# Performance Analysis on Location Tracking in PCS Networks

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## Abstract

*This paper presents a thorough performance analysis on various user location tracking strategies. including an enhanced caching strategy of ours. The results confirm favorable performance and reduced costfor our enhunced caching strategy.*

## 1. Introduction

In personal communication service (PCS) networks [1], the home location register (HLR) resides in the service control point (SCP) which connects to a regional signal transfer point (RSTP). Through a connection network, the RSTP connects to all local STPs (LSTP) in the region, performing message routing translation and screening functions in the signaling system 7 (SS7) network. The individual STPs actually represent the mated-pair configuration. Every LSTP comprises a local access transport area (LATA), which connects to multiple service switching points (SSPs). The mobile switching center (MSC) and a visitor location register (VLR) are collocated with an SSP. A registration area (RA) consists of one or more radio port coverage areas or cells [2]. We assume that each RA is served by a single VLR. The MSC of an RA is responsible for maintaining and accessing the VLR and for switching between radio ports. The VLR associated with an RA is responsible for maintaining a subset of user information contained in the HLR [3]. The VLR is collocated with the MSC, and the MSC/VLR combination will evolve to be SS7 compatible,

In a PCS network, a favorable location tracking strategy is essential to ensure successful mobile communication anywhere and anytime for users, The current standard location tracking schemes in a PCS include the IS-41 scheme [4] in North America and the MAP of the GSM system *[5]* in Europe. A number of user location tracking strategies, either caching or pointer forwarding strategies (e.g. [1-3,6-10]), have been proposed to reduce network communication cost for these two basic schemes. Caching strategies suit users who receive calls more frequently (i.e., with high users' call to mobility ratios (CMRs)) than change the PCS registration areas. For users with CMR around 5 and stable calls and move patterns, caching can result in *20-40%* cost reduction [1]. Pointer forwarding strategies, by contrast, suit users who frequently move among the PCS registration areas but receive calls not as frequently (i.e., with low CMRs). For users with CMRs $<$ 1, pointer forwarding strategies save cost without increasing the mean call setup time [8].

Based on the above observation, we propose an enhanced caching strategy [10] which uses forwarding pointers to locate users. The proposed strategy deploys the cache device at switch MSCNLR on a system-wide basis. The cached records keep users' location information obtained during their previous incoming calls. In many cases, it is indeed more feasible to save and reuse such location information than to query the HLR. As a user's moving to another RA will result in "cache hit but invalid', we use forwarding pointers to locate the user. By using forwarding pointers to replace updating a user's location information to the HLR (when he moves to a new RA), our new caching strategy reduces registration cost. In the cache part, we make use of two features -- users tend to revisit previous RAs and to visit previously called RAs -- to update the cached records and thus produce higher cache hit and valid ratios. The forwarding pointers in our strategy also help reduce the penalty due to cache hits but invalid, further decreasing the communication cost.

This paper provides a thorough analytic evaluation on the performance of user location strategies, including our enhanced caching strategy. The results affirm that, in comparison to other strategies, our strategy yields better performance at reduced cost.

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## 2. Analytic Model

### 2.1 Caching architectures of various strategies

The T-threshold caching strategy in [2] derives probabilities a, β and γ respectively for cache hit with threshold T, invalid cache records and cache miss:

$$\alpha = \Pr[\ t_c < t_m and t_C \le T\ ]$$

$$= \frac{\lambda_C}{\lambda_C + \lambda_m}\left[\ 1 - e^{-(\lambda_C+\lambda_m)T}\ \right]$$

(1)

$$\beta = \Pr[\ t_C \ge t_m and t_C \le T\ ]$$

$$= 1 - e^{\lambda_C T} - \frac{\lambda_C}{\lambda_C + \lambda_m}\left[\ 1 - e^{-(\lambda_C+\lambda_m)T}\ \right]$$

(2)

$$\gamma = \Pr\left[\ t_C > T\ \right] = e^{-\lambda_C T}$$

(3)

To suit our need, we redefine α, β and γ as

α : for cache hit with valid cache records

β : for cache hit with invalid cache records

γ : for cache miss (no cache records)

In (1), (2) and (3), the T-threshold is chosen from $t_C$ to be compared with the duration of cache records. $t_C$ represents the time interval between two consecutive calls directed from an RA to a remote user. To derive a general caching formula for our strategy, we adopt the same analytic model using $t_C$ but leaving out the T-threshold. Besides $t_c$, our analytic model also includes

$t_M$ : the time interval a user resides in an RA, and

$t_m$ : the time interval between the previous call to the user and the user's moving out of the RA.

$f_c(t)$, $f_M(t)$, and $f_m(t)$ are respectively the density functions of $t_c$, $t_M$ and $t_m$. If the incoming calls are random observers (for example, if the calls form a Poisson process) of $t_M$ [2], then

$$f_m(t) = \frac{1}{E[t_M]} \int_{t_1=t}^{\infty} f_M(t_1)dt_1$$

(4)

Let $f_h(t_c)$ be the density function of $t_c$ when $t_c < t_m$.

$$f_h(t_C) = f_C(t_C) \int_{t_m=t_C}^{\infty} f_m(t_m)dt_m$$

Assume that during the time period, if a user moves out of an RA, he will not return. (The effect that a user may return to a previously visited RA can be easily modeled by a two-dimensional random walk [8].) This assumption makes the derived hit ratio slightly lower than the true one. Probability $a$ for cache hit with valid cache record can be thus derived:

$$\alpha = \Pr[t_c < t_m] = \int_{t_C=0}^{\infty} f_h(t_C)dt_C$$

$$= \int_{t_C=0}^{\infty} \left[\ f_C(t_C) \int_{t_m=t_C}^{\infty} f_m(t_m)dt_m\ \right]dt_C$$

(5)

Assume $t_c$ and $t_M$ are exponentially distributed with mean 1 / $\lambda_c$ and mean 1 / $\lambda_m$; $t_m$ is also exponentially distributed. As $f_m(t) = f_M(t)$, (5) can be rewritten

$$\alpha = \int_{t_C=0}^{\infty} \lambda_C e^{-\lambda_C t_C}\left[\ \int_{t_m=t_C}^{\infty} \lambda_m e^{-\lambda_m t_m} dt_m\ \right]dt_C$$

$$= \int_{t_C=0}^{\infty} \lambda_C e^{-\lambda_C t_C} \lambda_m e^{-\lambda_m t_C} dt_C$$

$$= \frac{\lambda_C}{\lambda_C + \lambda_m}\left[1 - e^{-(\lambda_C+\lambda_m)t_C}\right]$$

(6)

Likewise, probability β will become

$$\beta = \Pr[t_c \ge t_m] = \int_{t_C=0}^{\infty} \left[f_C(t_C) - f_h(t_C)\right]dt_C$$

$$= 1 - e^{-\lambda_C t_C} - \frac{\lambda_C}{\lambda_C + \lambda_m}\left[\ 1 - e^{-(\lambda_C+\lambda_m)t_C}\ \right]$$

(7)

As mentioned, invalid cache records will result in "location miss" and extra cost penalty, such as HLR queries, in caching strategies. For improvement, our caching strategy employs enhanced pointers in cache entries to locate the user. Probability γ for no cache records indicates the call from a caller to the called user has not arrived and the cache record for the caller is still missing.

$= \Pr[t_c < t_M$ and $t_M - t_m = t_M$ (i.e., $t_m=0$)]

$$= \int_{t_C=0}^{\infty} f_C(t_C)dt_C \qquad = e^{-\lambda_C t_C}$$

(8)

### 2.2 The effect of cache record update

To illustrate cache record update, a user's portable moving sequence between two phone calls is assumed. In an 8 x 8 area, each RA sets up a VLR to maintain the user's location information. The user's movement routes **from** $R_0$ to $R_8$ by way of $R_6$, which keeps the user's cache record, and the user's cache record will be updated when he moves to $R_7$. In this case, we are interested to **how** (1) which **RAs** have the user's cache records before the user moves out of $R_0$ and (2) the user's moving route after moving out of $R_0$ between two calls. We then define

$$\alpha_{K+1} = m_{K+1} \times n$$

(9)

$\alpha_{K+1}$ = Prob [ user's cache record update]

$m_{K+1}$ = Prob [ user's moving out of $R_0$ between two calls ]

$n$ = Prob [ which RAs have user's cache record ]

The formula for cache record update can be derived from [9]. Assume the incoming calls to a user are a Poisson process, and the time the user resides in an RA is generally distributed. Let $t_c$ be the time interval between two consecutive calls to a user. Suppose the user resides in an RA, say $R_0$, when the previous call arrives, visits another **K** RAs and resides in the jth RA for a period $t_{Mj}$ ($0 \le j \le K$) after the call. Let

$t_m$ be the time interval between the arrival of the previous call and the user's moving out of $R_0$,

$t_{c,i}$ be the time interval between the user's entering $R_{Mi}$ and the arrival of the next phone call, and

$t_{Mi}$ be independently identically distributed random variables with general distribution $F_m(t_{Mi})$, density function $f_m(t_{Mi})$ and Laplace-Stieltjes Transform

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

Let $f_c(t)$ and $r_m(t)$ be the density functions of t, and $t_m$ respectively, $E[t_c] = 1/\lambda_c$ and $E[t_{Mi}] = 1/\lambda_m$.
Since the incoming calls are a Poisson process, $f_c(t) = \lambda_c e^{-\lambda_c t}$. Based on the memoryless property of the exponential distribution, $t_{c,i}$ has the same exponential distribution as $t_c$ for all i's, and based on the random observer property [9],

$$r_m(t) = \lambda_m \int_{\tau=t}^{\infty} f_m(\tau)d\tau = \lambda_m[1 - F_m(t)]$$

(10)

The Laplace-Stieltjes Transform for $t_m$ will be

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

$$= \int_{t=0}^{\infty} e^{-st}\lambda_m[\ 1 - F_m(t)\ ]dt$$

$$= \frac{\lambda_m}{s} - \int_{t=0}^{\infty} e^{-st}\lambda_m F_m(t)dt$$

$$= \frac{\lambda_m}{s} - \left[\frac{\lambda_m}{s} e^{-st} F_m(t)\ \Big|_{t=0}^{\infty} - \frac{\lambda_m}{s}\int_{t=0}^{\infty} e^{-st} f_m(t)dt\right]$$

$$= \frac{\lambda_m}{s}\left[1 - \int_{t=0}^{\infty} e^{-st} f_m(t)dt\right]$$

$$= \frac{\lambda_m}{s}\left[1 - f_m^*(s)\right]$$

(11)

Assume the user is at the **Kth** movement when passing the RA with the cache record. Now let us focus on the user's (K+1)th movement and get

$$m_{K+1} = \Pr[t_{M1} + t_{M2} + \ldots + t_{MK} < t_c \le t_{M1} + t_{M2} + \ldots + t_{MK+1}]$$

$$= \left(\prod_{i=1}^{K+1} \Pr[t_{c,i} > t_{Mi}]\right)\Pr[t_{c,K} \le t_{MK}]$$

$$= \left(1 - f_m^*(\lambda_c)\right)\left(f_m^*(\lambda_c)\right)^{K+1}$$

(12)

$$\Pr[t_{c,i} > t_{Mi}]$$

$$= \int_{t_{M,i}=0}^{\infty} \int_{t_{C,i}=t_{M,i}}^{\infty} \lambda_C e^{-\lambda_C t_{C,i}} f_m(t_{M,i})dt_{M,i}dt_{C,i}$$

$$= f_m^*(\lambda_C)$$

(13)

$$\Pr[t_{c,K} \le t_{MK}] = 1 - \Pr[t_{c,K} > t_{MK}]$$

$$= 1 - f_m^*(\lambda_C)$$

(14)

Assume the user's residence times are with Gamma distribution. (Most studies **use** exponential distribution, a special case of Gamma, for its simplicity.) With mean $1/\lambda_m$ and variance **V**, the Laplace-Stieltjes Transform of a Gamma random variable is expressed as

$$f_m^*(s) = \left(\frac{\lambda_m\gamma}{s + \lambda_m\gamma}\right)^{\gamma} \quad \text{Where } \gamma = \frac{1}{V\lambda_m^2}$$

The user's movement between two phone calls is significantly affected by the variance of residence times. When $s = \lambda_c$, $V = \frac{1}{\lambda_m^2}$ and $\gamma = 1$, we have

$$f_m^*(\lambda_c) = \left(\frac{\lambda_m}{\lambda_c + \lambda_m}\right)$$

Now $m_{K+1}$ of (9) can be obtained as

$$m_{K+1} = \left(1 - \frac{\lambda_m}{\lambda_c + \lambda_m}\right)\left(\frac{\lambda_m}{\lambda_c + \lambda_m}\right)^{K+1}$$

(15)

The probability for the user's cache record update in this example case ($n = 1/64$) is then derived:

$$\alpha_{K+1} = m_{K+1} \times n = \left(1 - \frac{\lambda_m}{\lambda_c + \lambda_m}\right)\left(\frac{\lambda_m}{\lambda_c + \lambda_m}\right)^{6+1} \times \frac{1}{64}$$

We can thus conclude: The probability of which RAs having the user's cache record depends on the number of VLRs in the PCS network, and *so* does the probability of the user's cache record update.

### 2.3 The forwarding pointer structures

**2.3.1 In cache miss cases.** Our enhanced caching strategy **first** characterizes users by call-to-mobility ratios (CMRs). The **CMR is** defined as the expected number **of** calls to a user during the period when the user visits a given RA. (Note that the CMR is defined here in terms of the calls received, not calls originated **from a** user.) If the user's call arrival rate is a mean rate $\lambda$, or $\lambda_C$, and the time the user resides in a given RA has a mean $1/\mu$ or $1/\lambda_m$, then the CMR, denoted **as p**, will be $CMR = p = \lambda / \mu$.

To conduct cost comparison between our strategy and the IS-41 scheme, we need to model the procedure of IS-41. Recall that when a user crosses several RAs between two consecutive calls, IS-41 needs to update the user's HLR each time the user moves to a new RA, but our strategy avoids unnecessary HLR updates because forwarding pointers are set up in all moves to locate the user. Let $C_B$ and $C_{C,F}$ respectively be the total cost for maintaining user information and locating the user between two consecutive calls for **IS-41** and for our strategy. Let

$M_{C,F}$ : expected cost of all enhanced FwdMOVE between two consecutive calls in our strategy

$F_{C,F}$ : average cost **of** our enhanced FwdFIND

M : total cost of all BasicMOVEs between two consecutive calls for IS-41

m : cost **of** a single invocation of BasicMOVE

F : cost of a single BasicFIND for IS-41

S : cost for setting up a forwarding pointer between VLRs during a FwdMOVE

T : cost for traversing a forwarding pointer between VLRs during a FwdFIND

K : number **of** RAs a user moves across between two calls; also the number of forwarding pointers

$$C_B = M + F = m/p + F$$

(16)

$$C_{C,F} = M_{C,F} / p + F_{C,F}$$

(17)

Let $\alpha$ (K) be the probability that there are K RA crossings between two call arrivals, expressed as [6,8]

$$\alpha(i) = \frac{\mu}{\lambda}[\, 1 - fm^*(\lambda)\, ]^2 [\, fm^*(\lambda)\, ]^{i-1}$$

(18)

When a user crosses K RA boundaries between two calls, there will be K pointer creations in our strategy. Unnecessary HLR updates can be avoided while the user moves. Thus,

$$M_{C,F} = \sum_{i=0}^{\infty} iS\alpha(i)$$

(19)

Let $\Theta$ (K) be the number of pointers traced in our enhanced FwdFIND operation. After the last BasicMOVE operation (if any), the user traverses K RA boundaries. Our enhanced FwdFIND operation will trace less than K RAs to locate the user if the user revisits RAs during the K moves (i.e., 'loop' exists among the K moves). Even if the user never revisits previously visited RAs, $\Theta$ (K) = K, and

$$F_{C,F} = \sum_{i=0}^{\infty} \Theta(K) T\alpha(i) + F$$

(20)

For better illustration, assume the RA residence time **of** a user is Gamma distributed with mean $1/\mu$. The Laplace transform of a Gamma distribution is $fm^*(s) = \left(\frac{\gamma\mu}{\lambda + \gamma\mu}\right)^{\gamma}$. Thus we have

$$g = fm^*(\lambda) = \left(\frac{\gamma\mu}{\lambda + \gamma\mu}\right)^{\gamma} = \left(\frac{\gamma}{p + \gamma}\right)^{\gamma}$$

When $\gamma = 1$, the RA residence time is exponential distribution. By setting $\gamma = 1$, $g = \frac{1}{1+p}$. (19) and (20) can be rewritten as

$$M_{C,F} = \frac{S}{P}$$

(21)

$$F_{C,F} = \frac{T \qquad (KT)}{p \quad [\, (1+p)^K - 1\, ]} + F$$

(22)

$$C_{C,F} = \frac{S+T \qquad (KT)}{p \quad [\, (1+p)^K - 1\, ]} + F$$

(23)

In IS-41, updating the WLR and performing a BasicFIND involve equal messages between HLR and VLR databases ( m = F). Without loss of generality, we normalize m = 1. Assume the cost for setting up a forwarding pointer is about twice the cost for traversing it (twice as many messages are involved) and set S = 2T. Let S = δ (6 < 1) as registering at the HLR is more expensive than setting up forwarding pointers. From (16), (21), (22) and (23), we obtain

$$\frac{M_{C,F}}{M} = \delta$$

(24)

$$\frac{F_{C,F}}{F} = 1 + \frac{6}{2p} \quad \frac{\delta K}{2[\,(1+p)^K - 1\,]}$$

(25)

$$\frac{C_{C,F}}{C_B} = \frac{p}{1+p}\left\{\, 1 + \frac{3\delta}{2p} - \frac{\delta K}{2[\,(1+p)^K - 1\,]} \,\right\} \quad (26)$$

**2.3.2 In** cache hit cases. Performance formulas **of** pointer forwarding strategies under the cache hit condition are also derived. Suppose the PCS network is a limited VLR system with sufficient cache size devices. After a period of operation, users get cache records and use them to make calls. For example, when probability y = 0 (CMR > 1), users making a phone call need not query the HLR because they can use cache records to locate the call receiver. Thus we obtain the cost formula for pointer traversal rates

$$M_{C,F} = \frac{S}{P}$$

(27)

$$F_{C,F} = \frac{T}{p} \quad \frac{(KT)}{[\,(1+p)^K - 1\,]}$$

(28)

$$C_{C,F} = \frac{S+T}{p} \quad \frac{(KT)}{[\,(1+p)^K - 1\,]}$$

(29)

Now we can rewrite (24), (25) and (26) into

$$\frac{M_{C,F}}{M} = \delta$$

(30)

$$\frac{F_{C,F}}{F} = \frac{\delta}{2p} \quad \frac{\delta K}{2[\,(1+p)^K - 1\,]}$$

(31)

$$\frac{C_{C,F}}{C_B} = \frac{P}{1+p}\left\{\, \frac{3\delta}{2p} \quad \frac{\delta K}{2[\,(1+p)^K - 1\,]} \,\right\} \quad (32)$$

## 3. Performance Analysis and Comparison

All the analytical results in this section are presented verbally, not in figures, due to limited pages.

### 3.1 Performance of caching strategies

**3.1.1** Location hit probability. The probability of location hit for our caching strategy includes both probabilities $a$ and β, in contrast to probability $a$ alone for other strategies. Location hit probabilities for the caching strategy in [2] and for our strategy are analyzed under CMR = 2–10 and CMR = 0.1–1. The result shows the probability for our strategy increases about 20 % under CMR = 2–10 due to enhanced pointers in cache entries. For CMR ≤ 1, the probability for our strategy is lifted about 50–70 %. It is achieved partly because low CMR brings about low cache record valid probability in general caching strategies (due to the users' frequent change of PCS registration areas) and partly because enhanced pointers are set **up** in cache entries of our strategy.

**3.1.2** Cache miss probability, γ . y under CMR = 0.1–lis analyzed for our strategy. The highest y (0.35~0.4) appears at CMR= 0.1 and then decreases with increased CMR. It reaches 0 roughly at CMR = 0.5 and stays at 0 up to CMR = 1. ( Due to unlimited cache sizes, probability y will be 0 when CMR>1.)

**3.1.3** Probability **of** updating cache records. The mean probabilities of updating cache records is collected in a network with 9 VLRs under CMR = 0.1–1 and 1.5–10. Recall that our strategy which updates cache records based on that users will visit previously called RAs results in higher probability α. Besides, the probability of which RAs' having a user's cache record depends on the number of VLRs in the PCS network. Probability $\alpha_{K+1}$ is evaluated under probability n = 1/9. The results indicate that users who change PCS registration areas frequently but receive calls less frequently have higher $\alpha_{K+1}$, and users who change PCS registration areas infrequently but receive calls frequently get lower $\alpha_{K+1}$. (The obtained results are decreasing functions of CMR -- they are dependent on the users' moving patterns.) The probability for a user to update its cache record in a network with different VLRs (n = **9**, 25, **49**, **81** etc) is collected under CMR = 0.1-1 and 1-10. It shows that the more VLRs a network has, the lower the probability to update a user's cache record, and vice versa.

## 3.2 Cost comparison for pointer forwarding

Performance comparison between our strategy and pointer forwarding structures is conducted under *3* different situations: ***Cache hit with valid cache records, cache hit with invalid cache records*** and ***cache miss.*** The performance parameters of interest are the traversal cost and total cost of each strategy.

**3.2.1 In cache miss cases.** Compared with the updating cost of registering at an HLR in IS-41, our strategy involves only the cost of setting up a forwarding pointer (6 $<$ 1). Without having to register at each HLR significantly reduces our updating cost. Both traversal and total costs of our strategy and of **IS-41** under CMR $\leq 2$ are compared. Traversal cost for our strategy appears higher than that of IS-41 because the call **to** the user in our strategy needs to traverse the pointer chain to locate the user's current position. However, the total cost for our strategy turns out (20–45 %) lower due *to* significantly reduced updating expense.

Cost comparison between our strategy, the per-user forwarding strategy [7] and the two-level pointer forwarding strategy *[6]* is given below. The result collected under CMR $\leq 2$ and $\delta = \mathbf{0.3}$ indicates the traversal cost of our enhanced pointers equals that **of** the per-user forwarding as both strategies use the same traversing procedure to locate users. However, our enhanced pointers are more efficient in the total cost, though by minimal degrees. Cost comparison between our strategy and the two-level pointer forwarding strategy (under CMR $\leq 2$, K = 1.5 and *6* = 0.3) shows that our strategy yields less traversal cost and slightly lower total cost (as the two-level pointer forwarding strategy involves a complicated operation --using two pointer parameters-- to optimize the performance of location tracking).

**3.2.2 In cache** hit **with invalid cache records cases.** Formulas **(21)** and **(27)** give the equal cost of our enhanced **FwdMOVE** in ***cache miss*** and ***cache hit with invalid cache records.*** Cost evaluation shows our enhanced forwarding pointers yield less updating cost than the per-user forwarding and two-level pointer forwarding strategies because users in our strategy can reduce updating cost when moving more frequently across RAs' boundaries. (Our strategy involves only the cost for setting up forwarding pointers, not the cost for registering to HLRs). The cost of forwarding pointers is also compared. The result displays a common trend that our strategy yields constantly and significantly lower cost than the IS-41, per-user forwarding and two-level pointer forwarding strategies.

**3.2.3 In cache hit with valid cache records cases.** There is no cost for our enhanced forwarding pointers in ***cache hit with valid cache records*** in which **we** can locate the user without employing the enhanced pointers. If the case is counted in, the result will turn out even more favorable for our strategy.

## 4. Conclusions

This paper presents a thorough performance analysis on location tracking strategies, including the existing caching strategies, pointer forwarding strategies and our enhanced caching strategy. Analytic evaluation shows that our strategy generates more desirable location hit probabilities than the other caching strategy under any CMRs. When the CMR is low, our strategy performs even better -- location hit probabilities are significantly increased and the penalty due to invalid cache records is consequently reduced. Our strategy also yields increased probability for ***cache hit with valid cache records*** because it uses the users' mobility feature of visiting previously called RAs to update cache records. Utilizing forwarding pointers in cache entries also makes our strategy avoid unnecessary HLR queries and updates. To sum up, our strategy outperforms other location tracking strategies in terms of registration cost, traversal cost and total cost.

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