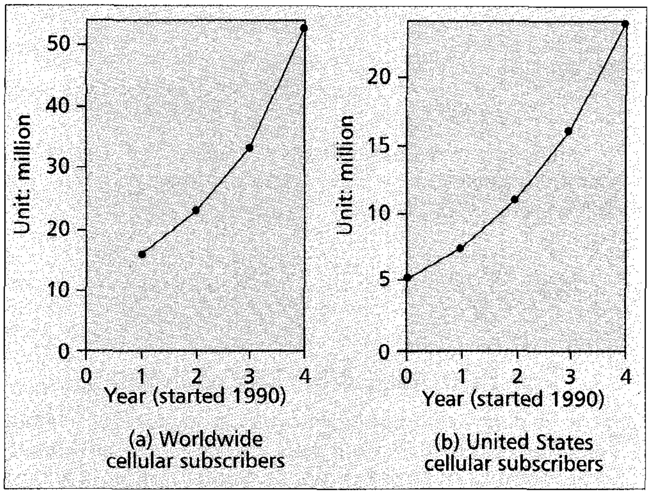


(a) Worldwide cellular subscribers

(b) United States cellular subscribers

■ **Figure 1.** *Cellular subscriber growth.*

database is full when a portable arrives is less than a threshold. This issue can be modeled by techniques 2 and 3 described in this article.

ISSUE 2

For a low-mobility/stationary PCS systems without handover (e.g., the CT2 systems developed in Asia Pacific regions), an appropriate performance model is required for capacity planning, which is different from the modeling of high-mobility cellular systems. An example of the "appropriate model" is technique 1, which is also a perfect modeling approach for nomadic computing networks where mobile users are stationary when they compute (survey data indicate that users seldom use their notebook when they are walking or driving).

ISSUE 3

While the cellular subscriber population grows every year, the average call holding time decreases. According to CTIA's Industry Survey, the average call holding time has been decreased from 2.24 min to 2.15 min. Thus, radio capacity planning for a PCS system should consider the change in average call holding time as well as that in incoming traffic. This issue can be modeled by technique 4.

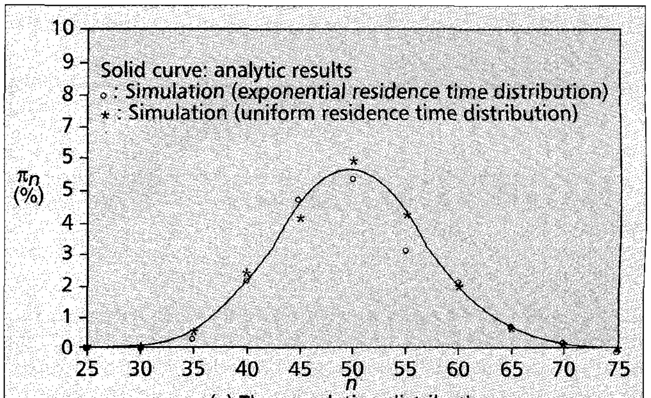
ISSUE 4

Rapid PCS customer population growth implies that PCS roaming management will generate large volumes of signaling traffic to the public switched telephone network. Thus, new roaming management protocols and evaluation methods should be developed. Techniques 2 and 3 model protocols that reduce deregistration traffic and those that reduce registration traffic.

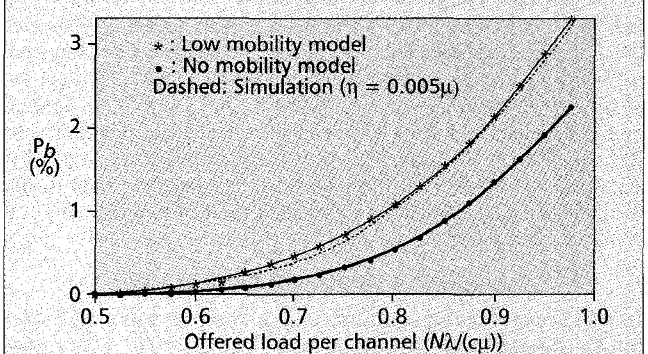
THE PORTABLE POPULATION MODEL

This section describes a portable population model. An important fact observed from this model is that the steady-state portable population in a cell is insensitive to the distribution of portable residence times.

Let N be the expected number of portables in a cell. Suppose the residence time of a portable in a cell has a general distribution $F(t)$ with mean $1/\eta$. In the steady state, the rate at which portables move into a cell equals the rate at which they move out of the cell. The arrivals of portables can be viewed as being generated from N input streams which have the same general distribution with arrival rate η. The net input stream to a cell can be approximated as a Poisson process with arrival rate $\lambda^* = N\eta$. Thus, the distribution for the portable population can be modeled by an $M/G/\infty$ queue with arrival rate λ^* and service rate η. Let π_n be the steady state probability that there are n portables in the cell. The steady-state probability π_n that there are n portables in the cell can be computed from [19]



(a) The population distribution



(b) Blocking for different models ($N = 50$, $c = 20$)

■ **Figure 2.** *Population distribution.*

$$\pi_n = \left(\frac{\lambda^*}{\eta}\right)^n \frac{e^{-\frac{\lambda^*}{\eta}}}{n!} \tag{1}$$

$$= \frac{N^n e^{-N}}{n!} \tag{2}$$

Figure 2a illustrates the population distribution when $N = 50$. The solid curve plots π_n based on Eq. 2. The "O" marks represent π_n obtained from simulation where the portable residence times are exponentially distributed, the "*" marks simulation results for a uniform portable residence time distribution. The figure indicates that the population distribution for a cell is insensitive to the portable residence time distributions, and Eq. 2 is consistent with the simulation results.

We list two modeling techniques based on the population model.

TECHNIQUE 1: LOW MOBILITY PCS NETWORK

Equation 2 can be used to study the blocking probability p_b for a PCS network of portables with low mobility. The idea is as follows. First, the blocking probability $p_b{}^n$ is derived for a cell when there are n portables. With the low mobility assumption, the blocking probability for the cell is then

$$p_b = \sum_{c<n<\infty} \pi_n p_b^{(n)} \tag{3}$$

where c is the number of channels in a cell.

Consider a PCS network where every cell has $c = 20$ channels. A phone call is dropped immediately if no channel is available. Suppose that the phone calls to/from a portable are a Poisson process with rate λ, and the call holding time is an

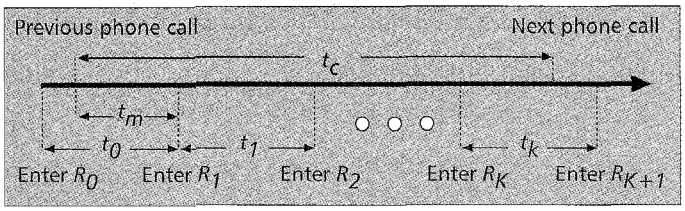


Figure 3. *The relationship among* t_c, t_i, *and* t_m.

exponentially distributed random variable with mean $1/\mu$. Figure 2b plots the blocking probability p_b against $N\lambda/c\mu$, the offered load carried by a channel. The curve marked • represents the no-mobility model, which is a blocking system with finite sources. In this model, the number of portables N in a cell is fixed. When $N \gg c$, the no-mobility model approaches the Erlang-B system. The curve marked * represents the low-mobility model (i.e., Eq. 3) wherein p_b^n in Eq. 3 is derived from the no-mobility model with population n. The dashed curve represents simulation results when the mobility $\eta = 0.005\mu$. Figure 2b indicates that our low-mobility model is consistent with the simulation study, while the no-mobility model cannot accurately or appropriately predict the cell blocking probability.

TECHNIQUE 2: PORTABLE REGISTRATION

In a PCS network, registration is the process by which portables inform the network of their current location (i.e., registration area or RA). Every registration area is associated with a location database, the VLR. A portable registers its location in the VLRs when it is powered on and moving between registration areas. If the VLR is full, the portable cannot access the services provided by the PCS network. When a portable leaves an RA or shuts off for a long period of time, the portable should be deregistered from the RA so that any resources previously assigned to the portable can be deallocated.

In IS-41 [20, 21], the registration process ensures that a portable registration in a new RA causes deregistration in the previous RA. This approach is referred to as *explicit deregistration*. Bellcore Personal Access Communications Systems (PACS) [6] specifies that a portable should be deregistered by default after a certain time period elapses without the portable reregistering. This scheme is referred to as *timeout deregistration* [9]. In the above registration schemes, it is important to determine (based on the amount of resources for an RA) the probability β that a portable cannot register (and receive service) because the database is full. The population model can be used to determine β for different registration schemes.

Let M be the amount of resources available in an RA. Suppose that the portable residence times have an arbitrary distribution with mean $1/\eta$, and let N be the expected number of portables in an RA; then β_{ED} (the probability β for explicit deregistration) is

$$\beta_{ED} = \sum_{M \le n < \infty} \pi_n \tag{4}$$

where π_n is given in Eq. 2. For the timeout scheme, the arrivals of portables seen by the scheme is the same as the explicit deregistration (i.e., the arrival rate $N\eta$). However, the expected portable residence time $E[\tau]$ seen by the timeout scheme is longer than $1/\eta$ because the scheme is only sure that a portable leaves the RA if the portable does not send a reregistration message within a timeout period T. For exponential portable residence time distribution, $E[\tau]$ can be expressed as

$$E[\tau] = \frac{T}{1 - e^{-\eta T}}$$

Thus, β_{TO} (the probability β of timeout deregistration) can be expressed by Eqs. 1 and 4 where η in Eq. 1 is replaced by $1/E[\tau]$; that is,

$$\beta_{TO} = \sum_{n=M}^{\infty} \pi_n^* \quad \text{where } \pi_n^* = \left(\frac{N\eta T}{1 - e^{-\eta T}}\right)^n \frac{e^{-\frac{N\eta T}{1-e^{-\eta T}}}}{N!}$$

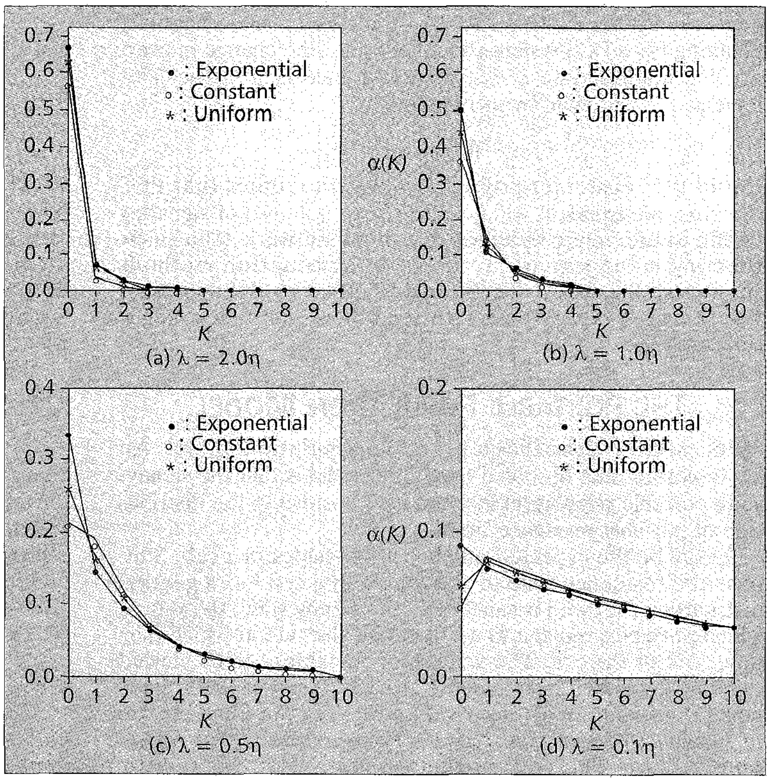
THE PORTABLE MOVEMENT MODEL

Here we describe a portable movement model [22] to study the patterns of incoming calls and portable movement. The probability $\alpha(K)$ that a portable moves across K RAs between two phone calls is derived assuming that the incoming calls to a portable are a Poisson process, and the time the portable resides in an RA has a general distribution. This study indicates that for a portable with different RA residence time distributions (such as exponential, constant, and uniform distributions) the $\alpha(K)$ distributions are similar if the portable mobility is high, and the $\alpha(K)$ distributions are very different if the portable mobility is low.

Let t_c be the time interval between two consecutive phone calls to a portable p. Suppose that the portable resides in an RA R_0 when the first phone call arrived. After the phone call, p visits another K RAs, and p resides in the ith RA for a time period $t_i (0 \le i \le K)$. Let t_m be the time interval between the arrival of the first phone call and the time when p moves out of R_0. The relationship among t_c, t_i and t_m is shown in Fig. 3.

We make the following assumptions:

- The phone calls to a portable are a Poisson process. In other words, t_c is exponentially distributed with mean $E[t_c] = 1/\lambda$.



(a) $\lambda = 2.0\eta$

(b) $\lambda = 1.0\eta$

(c) $\lambda = 0.5\eta$

(d) $\lambda = 0.1\eta$

Figure 4. $\alpha(K)$ *for different portable residence time distributions.*

- t_i are independent and identically distributed random variables with a general density function $f(t_i)$, and mean $E[t_i] = 1/\eta$.

The probability $\alpha(K)$ that p moves across K RAs between two phone calls is

$$\alpha(K) = \begin{cases} \Pr[t_m + t_1 + \ldots + t_{K-1} < t_c \le t_m + t_1 + \ldots + t_K] & K \ge 1 \\ \Pr[t_c < t_m] & K = 0 \end{cases} \quad (5)$$

From the random observer property of the Poisson call arrivals, the distribution of t_m can be derived from $f(t_0)$ using the excess life formula in the renewal theory [23]. Then from the distributions for t_c, t_i, and t_m, Eq. 5 is derived as

$$\alpha(K) = \begin{cases} \frac{\eta}{\lambda}[1 - f^*(\lambda)]^2 [f^*(\lambda)]^{K-1} & K \ge 1 \\ 1 - \frac{\eta}{\lambda}[1 - f^*(\lambda)] & K = 0 \end{cases} \quad (6)$$

where

$$f^*(s) = \int_{t=0}^{\infty} e^{-st} f(t)dt \quad (7)$$

is the Laplace-Stieltjes Transform for $f(t_i)$. Equation 6 is general enough to accommodate any portable mobility patterns. (i.e., arbitrary $f(t_i)$ functions). Note that the Laplace pairs for many functions are already available [24, 25].

If t_i is exponentially distributed, then from Eq. 6,

$$f^*(\lambda) = \frac{\eta}{\eta + \lambda},$$

and

$$\alpha(K) = \begin{cases} \frac{\eta^K \lambda}{(\eta + l)^{K+1}} & K \ge 1 \\ \frac{\lambda}{\eta + \lambda} & K = 0 \end{cases} \quad (8)$$

The intuition behind Eq. 8 is the following. Since t_0 is exponentially distributed, the "excess life" t_m has the same distribution as t_0 [23]. Since both t_c and t_m are exponentially distributed,

$$\alpha(0) = \Pr[t_c < t_m] = \int_{t_m=0}^{\infty} \int_{t_c=0}^{t_m} \lambda e^{-\lambda t_c} \eta e^{-\eta t_m} dt_c dt_m = \frac{\lambda}{\eta + \lambda}$$

which is consistent with the case $K = 0$ in Eq. 8. Now consider $K > 0$. When the portable moves into R_i, the remaining time before the second phone call has the same distribution as t_c (due to the memoryless property of an exponential distribution). If the portable does not receive the second phone call before it enters R_i, then the probability that the portable receives the second call before it leaves R_i is $q = \lambda/(\eta + \lambda)$. Thus, $\alpha(K)$ has a geometric distribution

$$\alpha(K) = q(1 - q)^K = \left(\frac{\lambda}{\eta + \lambda}\right)\left(\frac{\eta}{\eta + \lambda}\right)^K$$

The result is the same as the case $K \ge 1$ in Eq. 8.

For the constant portable residence time distribution with mean η, $f^*(\lambda) = e^{-\lambda/\eta}$, and

$$\alpha(K) = \begin{cases} \frac{\eta}{\lambda}\left(1 - e^{-\frac{\lambda}{\eta}}\right)^2 e^{-\frac{(K-1)\lambda}{\eta}} & K \ge 1 \\ 1 - \frac{\eta}{\lambda}\left(1 - e^{-\frac{\lambda}{\eta}}\right) & K = 0 \end{cases}$$

For the uniform portable residence time distribution in the range $[0, 2/\eta]$, $f^*(\lambda) = \eta/2\lambda(1 - e^{-2\lambda/\eta})$, and

$$\alpha(K) = \begin{cases} \frac{\eta}{\lambda}\left[1 - \frac{\eta}{2\lambda}\left(1 - e^{-\frac{2\lambda}{\eta}}\right)\right]^2 \left(1 - e^{-\frac{2\lambda}{\eta}}\right)^{K-1} & K \ge 1 \\ 1 - \frac{\eta}{\lambda}\left[1 - \frac{\eta}{2\lambda}\left(1 - e^{-\frac{2\lambda}{\eta}}\right)\right] & K = 0 \end{cases}$$

Figure 4 plots $\alpha(K)$ for different portable residence time distributions with different λ/η values. Figures 4a and b indicate that when $\lambda > \eta$, the $\alpha(K)$ distribution is insensitive to the portable residence time distributions. On the other hand, Figs. 4c and d indicate that when $\lambda < \eta$ for a small K, the probability $\alpha(K)$ is significantly affected by the portable residence time distributions.

Two applications of the portable movement model are described below.

TECHNIQUE 3: LOCATION TRACKING

In a PCS system, the RA of a called portable must be determined before a connection can be established. Due to the mobility of portables, the HLR is required to store the location (i.e., address of the visited RA) of a portable. The location record is modified when the portable moves to another RA. Every RA is associated with a VLR. (A VLR may serve one or more RAs. For demonstration purposes, we assume that each VLR serves an RA.) In IS-41, when a portable moves from an RA to another RA, it registers at the VLR of the new RA, and its new location is reported to the HLR.

A technique called *location forwarding* was proposed to reduce the location update cost in a PCS network [5]. The idea is described as follows. When a phone moves to a new RA, no message is sent to update the HLR. Instead, a message is sent to the old RA to create a forwarding pointer to the new RA. The cost of creating a forwarding pointer is assumed to be more economical than the modification of the location record at the HLR. When an incoming call arrives, the forwarding pointers are traced to find the actual location of the phone.

Suppose that during two incoming calls, the phone moves to new RAs K times, and the number of forwarding pointers traced to find the actual location is k. Then the cost saved in the location forwarding (compared with the IS-41 scheme) is K operations to update the HLR. On the other hand, the extra penalty paid in the location forwarding is k operations to trace the forwarding pointers when a portable is located. Since the phone may revisit an RA, we have $k \le K$. Thus, the key issue of modeling location forwarding is to derive the values for k and K. The K distribution can be derived based on the portable movement model (i.e., Eq. 5). The derivation of k can be done by using a two-dimensional random walk with reflecting barriers.

TECHNIQUE 4: HAND-OFF ALGORITHMS

As noted earlier, when a portable moves from one cell to another while a call is on progress, the call requires a new channel (in the new cell) to continue. If no channel is available in the new cell, the call will be dropped or forced terminated. The forced termination probability is an important criterion in the performance evaluation of the PCS network. Forced termination of an ongoing call is considered less desirable than blocking of a new call attempt. Several handoff schemes have been proposed (see [12] for a survey) to reduce forced termination. Performance modeling of the handoff schemes has been intensively studied. In most modeling efforts (either analytic analysis or simulation) [10–12, 14, 26], a single cell is studied by assuming that both new call attempts and handoff calls are Poisson processes with arrival rate λ_n and λ_h, respectively. Then modeling techniques are used to simulate the behavior of a specific handoff scheme with aggregate call arrivals where output measures such as p_o (the new call blocking probability), p_f (the forced termination probability), and p_{nc} (the probability that a call cannot complete due to blocking or forced termination) are derived. In this model, λ_h cannot be arbitrary selected. Rather, λ_h, p_o, and p_f are affected by each other and by the portable mobility rate η. Based on the portable movement model described in this section, a simple relationship among λ_h, p_o, p_f, and η can be derived using the following idea [11].

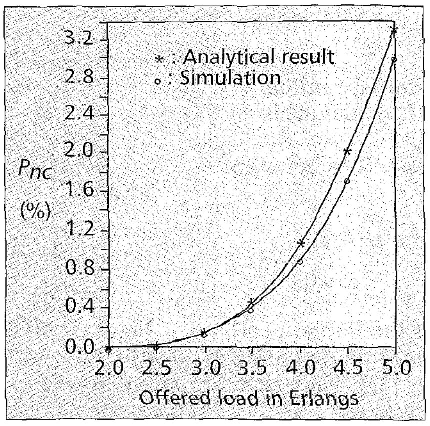


Figure 5. *The comparison of* p_{nc} *for analytical results and simulation results (*η *equals the call completion rate, and the number of channels in a cell is 10).*

Suppose that a portable moves across K cell boundaries during a call holding time, assuming that the call is completed; that is, K is the number of handoffs before the call is completed. The call is referred to as a *K-handoff call*. If we modify our portable movement model such that t_c represents a call holding time (and λ is replaced by μ in Eq. 6), then $a(K)$ is the probability of a K-handoff call. For a K-handoff call, let j be the number of portable moves before the call is blocked or successfully terminated, where $J \leq K$. The probability $\alpha(K)$ can be used to derive the expected number $E[J]$. The idea is the following. We first express the conditional probability $\Pr[J = j \mid K = k]$ as a function of p_f. Then $\Pr[J = j \mid K = k]$ is used to derive $E[J \mid K = k]$, the expected number of J for a k-handoff call.

$$E[J\mid K=k]=\sum_{j=0}^{k} j\Pr[J=j\mid K=k]=\frac{1-(1-p_f)^k}{p_f}$$

Finally, $E[J]$ is derived by using $E[J \mid K = k]$ and $\alpha(k)$:

$$E[J]=\sum_{k=1}^{\infty}E[J\mid K=k]\alpha(k)=\frac{\eta[1-f^*(\mu)]}{\mu[1-(1-p_f)f^*(\mu)]}$$

where f^* is defined in Eq. 7. By assuming homogeneous cells in a PCS network, λ_h is expressed as

$$\lambda_h = (1-p_o)E[J]\lambda_o \qquad (9)$$

Thus, we may derive p_o and p_f by an iterative process [10]: Select an initial λ_h value to obtain p_o and p_f for a particular handoff strategy (analytical models have been developed to derive p_o and p_f for the nonprioritized, guard channel, and queuing priority schemes [11]). Then Eq. 9 is used to compute the new λ_h value which is used to obtain new values for p_o and p_f. The process iterates until the value for λ_h converges.

Figure 5 compares p_{nc} (the probability that a call cannot complete due to blocking or forced termination) for the analytical and simulation results. The curves indicate that the analytical results are consistent with the simulation experiments.

CONCLUSIONS

This article described analytic approaches in developing practical models for large-scale PCS networks. Based on the flow equivalent assumption (the rate of portables moving into a cell equals the rate of portables moving out of the cell), a portable population model was described. The model provides the steady-state portable population distribution in a cell that is independent of the portable residence time distribution, which can be used by simulations to reduce the necessary execution time by reaching the steady state more rapidly. Additionally, this model can be used to study the blocking probability of a low-mobility (portable) PCS network and the performance of portable deregistration strategies.

Then we described a model for portable movement. The model assumes that the arrival calls to a portable form a Poisson process, and portable residence times have a general distribution. This model can be used to study location-tracking and handoff algorithms.

We showed that under some assumptions, the analytical techniques produce results consistent with those of the simulation experiments.

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BIOGRAPHY

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