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Implicit Deregistration with Forced Registration for PCS Mobility Management

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Abstract. Registration/deregistration with a mobility database called *Visitor Location Registers* (VLRs) is required in a PCS network when a mobile phone moves between registration areas. Several schemes were proposed to deregister a mobile phone after it moves out of a registration area. A simple scheme, called implicit deregistration, is studied in this paper, which does not specifically deregister any obsolete record in the VLR. If the VLR is full when a mobile phone arrives, a record in the VLR is deleted and the reclaimed storage is reassigned to the incoming mobile phone. It is possible that a valid record will be deleted. If so, the VLR record of a mobile phone may be deleted before a call to the mobile phone arrives. Our previous work assumed that the incoming call setup would be lost. In this paper, we propose forced registration to restore the VLR record before the call setup operation can proceed. With this modification, implicit deregistration totally eliminates the deregistration traffic at the cost of creating some forced registration traffic.

We derive the record-missing probability and the portion of the network traffic saved by implicit deregistration. Our study indicates that implicit deregistration with forced registration may significantly reduce the deregistration traffic if the user mobility is high and the number of mobile phones in a registration area is not very large.

Keywords: implicit deregistration, mobility management, personal communications, visitor location register

1. Introduction

In a personal communications services (PCS) network, registration is the process by which mobile phones inform the network of their current locations (*registration area* or RA). When a mobile phone enters an RA (either when it is powered on or when it moves between registration areas), it registers at the *Visitor Location Register* (VLR) corresponding to the RA and the address of the new RA is reported to the *Home Location Register* (HLR) of the mobile phone [2,4, 11]. Note that a VLR may control several RAs. Without loss of generality, we assume that every VLR associates with exactly one RA. To locate a mobile phone, the HLR of the mobile phone is accessed to find the current VLR address of the mobile phone. Using the VLR address, the mobile phone is located. The VLR may be full when a mobile phone arrives, and the mobile phone cannot access the services provided by the PCS network. When a mobile phone leaves an RA, or shuts off for a long period of time, the mobile phone should be deregistered from the RA so that the storage for the obsolete VLR record can be reused. However, both registration and deregistration may result in significant amount of network signaling traffic. Several approaches have been proposed to reduce the registration traffic. These approaches are described in [1,5] and the references therein. In this paper, we focus on reducing the deregistration traffic.

In IS-41 [2] and GSM MAP [4], the registration process ensures that a mobile phone's registration in a new VLR causes deregistration in the previous VLR. This approach is referred to as *explicit deregistration*. Like registration, such deregistration may create significant traffic in the network [10]. In [9], we suggested that the deregistration operation can be performed *implicitly*. In this implicit scheme, the record of a mobile phone is not deleted from the VLR when the mobile phone leaves that RA. Thus, the deregistration traffic is totally removed. If the VLR is full when a mobile phone P arrives in that RA, the implicit scheme deletes a record and the reclaimed storage is reassigned to P. We assume that the deleted record is selected randomly with equal probability. In doing so, a valid record may be replaced, and call setup to the corresponding mobile phone cannot follow the normal procedure. In [9], we assume that the call is lost. In this paper we suppose that, instead of call blocking, a "forced registration" operation is performed to restore the VLR record before call setup. The forced registration operation is similar to the VLR failure restoration operation [4] that restores the lost VLR records after a VLR database crash. In GSM, when a mobile phone makes a call, the call origination request is sent to the VLR. If the VLR record for the mobile phone was replaced due to the exercise of implicit deregistration, the request is rejected. Then the mobile phone is asked to initiate the location registration procedure. After the registration, the VLR record is recovered. Similarly, when a call termination is delivered to a mobile phone, the VLR record for the mobile phone may not exist. The serving VLR queries the HLR for the service information. Then, the target *Mobile Switching Center* (MSC) is asked to initiate paging of the mobile phone in all RAs of the serving VLR. If the paging is successful, the location information of the VLR record of the mobile phone is recovered. In the above call setup procedure, the network is "forced" to perform registration to recover the VLR record for a mobile phone.

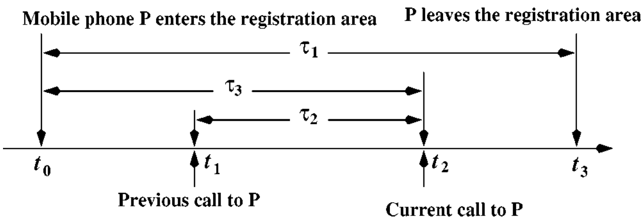

Figure 1. The timing diagram.

In our approach, implicit deregistration totally eliminates the deregistration traffic at the cost of creating some forced registration traffic. Thus, it is important to study when a PCS network can significantly benefit from implicit deregistration when compared to explicit deregistration. Let μ_1 be the deregistration traffic saved in implicit deregistration (compared with explicit deregistration) and μ_2 be the extra traffic created due to forced registration. The portion β of the network traffic saved in implicit deregistration is expressed as

$$\beta = \frac{\mu_1 - \alpha\mu_2}{\mu_1}, \tag{1}$$

where α is the ratio of a deregistration cost to a registration cost. In a typical mobile phone network, $1 < \alpha < 2$ (e.g., FarEasTone GSM network). If β is negative, then it implies that the cost of implicit deregistration with forced registration is higher than explicit registration.

In this paper, we use β to investigate the performance of implicit deregistration with forced registration.

2. The analytic model

This section proposes an analytic approach to model implicit deregistration with forced registration. Consider the timing diagram in figure 1. Suppose that the mobile phone P enters an RA at time t_0, and leaves the RA at time t_3. Then the residence time of P in the RA is $\tau_1 = t_3 - t_0$. Suppose that a call to P (either a call origination or a call termination) arrives at time t_2 (where $t_1 < t_2 < t_3$), and the previous call to P arrives at time t_1. Then the inter-call-arrival time is $\tau_2 = t_2 - t_1$. It is clear that before t_0, t_1 and t_2, P's VLR record may not exist if implicit deregistration is exercised and the record is replaced. We note that at times t_0, t_1 and t_2, P always has a record in the VLR (which is potentially restored by a forced registration). On the other hand, the VLR record of P may be replaced during the period $[\max(t_0, t_1), t_2]$ (in figure 1, $\max(t_0, t_1) = t_1$) if a registration or call setup for another mobile phone selects P's record for replacement during the period. Let the length of this period be $\tau = \min(\tau_2, \tau_3)$, where $\tau_3 = t_2 - t_0$ represents the period between when P enters the registration area and when the current call arrives at P. Thus, τ is the period during which the VLR record of P may be replaced when the current call to P arrives. To derive β in (1), we make the following assumptions:

- The call arrivals to a mobile phone are a Poisson process with the call arrival rate λ; i.e., the inter-call-arrival time τ_2 (the period between two consecutive call arrivals) is exponentially distributed with mean $1/\lambda$.
- The RA residence time τ_1 has a general density function $f_m(\tau_1)$ with mean $1/\eta$.

Since the Poisson call arrivals are random observers to the RA residence times, following the residual life theorem [7], the density function $r_m(\tau_3)$ for τ_3 is

$$r_m(\tau_3) = \eta \int_{t=\tau_3}^{\infty} f_m(t)\,\mathrm{d}t = \eta\big[1 - F_m(\tau_3)\big], \tag{2}$$

where $F_m(\cdot)$ is the distribution function of $f_m(\cdot)$. The density function $f(\tau)$ for $\tau = \min[\tau_2, \tau_3]$ is

$$\begin{aligned} f(\tau) &= \int_{\tau_2=\tau}^{\infty} \lambda e^{-\lambda\tau_2} r_m(\tau)\,\mathrm{d}\tau_2 + \int_{\tau_3=\tau}^{\infty} \lambda e^{-\lambda\tau} r_m(\tau_3)\,\mathrm{d}\tau_3 \\ &= e^{-\lambda\tau}\big\{r_m(\tau) + \lambda\big[1 - R_m(\tau_3)\big]\big\}, \end{aligned} \tag{3}$$

where $R_m(\cdot)$ is the distribution function of $r_m(\cdot)$. The Laplace transform $f^*(s)$ for the τ distribution is

$$\begin{aligned} f^*(s) &= \int_{\tau=0}^{\infty} e^{-s\tau} f(\tau)\,\mathrm{d}\tau \\ &= \frac{\lambda s + \lambda^2 + \eta s(1 - f_m^*(\lambda + s))}{(s+\lambda)^2}. \end{aligned} \tag{4}$$

The number of mobile phones in an RA changes from time to time. Let the expected number be N. If N is sufficiently large, the mobile phone arrivals (i.e., registration traffic) can be approximated by a Poisson process with rate $N\eta$ [8]. Also, the net call arrivals to the mobile phones in the VLR form a Poisson process with rate $N\lambda$.

Let M be the database size of the VLR. If the VLR record replacement is done (uniformly) randomly then

$$q = \frac{M-1}{M} \tag{5}$$

is the probability that the VLR record for a mobile phone P is not selected for replacement.

Let p be the record-missing probability that when a call to the mobile phone P arrives (i.e., the current call in figure 1), the VLR record r_P of P does not exist. That is, r_P is removed in the period τ either by a registration operation (with rate $N\eta$) or a call request to another mobile phone whose VLR record does not exist (with the rate $pN\lambda$), and r_P is selected for replacement (with probability $1 - q$). Note that the rate for the call arrivals to the mobile phones in the VLR is given by $N\lambda$. Since the probability p is the record-missing probability that when a call to the mobile phone P arrives, the VLR record of P does not exist. Thus, $pN\lambda$ is the rate of call requests for which the corresponding VLR records do not exist. Based on the above discussion, the rate of operations that may cause the replacement of a VLR record is

$$\lambda^* = (\eta + p\lambda)N. \tag{6}$$

Furthermore, the number X of such operations in period τ is a Poisson random variable with the probability mass function [7]

$$\Pr[X=n]=\frac{(\lambda^*\tau)^n}{n!}\mathrm{e}^{-\lambda^*\tau}.$$

Thus, the record-missing probability p can be expressed as

$$\begin{aligned} p &= 1-\int_{\tau=0}^{\infty}\left\{\sum_{n=0}^{\infty} q^n \Pr[X=n]\right\} f(\tau)\,\mathrm{d}\tau \\ &= 1-\sum_{n=0}^{\infty}\left\{\frac{(-q\lambda^*)^n}{n!}\left[\frac{\mathrm{d}^n f^*(s)}{\mathrm{d}s^n}\bigg|_{s=\lambda^*}\right]\right\}. \qquad (7)\end{aligned}$$

Observing that $f^*(s)$ is analytic in the right complex plane, so by using power series expansion, we have

$$\sum_{n=0}^{\infty}\left\{\frac{(-q)^n(\lambda^*)^n}{n!}\left[\frac{\mathrm{d}^n f^*(s)}{\mathrm{d}s^n}\bigg|_{s=\lambda^*}\right]\right\} = f^*(\lambda^*(1-q)). \quad (8)$$

From (4) and (8), (7) can be rewritten as

$$\begin{aligned} p &= 1-f^*\big(\lambda^*(1-q)\big) \\ &= \frac{A^2+\lambda A-\eta A[1-f_m^*(A+\lambda)]}{(A+\lambda)^2}, \qquad (9)\end{aligned}$$

where $A=\lambda^*(1-q)$.

We notice that from (6) and (5) we obtain

$$\lambda^*=\left(\frac{\eta+p\lambda}{1-q}\right)\left(\frac{N}{M}\right), \qquad (10)$$

thus, (9) is not affected by N or M individually, instead, (9) is affected by the ratio N/M.

With (9) and (10), the unknown p can be computed by using the following iterative procedure.

Step 1. Select the initial value for p.
Step 2. Compute λ^* based on (10).
Step 3. Let $p_{\mathrm{old}} \leftarrow p$.
Step 4. Compute p based on (9).
Step 5. Let δ be a predefined small value. If $|p-p_{\mathrm{old}}|<\delta p$, then exit. Otherwise, $p_{\mathrm{old}} \leftarrow p$ and go to step 2.

When the procedure exits at step 5, the p value will give the desired value. The above iterative procedure has been extensively used and validated by experiments [8]. Here we want to prove analytically that this iterative algorithm will converge to the unique solution. Let

$$g(p)=1-f^*\big(\lambda^*(1-q)\big)=1-f^*\left(\frac{(\eta+p\lambda)N}{M}\right),$$

which is the right-hand side of (9). We first show the existence and uniqueness of a solution for the equation (9). Notice that $f^*(s)$ is the Laplace transform of a probability density function, which is analytic in the right complex plane. Let $h(p)=p-g(p)$, we have $h(0)=-g(0)=-1+f^*(\eta N/M)<0$ and $h(1)=1-g(1)=f^*((\eta+\lambda)N/M)>0$, from the mean value theorem, there is a solution for (9), i.e., there exists a p^* in $(0,1)$ such that $h(p^*)=0$. For any positive number p in $(0,+\infty)$, we have ($X^{(i)}(s)$ denotes the ith derivative of the function $X(s)$)

$$g^{(1)}(p)=-f^{*(1)}\left[(\eta+p\lambda)\left(\frac{N}{M}\right)\right]\left(\frac{\lambda N}{M}\right)>0$$

and

$$g^{(2)}(p)=-f^{*(2)}\left[(\eta+p\lambda)\left(\frac{N}{M}\right)\right]\left(\frac{\lambda N}{M}\right)^2<0,$$

where we have used the fact that $f^{*(1)}(s)<0$ and $f^{*(2)}(s)>0$ on the positive real axis. We conclude that $g(p)$ is a concave function, and it is also an increasing function in $[0,1]$. Since $g(0)>0$ and $g(1)<1$, we conclude that there is only one point in $(0,1)$ at which $p=g(p)$, thus, the solution of $p=g(p)$ is unique in $(0,1)$. Next, we prove the convergence of the iterative algorithm. Let p_n denote the nth iteration obtained from the iteration algorithm, then we have $p_{n+1}=g(p_n)$, from which we have

$$\begin{aligned} p_{n+1}-p_n &= g(p_n)-g(p_{n-1}) \\ &= g^{(1)}(r_n)(p_n-p_{n-1}) \\ &= \cdots \\ &= \big[g^{(1)}(r_n)\big]\cdots\big[g^{(1)}(r_1)\big](p_1-p_0), \qquad (11)\end{aligned}$$

where $r_1, r_2, \ldots, r_n$ are the intermediate values from the mean value theorem. By noticing that $g^{(1)}(p)>0$ for any value in $(0,1]$ and (11), we observe that if $p_1>p_0$, p_n is nondecreasing; if $p_1\leqslant p_0$, p_n is nonincreasing, thus, the sequence $\{p_n\}$ is a monotonic sequence. Besides, the sequence is obviously bounded. Hence, the sequence will always converge and it will converge to the unique equilibrium point.

With the above iterative procedure, we will demonstrate the effects of input parameters such as λ, η and α on the record-missing probability p and the portion β of the network traffic saved in implicit deregistration with forced registration.

3. Numerical results

This section investigates the performance of implicit deregistration with forced registration based on the analytic model developed in the previous section. We assume that the RA residence times have a Gamma density function with mean $1/\eta$ and variance v. The Gamma distribution is selected because it can approximate many other distributions as well as experimental data [6]. The Laplace transform for the Gamma RA residence time distribution is

$$f_m^*(s)=\left(\frac{1}{1+\eta v s}\right)^{1/(\eta^2 v)}. \qquad (12)$$

From (12), (9) is rewritten as

$$p=\frac{A^2+\lambda A-\eta A[1-(1+\eta vA+\eta v\lambda)^{-1/(\eta^2 v)}]}{(A+\lambda)^2}, \qquad (13)$$

where $A=\lambda^*(1-q)$.

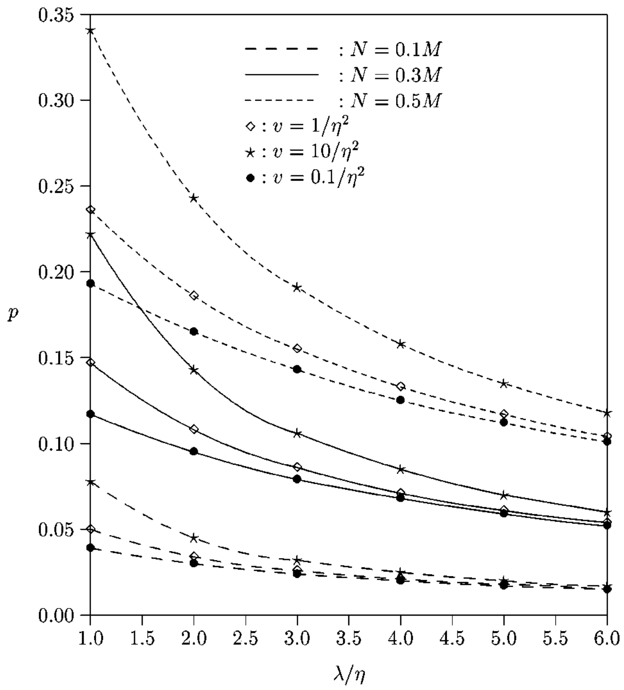

Figure 2. Effects of λ/η on p.

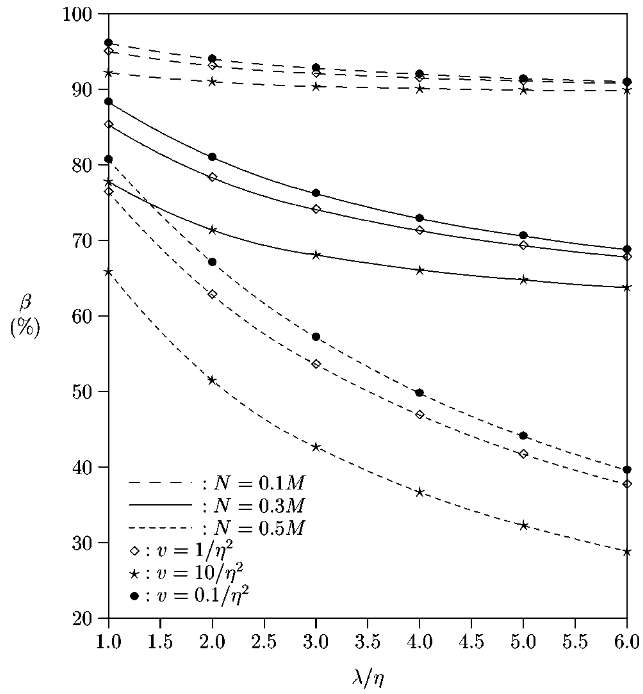

Figure 3. Effects of λ/η on β ($\alpha = 1$).

In appendix, we partially validate (13) for the case when the RA residence time distribution is exponentially distributed.

From (13) and since $\mu_1 = N\eta$ and $\mu_2 = pN\lambda$, (1) can be rewritten as

$$\beta = 1 - \left(\frac{\alpha\lambda}{\eta}\right) \times \left\{\frac{A^2 + \lambda A - \eta A[1 - (1 + \eta v A + \eta v \lambda)^{-1/(\eta^2 v)}]}{(A+\lambda)^2}\right\}, \tag{14}$$

where $A = \lambda^*(1 - q)$.

Based on (13) and (14), we investigate the performance of implicit deregistration with forced registration as follows.

3.1. Effects of λ/η

Based on (13), figure 2 plots the record-missing probability p against λ/η (the expected number of calls to a mobile phone when the mobile phone is in an RA) with $N/M = 0.1$, 0.3, 0.5 and $v = 0.1/\eta^2$, $1/\eta^2$, $10/\eta^2$. The figure indicates that p decreases significantly as λ/η increases, especially when N/M is large. That is, if the call arrival rate is low or the mobile phone's mobility is high, it is more likely that when a call arrives, the corresponding VLR record has been replaced. The figure also shows an intuitive result that as N/M increases, p increases (the more the mobile phones in the VLR, the higher the record-missing probability).

Based on (14), we compute the portion β of the network traffic saved in implicit deregistration with forced registration. The results are plotted in figure 3, where $N/M = 0.1, 0.3, 0.5$, $v = 0.1/\eta^2$, $1/\eta^2$, $10/\eta^2$, and $\alpha = 1$. The figure indicates that by exercising implicit deregistration, the portion of deregistration traffic can be significantly reduced if the expected number of mobile phones in an RA is not very large or the mobile phone's mobility is high. Specifically, for $N < 0.5M$, implicit deregistration is beneficial to a PCS network if $\lambda/\eta < 4$ (the number of calls to a mobile phone is less than 4 when the mobile phone is in an RA).

In practice, a PCS service provider can partition the VLR storage into two parts. The first part of the storage is used for mobile phones with low mobility where explicit deregistration is exercised. The second part of the VLR accommodates the records for mobile phones with high mobility where implicit deregistration is employed.

Figure 3 also indicates that β is more sensitive to λ/η for a large N/M than a small one. In other words, when the number of mobile phones in the system is large, the ratio of the call arrival rate to the mobile phone's mobility rate significantly affects the performance of implicit deregistration with forced registration.

3.2. Effects of v

Both figures 2 and 3 demonstrate how the variance v of the Gamma cell residence time distribution affects the system performance with a fixed mean $1/\eta$. Figure 2 shows that as v increases, the record-missing probability p increases rapidly, especially for the case where $\lambda/\eta \leqslant 2.5$. Figure 3 shows that the portion β of the network traffic saved in implicit deregistration decreases as v increases. Moreover, when $v \leqslant 1/\eta^2$, the variance of the RA residence time distribution only has insignificant effects on p and β. On the other hand, when $v > 1/\eta^2$, p and β are significantly affected by v.

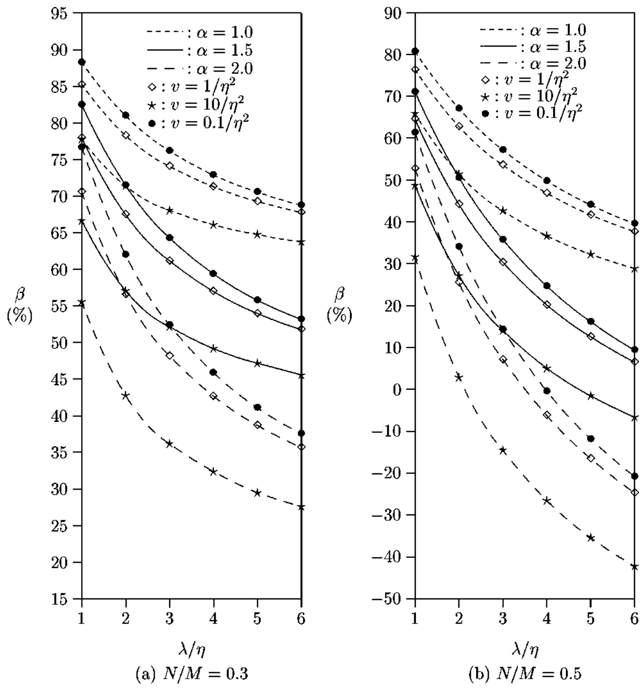

Figure 4. Effects of α on β.

3.3. Effects of α

Figure 4 plots β as a function of λ/η and α. It is apparent that with fixed mean and variance, β decreases as α increases. The non-intuitive result is that β is more sensitive to λ/η for a large α than a small one. We observe that when $N/M \leqslant 0.3$, β is positive even if λ/η is large. However, for $N/M = 0.5$ and $\alpha = 2$, β is negative for the cases where $\lambda/\eta \geqslant 3$. That is, if the number of mobile phones and the ratio of the deregistration cost to the extra forced registration cost are large, a PCS network cannot benefit from implicit deregistration with forced registration.

4. Conclusions and future research

This paper proposed an analytic model to investigate the performance of implicit deregistration with forced registration. The portion β of the network traffic saved when implicit deregistration is used is considered as the output measure. The study indicated that the expected number of mobile phones, the mobile phone's mobility and the ratio of a deregistration cost to a registration cost significantly affect the performance of β. Furthermore, we observed that β is significantly affected by the variance of the RA residence time distribution.

Besides the performance of β, several issues regarding implicit deregistration were discussed in [9]. Some additional issues are discussed here:

- *Effects of database failure*. When a mobility database fails, the records are recovered through radio contacts from the mobile phones. Thus, the failure restoration procedure [3,4] for systems exercising implicit deregistration is the same as IS-41 or GSM MAP.
- *Database revisit*. A mobile phone may revisit a VLR that already has an (undeleted) entry for the mobile phone. A search operation is required to reuse the entry for the current visit of the mobile phone. Compared to the cost of transmission, the search cost can be ignored.
- *Deregistration cost saving*. The deregistration cost saving depends on the message delivery distance between the HLR and the new and the old VLRs. The actual cost estimation may significantly vary from one PCS network to another. For example, the cost of a deregistration operation is roughly estimated as 50% of a registration operation in a GSM operator in Taiwan.

Our study suggested that a PCS service provider can partition the VLR storage into two parts. The first part of the storage is used for the mobile phones with low mobility where explicit deregistration is exercised. The second part of the VLR accommodates the records for the mobile phones with high mobility where implicit deregistration is employed.

This paper only considered a simple uniform random replacement policy for implicit deregistration. We anticipate that the scheme will be more effective if a sophisticated replacement policy is used. Thus, the design and modeling of new heuristics for record replacement will be an important future research direction for implicit deregistration.

Appendix. Validating the p derivation for the case with exponential RA residence times

Consider a special case where τ_1 is exponentially distributed. In this case (2) and (3) are rewritten as

$$r_m(t) = f_m(t) = \eta e^{-\eta t} \, f(\tau) = (\lambda + \eta) e^{-(\lambda+\eta)\tau},$$
$$f^*(s) = \frac{\lambda + \eta}{s + \lambda + \eta}. \tag{A.1}$$

Substitute (A.1) into (7), replace λ^* by $(\eta + p\lambda)N$, and let $\theta = N/M$. We then have

$$p = 1 - \frac{\lambda + \eta}{\lambda + \eta + \lambda^*(1-q)} = \frac{\theta\eta + \theta\lambda p}{(\theta+1)\eta + \lambda + \theta\lambda p} = \frac{a + bp}{c + bp}, \tag{A.2}$$

where $a = \theta\eta$, $b = \theta\lambda$, and $c = (\theta + 1)\eta + \lambda$. By replacing v by $1/\eta^2$ in (13), we have

$$p = \frac{A^2 + \lambda A - \eta A[1 - 1/(1 + A/\eta + \lambda/\eta)]}{(A + \lambda)^2} = \frac{\theta\eta + \theta\lambda p}{(\theta+1)\eta + \lambda + \theta\lambda p} = \frac{a + bp}{c + bp}, \tag{A.3}$$

where $A = \lambda^*(1 - q)$.

It is clear that (A.3) is the same as (A.2). Thus, we partially validate (13) for the case when the RA residence time distribution is exponentially distributed.

Both equations (A.2) and (A.3) can be rewritten as

$$bp^2 + (c - b)p - a = 0. \tag{A.4}$$

Since $0 \leqslant p \leqslant 1$ and $ab > 0$, the only solution for (A.4) is

$$p = \frac{-(c - b) + \sqrt{(c - b)^2 + 4ab}}{2b}. \tag{A.5}$$

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