Deregistration Strategies for PCS Networks

Yi-Bing Lin, *Senior Member, IEEE*

***Abstract*— This paper studies three deregistration strategies (explicit, implicit, and timeout (TO) deregistration) for personal communication service (PCS) networks to determine the network conditions under which each strategy gives the best performance. Two performance measures are considered: 1) the probability α that a portable cannot register (and receive service) and 2) the number of deregistration messages sent in a strategy. For the same database size, α is smaller for explicit deregistration (ED) than it is for TO or implicit deregistration (ID). On the other hand, ID does not create any deregistration message traffic. With an appropriate TO period, the deregistration message traffic for TO deregistration is much smaller than the traffic for ED. Suppose that there are N portables in a registration area (RA) on the average. To ensure that $\alpha < 10^{-3}$, our study indicates that if the database size is larger than 4N, then the implicit scheme should be selected (to eliminate deregistration traffic). If the database size is smaller than 1.5N, then the explicit scheme should be selected. Otherwise, the TO scheme should be selected to achieve the best performance.**

***Index Terms*— Deregistration, home-location register, mobility management, personal communications services, registration, visitor-location register.**

I. Introduction

THIS PAPER studies three deregistration strategies for personal communication service (PCS) networks. In a PCS network, registration is the process by which portables inform the network of their current location (registration area or RA). We assume that a location database (i.e., visitor-location register or VLR) is assigned to exact one RA (although a VLR may cover several RA's in the existing PCS systems). A portable registers its location when it is powered on and when it moves between RA's. If the database is full when a portable arrives, 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 resource previously assigned to the portable can be deallocated.

In IS-41 [1], [3], 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 (ED). This approach to deregistration may create significant traffic in the network [8]. Also, ED does not provide a means of deregistering portables that are shut off, broken, or otherwise disabled for a significant period of time. Bellcore personal access communications systems (PACS's) [2] suggest that a portable be deregistered by default after a certain time period elapses without the portable reregistering. This scheme is referred to as timeout (TO) deregistration [11]. Another possibility is to perform deregistration *implicitly* [2], [7]. Suppose that the database is full when a portable p arrives at an RA. The implicit scheme selects a record based on some replacement strategy. This record is deleted and is then reassigned to p. Note that the record being replaced may be valid, in which case the corresponding portable is forced to deregister. Thus, the size of the registration database (i.e., the amount of resources) must be sufficiently large so as to ensure that the probability of a valid registration record being replaced is extremely low (say 10^{-3}). Lin and Noerpel [7] proposed an analytical model to determine the database size for an implicit scheme that selects the oldest record for replacement. This paper proposes analytical models to study the explicit scheme, implicit scheme with a new replacement strategy, and TO scheme.

Manuscript received July 29, 1996; revised November 21, 1996. This work was supported in part by the National Science Council under Contract NSC 86-2213-E-009-074.

The author is with the Department and Institute of Computer Science and Information Engineering, National Chiao-Tung University, Taiwan, R.O.C. (e-mail: liny@csie.nctu.edu.tw).

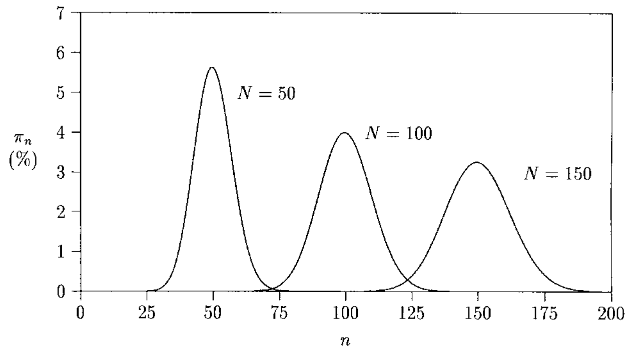
Publisher Item Identifier S 0018-9545(98)00715-4.

II. Explicit Deregistration

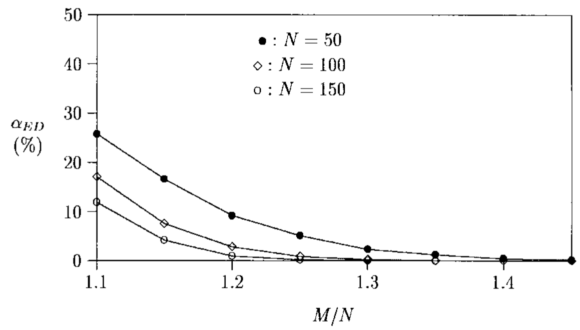
In the explicit scheme, a registration record is deleted when the corresponding portable moves out of the RA. Thus, the database is full if and only if the number of portables in the RA is larger than the size of the database. To derive the probability that a portable cannot register at a particular RA, we first derive the distribution for the number of portables in an RA. Let N be the expected number of portables in an RA. Suppose that the residence time of a portable in an RA has a general distribution with the density function $f(t)$ and mean $1/\mu$. In the steady state, the rate at which portables move into an RA equals the rate at which portables move out of the RA. In other words, the rate at which portables move into an RA is $\eta = N\mu$. The arrival of portables can be viewed as being generated from N input streams, which have the same general distribution with arrival rate μ. If N is reasonably large in an RA, the net input stream is approximated as a Poisson process with arrival rate η. Thus, the distribution for the portable population can be modeled by an $M/G/\infty$ queue with arrival rate η and mean residence time $1/\mu$. Let π_n be the steady-state probability that there are n portables in the RA. This model was validated against simulation experiments by Lin and Chen [6]. By the standard technique [4]

$$\pi_n = \frac{(\eta/\mu)^n e^{-(\eta/\mu)}}{n!} = \frac{N^n e^{-N}}{n!}. \quad (1)$$

Fig. 1(a) plots the population distribution when $N = 50$, 100, and 150, respectively. Skew distributions are observed for small N values. We note that the typical number of portables



(a)



(b)

Fig. 1. The performance of the explicit scheme. (a) The population distribution. (b) The probability that a portable cannot register in the explicit scheme.

in a RA is much larger than 150. The numbers 50, 100, and 150 are selected only for the demonstration purpose.

Suppose that the size of the registration database is M. Let α_{ED} be the probability that the registration database is full when a portable arrives (and thus the portable cannot register). Then

$$\alpha_{ED} = \sum_{M \le n < \infty} \pi_n.$$

Fig. 1(b) plots α_{ED} for different N values. The figure indicates that for $M \ge 1.5N$ (where $N > 50$), the explicit scheme can accommodate almost all arriving portables (i.e., $\alpha_{ED} < 10^{-3}$). Note that the rate of the deregistration messages sent in the network is $N\mu$ per RA. The deregistration messages may significantly contribute to the PCS network traffic.

III. Implicit Deregistration

In the implicit scheme, no deregistration message is sent upon the movement of a portable. The obsolete record is kept in the database. When the database is full, the scheme reclaims a record (for the incoming portable) based on some strategy. A possible replacement strategy is described below.

A. Strategy ID

At time t, a portable p is said to be *inactive* for a time period δ if p has not interacted (sending or receiving messages) with the RA since $t - \delta$. Define a threshold X. If p is inactive for a time period $\delta > X$, we may expect that p has already left the RA. On the other hand, if there is a phone call for p or p registers (i.e., moves into the RA) within the period X, then the implicit scheme assumes that p is still in the RA. The implicit deregistration (ID) strategy works as follows. When p_m arrives at an RA, let p_{m_1} and p_{m_2} be the oldest and the second oldest portables in the RA (i.e., for all the portables p_{m_3} in the RA, we have $m_1 < m_2 < m_3$). When p_m arrives, the inactive time periods for p_{m_1} and p_{m_2} are δ_1 and δ_2, respectively. If $\delta_1 > X$, ID assumes that p_{m_1} is not in the RA, and p_{m_1} is selected for replacement. Otherwise, if $\delta_2 > X$, then ID assumes that p_{m_2} is not in the RA and is selected for replacement. If $\delta_1 < X$ (or $t < X$) and $\delta_2 < X$ (or $t_2 < X$), then p_{m_1} is selected for replacement. In ID, more than two portables may be considered for replacement. For demonstration purposes, here we consider only the oldest two portables. The following notation is introduced.

1) t: the time period between p_{m_1}'s arrival and p_m's arrival [c.f. Fig. 2(a)].
2) t_1: the time period between p_{m_1}'s arrival and p_{m_2}'s arrival [c.f. Fig. 3(a)].
3) t_2: the time period between p_{m_2}'s arrival and p_m's arrival [c.f. Fig. 3(a)]. Note that $t_2 = t - t_1$.
4) τ_1: the residence time of p_{m_1} [c.f. Fig. 2(a)].
5) τ_2: the residence time of p_{m_2} [c.f. Fig. 3(a)].
6) n: the number of portables that arrive in the period t (excluding p_{m_1}). Note that $n = m - m_1$.
7) n_1: the number of portables that arrive in the period t_1 (excluding p_{m_1}). Note that $n_1 = m_2 - m_1$.
8) n_2: the number of portables that arrive in the period t_2 (excluding p_{m_2}). Note that $n_2 = n - n_1 = m - m_2$.
9) δ_1: the time interval between the last phone call to p_{m_1} before p_m's arrival and the time when p_m arrives [c.f. Fig. 2(b)]. Note that there is no phone call to p_{m_1} in the time period δ_1.
10) δ_2: the time interval between the last phone call to p_{m_2} before p_m's arrival and the time when p_m arrives [c.f. Fig. 3(b)].
11) x_1: the time interval between the last phone call to p_{m_1} and the time when p_{m_1} moves out [c.f. Fig. 2(b)].
12) x_2: the time interval between the last phone call to p_{m_2} and the time when p_{m_2} moves out [c.f. Fig. 3(b)].

Since the portable arrivals to an RA form a Poisson process, t has an Erlang distribution with the density function

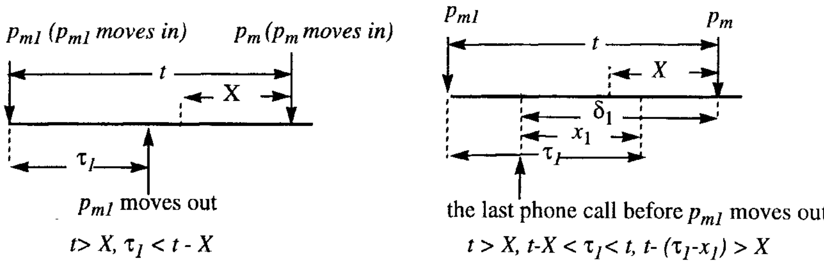
$$g_n(t) = \frac{(\eta t)^{n-1}}{(n-1)!} e^{-\eta t}.$$

Similarly, t_1 and t_2 have the Erlang density functions $g_{n_1}(t_1)$ and $g_{n_2}(t_2)$, respectively. If we assume exponential portable residence times, then τ_1 and τ_2 have an identical density function

$$f(\tau) = \mu e^{-\mu\tau}.$$

Let the intercall arrival times to a portable be exponentially distributed with the density function

$$r(x) = \lambda e^{-\lambda x}.$$



(a) (b)

Fig. 2. The timing diagram for ID Case 1. (a) $t > X, \tau_1 < t - X$. (b) $t > X, t - X < \tau_1 < t,\ t - (\tau_1 - x_1) > X$.

Since the movements of a portable are a Poisson process, a portable is a random observer of the call interarrival times when it moves out of the RA. From the random observer property of the Poisson process and the memoryless property of the exponential distribution, both x_1 and x_2 have the same density function $r(\cdot)$. Similarly, the arrival of p_m is a random observer of the call arrivals to p_{m_1} and p_{m_2}, and δ_1 and δ_2 also have the same density function r.

Let $\gamma_1(m_1)$ be the probability that $\delta_1 > X$ and p_{m_1} is not in the RA. Let $\gamma_2(m_1, m_2)$ be the probability that $\delta_1 < X$ (or $t < X$), $\delta_2 > X$, and p_{m_2} is not in the RA. Let $\gamma_3(m_1, m_2)$ be the probability that $\delta_1 < X$ (or $t < X$), $\delta_2 < X$ (or $t_2 < X$), and p_{m_1} is not in the RA. Then

$$\gamma_{ID} = \gamma_1(m_1) + \gamma_2(m_1, m_2) + \gamma_3(m_1, m_2)$$

is the probability that the portable (either p_{m_1} or p_{m_2}) selected by ID is not in the RA.

The probability γ_{ID} is derived in the following three cases.

1) Case 1: ID assumes that p_{m_1} is not in the RA, and p_{m_1} is not in the RA.

That is, ID assumes that p_{m_1} has moved out of the RA when p_m moves in, which implies that the inactive period δ_1 is longer than the threshold X when p_m arrives, and $\delta_1 > X \ \Rightarrow\ t > X$. Since p_{m_1} is not in the RA when p_m arrives, either $\tau_1 < t - X$ [c.f. Fig. 2(a)] or $t - X < \tau_1 < t$, and $\delta_1 = t - (\tau_1 - x_1) > X$ [c.f. Fig. 2(b)]. The probability for Fig. 2(a) is

$$\begin{aligned}
\Pr[t > X, \tau_1 < t - X] &= \int_{t=X}^{\infty} \int_{\tau_1=0}^{t-X} g_n(t) f(\tau_1)\, d\tau_1\, dt \\
&= \int_{t=X}^{\infty} \frac{(\eta t)^{n-1}}{(n-1)!} e^{-\eta t}[1 - e^{-\mu(t-X)}]\, dt \qquad (2)\\
&= \sum_{i=0}^{n-1} e^{-\eta X} \left\{ \frac{(\eta X)^i}{i!} - \left(\frac{\eta}{\eta+\mu}\right)^n \frac{[(\eta+\mu)X]^i}{i!} \right\}. \qquad (3)
\end{aligned}$$

(3) is derived from (2) based on the fact that

$$\int_{t=X}^{\infty} \frac{(\eta t)^{n-1}}{(n-1)!} e^{-\eta t}\, dt = \sum_{i=0}^{n-1} \frac{(\eta X)^i}{i!} e^{-\eta X}.$$

Since $\delta_1 > X$ implies $x_1 > \tau_1 + X - t$, the probability for Fig. 2(b) is

$$\begin{aligned}
&\Pr[t > X, t - X < \tau_1 < t, x_1 > \tau_1 + X - t] \\
&\quad = \int_{t=X}^{\infty} \int_{\tau_1=t-X}^{t} \int_{x_1=\tau_1+X-t}^{\infty} g_n(t) f(\tau_1) r(x_1)\, dx_1 \cdot d\tau_1\, dt \\
&\quad = \sum_{i=0}^{n-1} \left(\frac{\mu}{\mu+\lambda}\right)\left(\frac{\eta}{\eta+\mu}\right)^n \frac{[(\eta+\mu)X]^i}{i} \times [e^{-\eta X} - e^{-(\eta+\mu+\lambda)X}]. \qquad (4)
\end{aligned}$$

Thus, $\gamma_1(m_1) = (3) + (4)$.

2) Case 2: ID assumes that p_{m_1} is in the RA, p_{m_2} is not in the RA, and p_{m_2} is not in the RA. Since ID assumes that p_{m_2} is not in the RA when p_m moves in, it implies that the inactive period δ_1 is longer than the threshold X, and

$$\delta_2 > X \Rightarrow t_2 > X \Rightarrow t > X. \qquad (5)$$

As in the situations described in Case 1, either $\tau_2 < t_2 - X$ [c.f. Fig. 3(a) and (c)] or $t_2 - X < \tau_2 < t_2$, and $\delta_2 = t_2 - (\tau_2 - x_2) > X$ [c.f. Fig. 3(b) and (d)]. Since ID assumes that p_{m_1} is in the RA and $t_2 > X$, it implies that $t = t_1 + t_2 > X$ and $\tau_1 > t - X$. There are two cases.

3) Case 2a: $\tau_1 > t$ and $\delta_1 < X$ [c.f. Fig. 3(a) and (b)].

4) Case 2b: $t - X < \tau_1 < t$ and $\delta_1 = t - (\tau_1 - x_1) < X$ [c.f. Fig. 3(c) and (d)].

From (5) and Cases 2a and 2b, there are four combinations for Case 2, as illustrated in Fig. 3. The probability for Fig. 3(a) is

$$\begin{aligned}
&\Pr[t_1 > 0, t_2 > X, \tau_1 > t, \delta_1 < X, \tau_2 < t_2 - X] \\
&\quad = \int_{t_2=X}^{\infty} g_{n_2}(t_2) \int_{t_1=0}^{\infty} g_{n_1}(t_1) \int_{\tau_1=t_1+t_2}^{\infty} f(\tau_1) \cdot \int_{\delta_1=0}^{X} r(\delta_1) \int_{\tau_2=0}^{t_2-X} f(\tau_2)\, d\tau_2\, d\delta_1\, d\tau_1\, dt_1\, dt_2 \\
&\quad = \int_{t_2=X}^{\infty} g_{n_2}(t_2) \int_{t_1=0}^{\infty} g_{n_1}(t_1) e^{-\mu(t_1+t_2)}(1 - e^{-\lambda X}) \cdot [1 - e^{-\mu(t_2-X)}]\, dt_1\, dt_2 \\
&\quad = (1 - e^{-\lambda X}) \int_{t_2=X}^{\infty} g_{n_2}(t_2) e^{-\mu t_2}[1 - e^{-\mu(t_2-X)}] \cdot \int_{t_1=0}^{\infty} \frac{(\eta t_1)^{n_1-1}}{(n_1-1)!} e^{-(\eta+\mu)t_1}\, dt_1\, dt_2
\end{aligned}$$

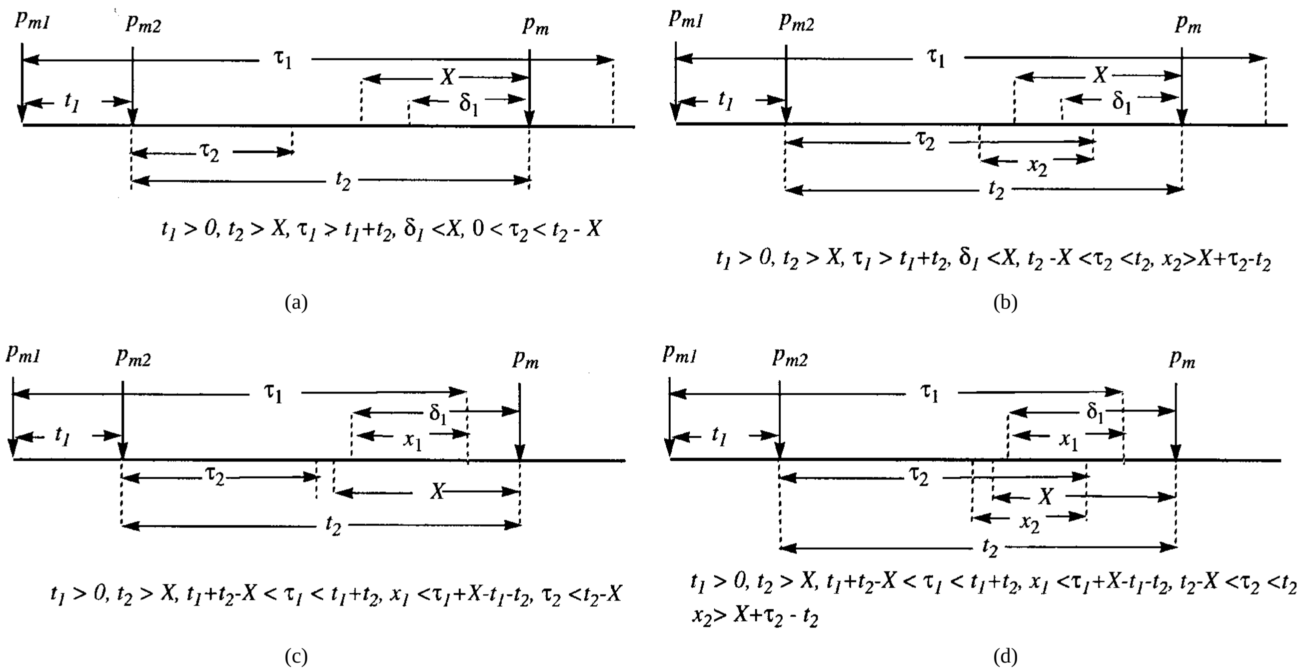


Fig. 3. The timing diagram for ID Case 2. (a) $t_1 > 0,\ t_2 > X, \tau_1 > t_1 + t_2,\ \delta_1 < X, 0 < \tau_2 < t_2 - X$. (b) $t_1 > 0, t_2 > X, \tau_1 > t_1 + t_2, \delta_1 < X, t_2 - X < \tau_2 < t_2, x_2 > X + \tau_2 - t_2$. (c) $t_1 > 0, t_2 > X, t_1 + t_2 - X < \tau_1 < t_1 + t_2, x_1 < \tau_1 + X - t_1 - t_2, \tau_2 < t_2 - X$. (d) $t_1 > 0, t_2 > X, t_1 + t_2 - X < \tau_1 < t_1 + t_2, x_1 < \tau_1 + X - t_1 - t_2, t_2 - X < \tau_2 < t_2 x_2 > X + \tau_2 - t_2$.

$$
\begin{aligned}
&= \left(\frac{\eta}{\eta+\mu}\right)^{n_1} (1 - e^{-\lambda X}) \int_{t_2=X}^{\infty} \frac{(\eta t_2)^{n_2-1}}{(n_2-1)!} \\
&\quad \cdot [e^{-(\eta+\mu)t_2} - e^{-(\eta+2\mu)t_2+\mu X}]\, dt_2 \\
&= \sum_{i=0}^{n_2-1} \left(\frac{\eta}{\eta+\mu}\right)^{n_1} (1 - e^{-\lambda X}) e^{-(\eta+\mu)X} \\
&\quad \cdot \left\{ \left(\frac{\eta}{\eta+\mu}\right)^{n_2} \frac{[(\eta+\mu)X]^i}{i!} \right. \\
&\qquad \left. - \left(\frac{\eta}{\eta+2\mu}\right)^{n_2} \frac{[(\eta+2\mu)X]^i}{i!} \right\}. \qquad (6)
\end{aligned}
$$

The probability for Fig. 3(b) is

$$
\begin{aligned}
&\Pr [t_1 > 0, t_2 > X, \tau_1 > t, \delta_1 < X, \\
&\qquad t_2 - X < \tau_2 < t_2, x_2 > X + \tau_2 - t_2] \\
&= \int_{t_1=0}^{\infty} g_{n_1}(t_1) \int_{t_2=X}^{\infty} g_{n_2}(t_2) \int_{\tau_1=t_1+t_2}^{\infty} f(\tau_1) \\
&\quad \cdot \int_{\delta_1=0}^{X} r(\delta_1) \int_{\tau_2=t_2-X}^{t_2} f(\tau_2) \\
&\quad \times \int_{x_2=X+\tau_2-t_2}^{\infty} r(x_2)\, dx_2\, d\tau_2 d\delta_1\, d\tau_1\, dt_2\, dt_1 \\
&= \sum_{i=0}^{n_2-1} \left(\frac{\eta}{\eta+2\mu}\right)^{n_2} \left(\frac{\eta}{\eta+\mu}\right)^{n_1} \\
&\quad \cdot \left(\frac{\mu}{\lambda+\mu}\right) \frac{[(\eta+2\mu)X]^i}{i!} \\
&\quad \times e^{-(\eta+\mu)X}(1 - e^{-\lambda X})[1 - e^{-(\lambda+\mu)X}]. \qquad (7)
\end{aligned}
$$

The probability for Fig. 3(c) is

$$
\begin{aligned}
&\Pr [t_1 > 0, t_2 > X, t - X < \tau_1 < t, \\
&\qquad x_1 < \tau_1 + X - t, \tau_2 < t_2 - X] \\
&= \int_{t_1=0}^{\infty} g_{n_1}(t_1) \int_{t_2=X}^{\infty} g_{n_2}(t_2) \int_{\tau_1=t_1+t_2-X}^{t_1+t_2} f(\tau_1) \\
&\quad \times \int_{x_1=0}^{\tau_1+X-t_1-t_2} r(x_1) \int_{\tau_2=0}^{t_2-X} f(\tau_2)\, d\tau_2\, dx_1\, d\tau_1 \\
&\quad \cdot dt_2\, dt_1 \\
&= \sum_{i=0}^{n_2-1} \left(\frac{\eta}{\eta+\mu}\right)^{n_1} e^{-\eta X} \left\{ \left(\frac{\eta}{\eta+\mu}\right)^{n_2} \frac{[(\eta+\mu)X]^i}{i!} \right. \\
&\quad \left. - \left(\frac{\eta}{\eta+2\mu}\right)^{n_2} \frac{[(\eta+2\mu)X]^i}{i!} \right\} \\
&\quad \times \left\{ 1 - e^{-\mu X} - \left(\frac{\mu}{\lambda+\mu}\right) [1 - e^{-(\lambda+\mu)X}] \right\}. \qquad (8)
\end{aligned}
$$

The probability for Fig. 3(d) is

$$
\begin{aligned}
&\Pr [t_1 > 0, t_2 > X, t - X < \tau_1 < t, x_1 < \tau_1 \\
&\qquad + X - t, t_2 - X < \tau_2 < t_2, x_2 > X + \tau_2 - t_2] \\
&= \int_{t_2=X}^{\infty} g_{n_2}(t_2) \int_{t_1=0}^{\infty} g_{n_1}(t_1) \int_{\tau_1=t_1+t_2-X}^{t_1+t_2} f(\tau_1) \\
&\quad \times \int_{x_1=0}^{\tau_1+X-t_1-t_2} r(x_1) \int_{\tau_2=t_2-X}^{t_2} f(\tau_2) \\
&\quad \times \int_{x_2=X+\tau_2-t_2}^{\infty} r(x_2)\, dx_2\, d\tau_2\, dx_1\, d\tau_1\, dt_1\, dt_2
\end{aligned}
$$

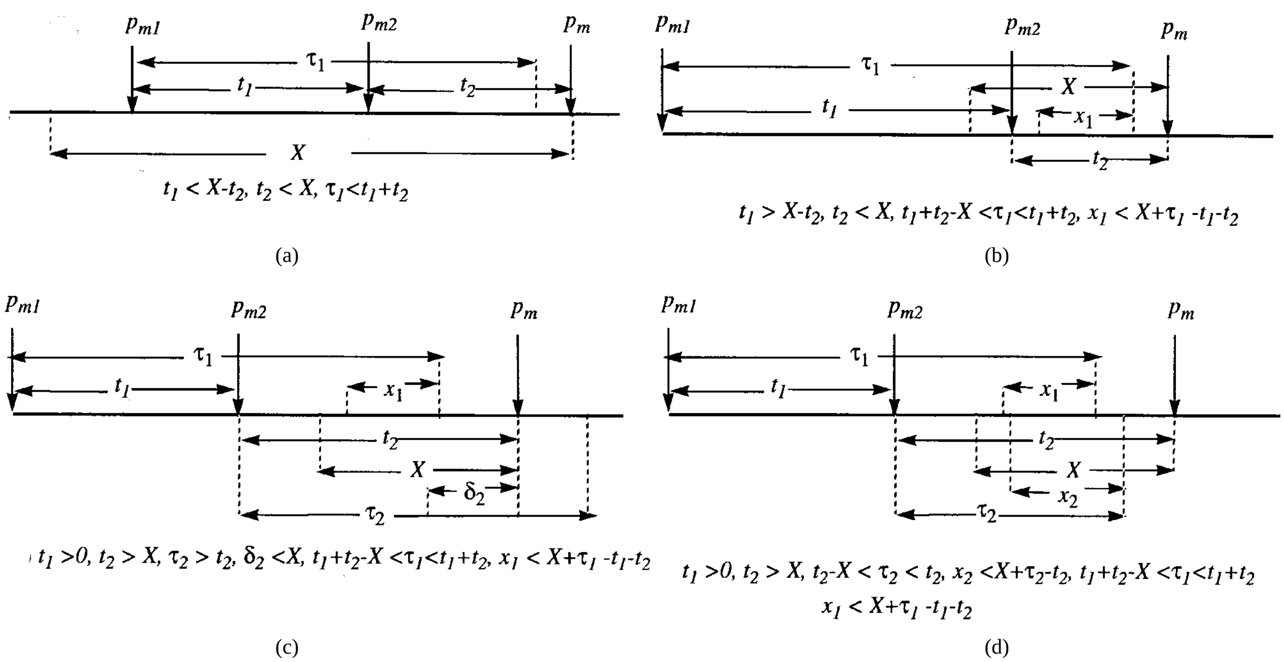


Fig. 4. The timing diagram for ID Case 3.

$$= \sum_{i=0}^{n_2-1} \left(\frac{\eta}{\eta+\mu}\right)^{n_1+n_2} \frac{[(\eta+\mu)X]^i}{i!} \cdot e^{-\eta X}[1-e^{-(\lambda+\mu)X}] \times \left\{1-e^{-\mu X} - \left(\frac{\mu}{\lambda+\mu}\right)[1-e^{-(\lambda+\mu)X}]\right\}. \quad (9)$$

Thus, $\gamma_2(m_1, m_2) = (6) + (7) + (8) + (9)$.

5) Case 3: **ID assumes that both p_{m_1} and p_{m_2} are in the RA, but** p_{m_1} *is not in the RA.* Note that $\tau_1 < t$. ID assumes that p_{m_2} is in the RA, which implies that $\delta_2 < X$ or $t_2 < X$. There are three possibilities.

- $t_2 < X$ [c.f. Fig. 4(a) and (b)]. Since ID assumes that p_{m_1} is in the RA, we have $\delta_1 < X$ or $t_1 < X$. There are two cases.

6) Case 3a: $t < X \Rightarrow t_1 < X - t_2$, as shown in Fig. 4(a). The probability is

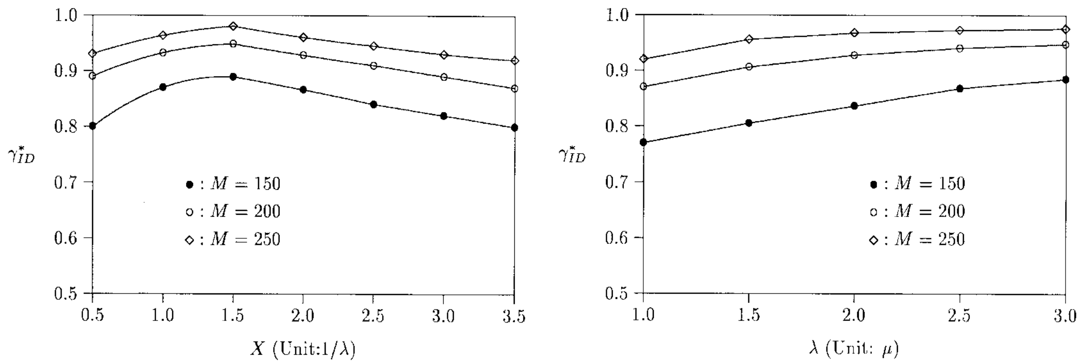
$$\begin{aligned}\Pr[\tau_1 < t_1 + t_2 < X] &= \int_{t_2=0}^{X} g_{n_2}(t_2) \int_{t_1=0}^{X-t_2} g_{n_1}(t_1) \int_{\tau_1=0}^{t_1+t_2} f(\tau_1)\,d\tau_1 \cdot dt_1\,dt_2 \\ &= 1 - \left(\frac{\eta}{\eta+\mu}\right)^{n_1+n_2} - \sum_{j=0}^{n_2-1}\left(\frac{X^j e^{-\eta X}}{j!}\right) \cdot \left[\eta^j - \left(\frac{\eta}{\eta+\mu}\right)^{n_1+n_2}(\eta+\mu)^j e^{-\mu X}\right] \\ &\quad - \sum_{i=0}^{n_1-1} \frac{X^{n_2+i}\eta^{n_2}e^{-\eta X}}{(n_2+i)!}\left[\eta^i - \left(\frac{\eta}{\eta+\mu}\right)^{n_1} \cdot (\eta+\mu)^i e^{-\mu X}\right].\end{aligned} \quad (10)$$

7) Case 3b: $t > X \Rightarrow t_1 > X - t_2$. Since $\delta_1 < X$, we have $t - (\tau_1 - x_1) < X$ and $t - X < \tau_1 < t$, as shown in Fig. 4(b). The probability is

$$\begin{aligned}\Pr&[t_1 > X - t_2, t_2 < X, t - X < \tau_1 < t, x_1 < X + \tau_1 - t] \\ &= \int_{t_2=0}^{X} g_{n_2}(t_2) \int_{t_1=X-t_2}^{\infty} g_{n_1}(t_1) \int_{\tau_1=t_1+t_2-X}^{t_1+t_2} f(\tau_1) \times \int_{x_1=0}^{X+\tau_1-t_1-t_2} r(\delta_1)\,d\delta_1\,d\tau_1\,dt_1\,dt_2 \\ &= \sum_{i=0}^{n_1-1}\left(\frac{\eta}{\eta+\mu}\right)^{n_1} \frac{\eta^{n_2}(\eta+\mu)^i X^{n_2+i}}{(n_2+i)!} e^{-\eta X} \times \left\{1-e^{-\mu X} - \left(\frac{\mu}{\lambda+\mu}\right)[1-e^{-(\lambda+\mu)X}]\right\}.\end{aligned} \quad (11)$$

- $t_2 > X, \tau_2 > t_2$ and $\delta_2 < X$ [c.f. Fig. 4(c)]. Since $t = t_1 + t_2 > X$ and ID assumes that p_{m_1} is in the RA, the situation is the same as in Case 3b (i.e., $t - X < \tau_1 < t$ and $\delta_1 = t - (\tau_1 - x_1) < X$), and

$$\begin{aligned}\Pr&[t_1 > 0, t_2 > X, \tau_2 > t_2, \delta_2 < X, t - X < \tau_1 < t, x_1 < X + \tau_1 - t] \\ &= \int_{t_2=X}^{\infty} g_{n_2}(t_2) \int_{t_1=0}^{\infty} g_{n_1}(t_1) \int_{\tau_2=t_2}^{\infty} f(\tau_2) \cdot \int_{\delta_2=0}^{X} r(\delta_2) \int_{\tau_1=t_1+t_2-X}^{t_1+t_2} f(\tau_1) \times \int_{x_1=0}^{X+\tau_1-t_1-t_2} \cdot r(x_1)\,dx_1\,d\tau_1\,d\delta_2 \cdot d\tau_2\,dt_1\,dt_2 \\ &= \sum_{i=0}^{n_2-1}\left(\frac{\eta}{\eta+2\mu}\right)^{n_1+n_2} \frac{[(\eta+2\mu)X]^i}{i!} \cdot e^{-(\eta+\mu)X}(1-e^{-\lambda X})\end{aligned}$$



(a) (b)

Fig. 5. Performance of ID. (a) The effect of X on ID ($\lambda = 2\mu$). (b) The effect of λ on ID ($X = 1.5/\lambda$).

$$\times \left[1 - e^{-\mu X} - \left(\frac{\mu}{\lambda+\mu}\right)(1 - e^{-(\lambda+\mu)X})\right]. \quad (12)$$

- $t_2 > X, t_2 - X\ \tau_2 < t_2$, and $\delta_2 = t_2 - (\tau_2 - x_2) < X$ as shown in Fig. 4(d). Since $t = t_1 + t_2 > X$ and ID assumes that p_{m_1} is in the RA, the situation is the same as Case 3b (i.e., $t - X < \tau_1 < t$ and $\delta_1 = t - (\tau_1 - x_1) < X$), and

$$\begin{aligned}
&\Pr[t_1 > 0, t_2 > X, t_2 - X < \tau_2 < t_2, x_2 < X + \tau_2 - t_2,\\
&\qquad t - X < \tau_1 < t, x_1 < X + \tau_1 - t]\\
&= \int_{t_2=0}^{X} g_{n_2}(t_2) \int_{t_1=0}^{\infty} g_{n_1}(t_1) \int_{\tau_2=t_2-X}^{t_2} f(\tau_2)\\
&\cdot \int_{x_2=0}^{X+\tau_2-t_2} r(x_2) \int_{\tau_1=t_1+t_2-X}^{t_1+t_2} f(\tau_1) \int_{x_1=0}^{\tau_1+X-t_1-t_2}\\
&\cdot r(x_1)\, dx_1\, d\tau_1\, dx_2\, d\tau_2\, dt_1\, dt_2\\
&= \sum_{i=0}^{n_2-1} \left(\frac{\eta}{\eta+\mu}\right)^{n_1} \left(\frac{\eta}{\eta+2\mu}\right)^{n_2} \frac{[(\eta+2\mu)X]^i}{i!} e^{-\eta X}\\
&\times \left[1 - e^{-\mu X} - \left(\frac{\mu}{\lambda+\mu}\right)(1 - e^{-(\lambda+\mu)X})\right]^2. \quad (13)
\end{aligned}$$

Thus, $\gamma_3(m_1, m_2) = (10) + (11) + (12) + (13)$.

Suppose that the size of the database is M. For the oldest portable p_{m_1}, it is apparent that $m_1 \le m - M$. Similarly, for the second oldest portable p_{m_2}, $m_2 \le m - M + 1$. Since

$$\begin{aligned}
&\gamma_1(m_1) + \gamma_2(m_1, m_2) + \gamma_3(m_1, m_2)\\
&\quad > \gamma_1(m - M) + \gamma_2(m - M, m - M + 1)\\
&\quad\quad + \gamma_3(m - M, m - M + 1)
\end{aligned}$$

a lower bound γ^*_{ID} for γ_{ID} is

$$\begin{aligned}
\gamma^*_{ID} &= \gamma_1(m - M) + \gamma_2(m - M, m - M + 1)\\
&\quad + \gamma_3(m - M, m - M + 1).
\end{aligned}$$

Fig. 5(a) illustrates the effect of X on γ^*_{ID}. The figure indicates that the maximum value for γ^*_{ID} occurs when $X \simeq 1.5$ (for $\lambda = 2\mu$). The figure indicates that erring on the side of an X value that is too large will degrade performance less than erring on the side of an X value that is too small. It is apparent that the performance of ID improves as λ increases. Fig. 5(b) illustrates that γ^*_{ID} is an increasing function of λ.

Let α_{ID} be the probability that a portable (either p_{m_1} or p_{m_2}) cannot register (i.e., is forced to deregister) when p_m arrives. An upper bound α^*_{ID} for α_{ID} is

$$\alpha_{ID} \le \alpha^*_{ID} = 1 - \gamma^*_{ID}.$$

Fig. 9(a) indicates that $\alpha^*_{ID} < 10^{-3}$ for $M > 4N$.

IV. Timeout Deregistration

In the TO scheme, a portable sends a reregistration message to the RA for every time period T. The TO scheme is better than the explicit scheme if the reregistration traffic (in TO) is less than the deregistration traffic [in ED]. This section derives the number of reregistration messages sent in the TO scheme. Let $E[K]$ be the expected number of reregistration messages sent before a portable leaves an RA. Let $f(\tau)$ be the portable residence time distribution (with mean $1/\mu$). Then

$$E[K] = \sum_{k=0}^{\infty} k \int_{\tau=kT}^{(k+1)T} f(\tau)\, d\tau. \quad (14)$$

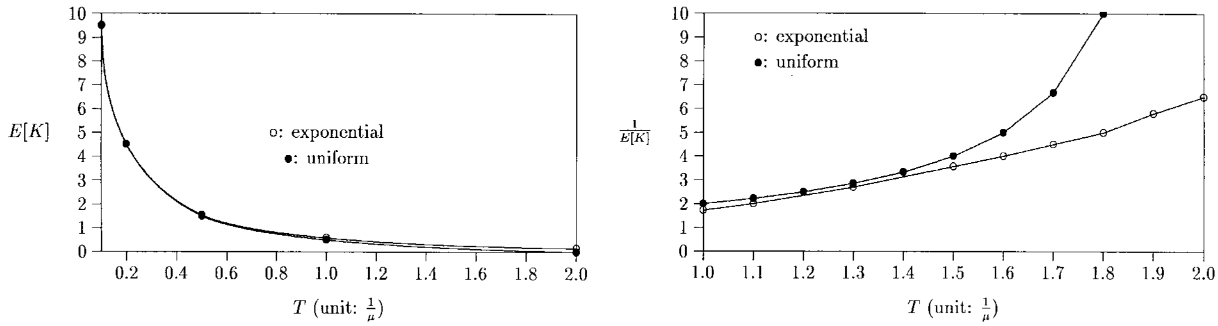
For the exponential residence time distribution, (14) is rewritten as

$$E[K] = \sum_{k=0}^{\infty} \int_{\tau=kT}^{(k+1)T} k\mu e^{-\mu\tau}\, d\tau = \frac{e^{-\mu T}}{1 - e^{-\mu T}}.$$

For the uniform residence time distribution in $[0, 2/\mu]$

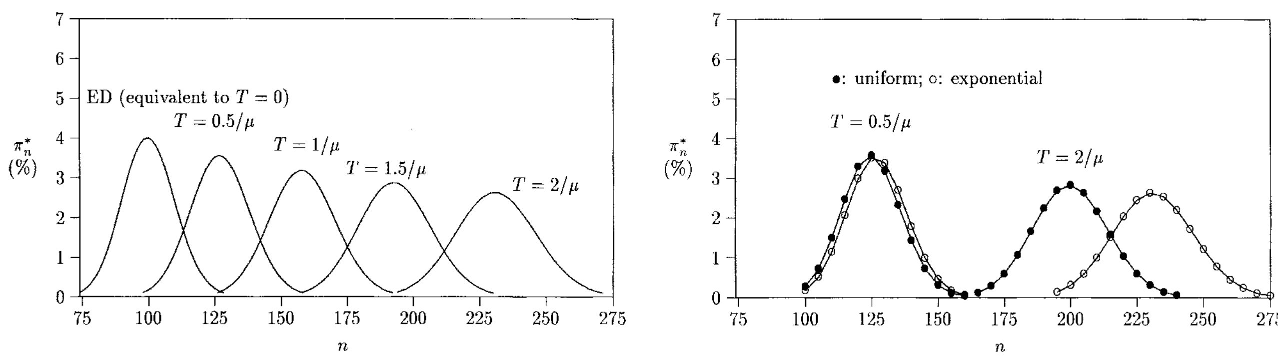
$$\begin{aligned}
E[K] &= \sum_{k=0}^{\lfloor 2/\mu T \rfloor - 1} \int_{\tau=kT}^{(k+1)T} k\frac{\mu}{2}\, d\tau + \int_{\tau=\lfloor 2/\mu T \rfloor T}^{2/\mu} k\frac{\mu}{2}\, d\tau\\
&= \left\lfloor \frac{2}{\mu T} \right\rfloor \left(\frac{\mu}{2}\right) \left[\frac{T}{2}\left(\left\lfloor \frac{2}{\mu T} \right\rfloor - 1\right)\right.\\
&\quad \left. + \left(\frac{2}{\mu} - \left\lfloor \frac{2}{\mu T} \right\rfloor T\right)\right].
\end{aligned}$$

Fig. 6(a) plots $E[K]$ against T. The figure indicates that $E[K] < 0.24$ if $T > 1.8/\mu$ for the exponential residence times and $T > 1.52/\mu$ for the uniform residence times. In the explicit scheme, a deregistration message is sent when a portable moves out of the RA. On the other hand, in the TO scheme, the number of reregistration messages sent by a portable is $E[K]$. Thus, the deregistration traffic in the explicit scheme is $\frac{1}{E[K]}$ times the reregistration traffic in the TO scheme. For



(a) (b)

Fig. 6. The expected number of reregistration messages. (a) The registration message overhead in the TO scheme. (b) Comparison of the de(re)registration message overhead for the explicit scheme and the TO scheme.



(a) (b)

Fig. 7. The portable distribution seen by the TO scheme. (a) The impact of T. (b) The impact of the residual time distributions.

example, if $T = 1.8/\mu$, the deregistration traffic generated by the explicit scheme is about four–five times the traffic generated by the TO scheme assuming exponential residence times [c.f. Fig. 6 (b)]. In other words, if T is sufficiently large, then the TO scheme significantly reduces the network traffic due to deregistration (compared with the explicit scheme).

The portable residence time τ^* seen by the TO scheme is different from the true portable residence time τ (the TO scheme only differentiates on multiples of T). Since $\tau^* = \lceil \tau/T \rceil T$, the expected residence time $E[\tau^*]$ seen by the TO scheme is

$$E[\tau^*] = \sum_{k=0}^{\infty} \int_{\tau=kT}^{(k+1)T} (k+1)Tf(\tau)\,d\tau = (E[K]+1)T.$$

For the exponential residence time distribution

$$E[\tau^*] = \frac{T}{1 - e^{-\mu T}}. \tag{15}$$

From (15) and the $M/G/\infty$ model described in Section II, the steady-state probability π_n^* that the TO scheme sees n portables in the RA is

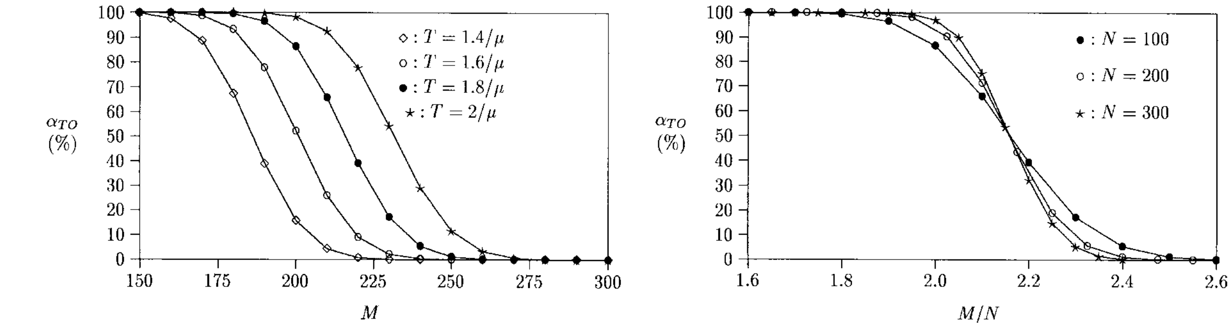
$$\pi_n^* = \left(\frac{N\mu T}{1 - e^{-\mu T}}\right)^n \frac{e^{-(N\mu T/1-e^{-\mu T})}}{n!}.$$

The π_n^* distribution is plotted in Fig. 7 for different T values. Fig. 7(a) indicates that the portable seen by the TO scheme increases as T increases. Fig. 7(b) indicates that the number of portables seen by the TO registration scheme is closer to the true number for the uniform residence times than for the exponential residence times. Let α_{TO} be the probability that the TO scheme sees a full registration database in an RA when a portable arrives. Then

$$\alpha_{TO} = \sum_{n=M}^{\infty} \pi_n^*.$$

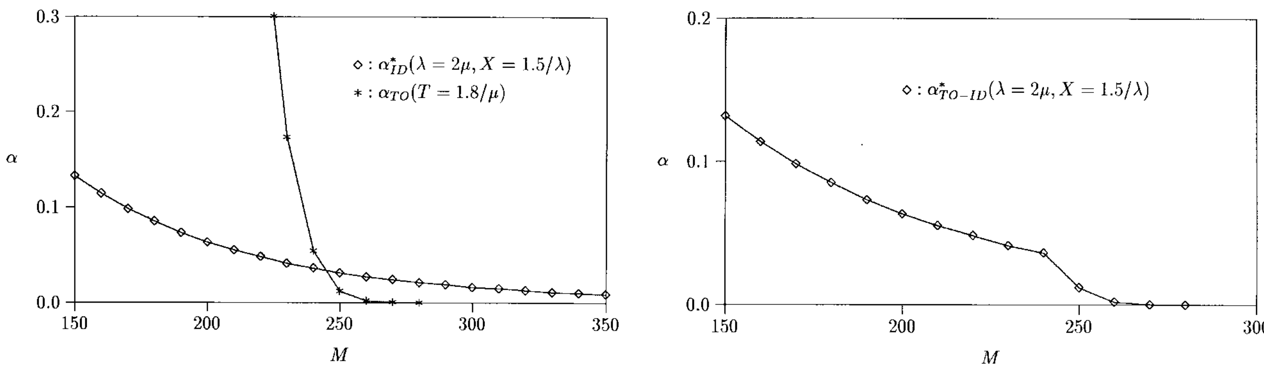
Suppose that p is not allowed to register if the TO scheme sees a full database at p's arrival. Then α_{TO} is the probability that a portable (i.e., p) cannot register (and receive services). Fig. 8 plots α_{TO} against M. It is clear that α_{TO} is a decreasing function of the database size M and is an increasing function of T [c.f. Fig. 8(a)]. It is interesting to note that for the same M/N ratio, the α_{TO} value for a small N is smaller than the α_{TO} for a large N when $M/N < 2.17$. The opposite is true when $M/N > 2.17$ [c.f. Fig. 8(b)]. Fig. 9(a) compares α_{TO} with α_{ID}^*. For $M > 2.5N$ (where $N = 100$), $\alpha_{TO} < \alpha_{ID}^*$. Note that $\alpha_{TO} < 10^{-3}$ for $M > 2.5N$. However, when $M < 2N$, α_{TO} is much larger than α_{ID}^*.

Other replacement strategies can be used if the TO scheme sees a full database when a portable p arrives. Let us consider



(a) (b)

Fig. 8. The probability that the TO scheme sees a full registration database when a portable arrives. (a) The impact of T $(N = 100)$. (b) The impact of N $(T = 1.8)$.



(a) (b)

Fig. 9. Performance for different deregistration schemes $(N = 100)$. (a) The α values for different schemes. (b) The performance for the TO scheme with different replacement strategies $(T = 1.8/\mu)$.

the replacement strategies used in ID in the previous section. Let α_{TO-ID} be the probability that p cannot register in the TO scheme with the ID replacement strategy. Then

$$\alpha_{TO-ID} < \alpha^*_{TO-ID} = \min(\alpha_{TO}, \alpha^*_{ID}).$$

Fig. 9(b) plots α^*_{TO-ID}. The figure indicates that with the ID replacement strategy, the performance of the TO scheme is significantly improved.

V. Conclusions

This paper has studied three deregistration strategies for PCS networks. Two output measures were considered: the number of messages sent in the deregistration strategies and the probability α that a portable cannot register (and receive service). Assume 100 portables in an RA on the average. To satisfy the constraint that $\alpha < 10^{-3}$, the size of the database required in the explicit scheme is $M \simeq 1.5N$, which is smaller than the database size for the implicit scheme $(M \simeq 4N)$ and the TO scheme $(M \simeq 2.5N)$. On the other hand, the number of deregistration messages sent in the explicit scheme is four–five times the number of messages sent in the TO scheme (with the registration period $T = 1.8/\mu$). In the implicit scheme, neither deregistration nor reregistration messages are sent. Our study indicates that if the database size is expected to be large, then the implicit scheme should be used to eliminate the deregistration message traffic. If the database size has to be small, on the other hand, then the explicit scheme should be used to achieve a low α value. If the database size is between 2.5–4N, then the TO scheme with the ID replacement strategy should be used to ensure a reasonably small α value and a low level of reregistration message traffic.

In summary, ID and ED are mutually exclusive. TO deregistration is a useful tool to clean up registration databases and can be combined with either one of the ID or ED approaches. In PACS [5], [10], polling reregistration was introduced so that the system can poll the portables to see if the portables are still in the RA [9]. A combination of TO deregistration, ID, and polling reregistration might be best in all circumstances. Performance modeling of such a combination will be one of our future research directions.

Acknowledgment

The author would like to thank J. R. Cruz, S. Y. Hwang, A. R. Noerpel, and the reviewers for their valuable comments and assistance in improving the quality of this paper.

REFERENCES

[1] "Cellular radio-telecommunications intersystem operations," EIA/TIA Tech. Rep. IS-41 Revision B, 1991.

[2] "Network and operations plan for access services to personal communications services systems, issue 2," Bellcore Tech. Rep. SR-TSV-002459, 1992.

[3] C. N. Lo *et al*., "An estimate of network database transaction volume to support universal personal communication services," in *8th ITC Specialist Seminar on Universal Personal Telecommunications*, 1992.

[4] "Generic criteria for version 0.1 wireless access communications systems (WACS) and supplement," Bellcore Tech. Rep. TR-INS-001313, 1994.

[5] P. Porter, D. Harasty, M. Beller, A. R. Noerpel, and V. Varma, "The terminal registration/deregistration protocol for personal communication systems," in *Wireless 93 Conf. Wireless Commun.*, July 1993.

[6] Y.-B. Lin and A. Noerpel, "Implicit deregistration in a PCS network," *IEEE Trans. Veh. Technol.*, vol. 43, no. 4, pp. 1006–1010, 1994.

[7] Y.-B. Lin and W. Chen, "Impact of busy lines and mobility on call blocking in a PCS network," *Int. J. Commun. Syst.*, vol. 9, pp. 35–45, 1996.

[8] L. Kleinrock, *Queueing Systems: Volume I—Theory*. New York: Wiley, 1976.

[9] A. R. Noerpel, Y.-B. Lin, and H. Sherry, "PACS: Personal access communications system—A tutorial," *IEEE Personal Commun. Mag.*, pp. 32–43, June 1996.

[10] Y.-B. Lin, "PACS network signaling using AIN/ISDN," *IEEE Personal Commun. Mag.*, vol. 4, no. 3, pp. 33–39, 1997.

[11] A. R. Noerpel, L. F. Chang, and Y.-B. Lin, "Performance modeling of polling de-registration for unlicensed PCS," *IEEE J. Select. Areas Commun.*, vol. 14, no. 4, pp. 728–734, 1996.

Yi-Bing Lin (S'80–M'96–SM'96) received the B.S.E.E. degree from National Cheng Kung University, Taiwan, R.O.C., in 1983 and the Ph.D. degree in computer science from the University of Washington, Seattle, in 1990.

From 1990 to 1995, he was with the Applied Research Area at Bell Communications Research (Bellcore), Morristown, NJ. He is currently with the Department of Computer Science and Information Engineering, National Chiao Tung University, Taiwan, R.O.C., where he was appointed Full Professor in 1995. In 1996, he was appointed Deputy Director of the Microelectronics and Information Systems Research Center, NCTU. His current research interests include design and analysis of personal communications services network, mobile computing, distributed simulation, and performance modeling.

Dr. Lin is an Associate Editor of the *ACM Transactions on Modeling and Computer Simulation*, a Subject Area Editor of the *Journal of Parallel and Distributed Computing*, an Associate Editor of the *International Journal in Computer Simulation*, an Associate Editor of *IEEE Networks*, an Associate Editor of *SIMULATION*, an Area Editor of *ACM Mobile Computing and Communication Review*, a Columnist of *ACM Simulation Digest*, a Member of the editorial boards of *International Journal of Communications* and *Computer Simulation Modeling and Analysis*, and Guest Editor for the *ACM/Baltzer WINET* Special Issue on Personal Communications and the IEEE TRANSACTIONS ON COMPUTERS Special Issue on Mobile Computing. He was Program Chair for the 8th Workshop on Distributed and Parallel Simulation, General Chair for the 9th Workshop on Distributed and Parallel Simulation, Program Chair for the 2nd International Mobile Computing Conference, and Publicity Chair of ACM Sigmobile.