Performance Analysis of Pointer Forwarding Scheme for Wireless Cellular Networks

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Abstract—**Location management, a way to track mobile subscribers for service delivery, plays a very significant role in the current and the future wireless mobile networks in effectively delivering services to the mobile users on the move. Many schemes have been proposed and investigated extensively in the last decade. However, most performance analyses were carried out either under simplistic assumptions on some time variables or via simulations. In this paper, we present a new analytical approach to investigate the tradeoff (cost) analysis for location management schemes under fairly general assumption. In this paper, we focus on *Pointer Forwarding Scheme (PFS)* and present analytical formulae to compute the total costs. Numerical results show that the traditional exponential approximation may lead to incorrect decision making in the location management scheme. However, our analytical results can be easily used to find the appropriate parameters in PFS.**

I. INTRODUCTION

IN wireless mobile networks, in order to effectively deliver a service to a mobile user, the location of a called mobile user must be determined within a certain time limit (before the service is blocked). *Location management* is used to track the mobile users that move from place to place in the coverage area of a wireless mobile network or in the coverage area of multiple communications networks working together to fulfill the grand vision of ubiquitous communications. Thus, the location management (also called *mobility management*) is a key component for the effective operations of wireless networks to deliver wireless Internet services (see [4] and references therein).

The coverage area of a wireless cellular network is populated with base stations, each of which is responsible for communications of the mobile users traveling in its coverage area called *cells*. A group of cells form a *registration area (RA)*, which is managed by *mobile switching center* (MSC) directly connecting to the backbone wireline networks such as *Public Switched Telephone Networks (PSTN)*. In the second and some third generation wireless networks, the standard signaling protocols IS-41 ([1]) and GSM MAP ([2]) are used, in which two-level hierarchical strategies with a two-tier system of Home Location Register (HLR) and Visitor Location Register (VLR) databases are developed. The HLR stores the user profiles of its registered mobiles, which include information such as the mobile's identification number, the type of services subscribed, the quality of service (QoS) requirements and the current location information. The VLR stores replications of users' profiles and the temporary identification number for those mobiles which are currently visiting the associated RA. There are two basic operations in the location management: *registration* and *location tracking*. The registration is the process that a mobile informs the system of its current location. Whenever and wherever a mobile user travels in the system's coverage, the mobile's location will be reported to the HLR (registration) according to some strategies. When a call service arriving to the mobile, the location information in HLR will be used to locate (*find*) the mobile. When the mobile visits a new RA, a temporary record will be created in the VLR of the visited system, and the VLR will then send a registration message to the HLR.

The signaling traffic due to *find* and *registration* can be significant. Various schemes to reduce such traffic have been proposed. In [10], the location cache scheme was proposed and shown significant improvement over IS-41 scheme when the frequency of the incoming calls is high with respect to the mobility. To reduce the signaling traffic from the mobile to HLR, the *pointer forwarding scheme* ([9]) was proposed based on the observation that it may be better to setup a forwarding pointer from the previous VLR to avoid more expensive registration operations from the mobile. By storing location profile, registration traffic can also be reduced. This idea leads to the *alternative location algorithm (ALA)* and *two location algorithm (TLA)* ([12] and references therein). Observing that the signaling cost can significantly affected by the location database distribution, Ho and Akyildiz proposed the *local anchor scheme* to localize the registration traffic ([7]) and the dynamic hierarchical database architecture using *directory registers* ([8]). Although most studies focus on the second generation personal communications networks (PCN), all location management schemes will be useful in the future generation wireless networks ([4]).

Signaling traffic cost analysis relies on many factors such as terminating call arrivals and users' mobility. Cost analysis of most location management schemes were carried out under the assumption that some time variables are exponentially distributed. For example, the time between two *served* calls, which we called *inter-service time* ([6]), was usually assumed to be exponentially distributed. Even if the call arrivals terminating at a mobile, say, $\mathcal{T}$, can be approximately modeled by Poisson process, the inter-service time is not identical to the inter-arrival time due to the *busy-line effect* ([6]), i.e., some call arrivals for the mobile $\mathcal{T}$ may be blocked because $\mathcal{T}$ is serving another call, hence the served calls are in fact a "sampled" Poisson process, thus will be most likely not Poisson process. Moreover,

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due to the new trend of applications and user habits, even the inter-arrival time for the terminating calls to a mobile may not be exponentially distributed anymore. We observe that some adaptive or dynamic schemes for choosing some location management parameters really depend on the explicit form of the overall cost ([13]), it will be doubtful whether we can use these schemes in the future generation wireless networks. In this paper, we develop a new approach using more general modeling for the time variables involved and present general analytical results for the signaling cost analysis. Our results can be used to investigate the dynamic location management schemes. Due to page limitation, we will concentrate only on *Pointer Forwarding Scheme (PFS)* in this paper.

II. LOCATION MANAGEMENT SCHEMES

A. *IS-41 Scheme*

Before we present PFS, we briefly go over the IS-41 scheme (or GSM MAP). We use the terminology used in [9]. An operation *move* means that a mobile user moves from one RA to another while an operation *find* is the process to determine the RA a mobile user is currently visiting. The *move* and *find* in second generation location management schemes (such as in IS-41 or GSM MAP) are called *basic move* and *basic find*. In *basic move* operation, a mobile detects if it is in a new RA. If it is, it will sends a registration message to the new VLR, the VLR will send a message to HLR. The HLR will send a de-registration message to the old VLR, which will, upon receiving the de-registration message, send HLR the cancellation confirmation. The HLR will also send a cancellation confirmation message to the new VLR. In the *basic find*, call to a mobile $\mathcal{T}$ is detected at a local switch. If the called party is in the same RA, the connection can be setup directly without querying the HLR. Otherwise, the local switch (VLR) queries the HLR for the callee, then HLR will query the callee's VLR. Upon receiving callee's location, the HLR will forward the location to the caller's local switch.

B. *Pointer Forwarding Scheme (PFS)*

The PFS modifies the *move* and *find* as follows. When a mobile $\mathcal{T}$ moves from one RA to another, it will inform its local switch (and VLR) at the new RA, which will determine whether to invoke the *basic move* or the *forwarding move*. In the *forwarding move*, the new VLR exchanges messages with the old VLR to setup pointer from the old VLR to the new VLR, but does not involve the HLR. A subsequent call to the mobile $\mathcal{T}$ from some other switches will invoke the *forwarding find* procedure to locate the mobile: queries the mobile's HLR as in the *basic find*, and obtains a "potentially outdated" pointer to the old VLR, which will then direct the *find* to the new VLR using the pointer to locate the mobile $\mathcal{T}$. To ensure that the time taken by the *forwarding find* is within the tolerable limit, the length of the chain of forwarding pointers must be limited. This can be done by setup the threshold for chain length to be a number, say, K, i.e., whenever the mobile $\mathcal{T}$ crosses K RA boundaries, it will register itself through the *basic move* (i.e., basic registration with HLR). In this way, the signaling traffic between the mobile and HLR can be curbed potentially.

III. COST ANALYSIS

In order to carry out location update cost analysis, we need to model some of the time variables appropriately and compute the probability distribution of the number of RA boundary crossings, which is characterized in detail in [6].

A. *Probability Distribution of the Number of Boundary Crossings*

Assume that the incoming calls to a mobile terminal, say, $\mathcal{T}$, form a Poisson process, the time the mobile terminal stays in a registration area (RA) (also called the *RA residence time*) has a general non-lattice distribution. We will derive the probability $\alpha(K)$ that a mobile terminal moves across K RAs between two served calls arriving to the mobile terminal $\mathcal{T}$. The time between the end of a call served and the start of the following call served by the mobile terminal is called *the inter-service time.*

Let $t_1, t_2, \ldots$ denote the RA residence times and r_1 denotes the residual RA residence time (i.e., the time interval between the time instant the call registers to the network and the time instant the mobile terminal exits the first RA). Let t_c denote the inter-service time between two consecutive served calls to a mobile terminal $\mathcal{T}$. Suppose that the mobile terminal is in a RA R_1 when the previous call arrives and accepted by $\mathcal{T}$, it then moves K RAs during the inter-service time, and $\mathcal{T}$ resides in the jth RA for a period t_j $(1 \leq j \leq K+1)$. We consider a homogeneous wireless mobile network, i.e., all RAs in the network are statistically identical. Assume $t_1, t_2, \ldots$ are independent and identically distributed (iid) with a general probability density function $f(t)$, let t_c be generally distributed with probability density function $f_c(t)$, and let $f_r(t)$ be the probability density function of r_1. Let $f^*(s)$, $f_c^*(s)$ and $f_r^*(s)$ denote the Laplace-Stieltjes (L-S) transforms (or simply Laplace transforms) of $f(t)$, $f_c(t)$ and $f_r(t)$, respectively. Let $E[t_c] = 1/\lambda_c$ and $E[t_i] = 1/\lambda_m$. From the residual life theorem ([11]), we have

$$\begin{aligned} f_r(t) &= \lambda_m \int_t^\infty f(\tau)d\tau = \lambda_m\,[1 - F(t)], \\ f_r^*(s) &= \frac{\lambda_m}{s}[1 - f^*(s)], \qquad (1) \end{aligned}$$

where $F(t)$ is the distribution function of $f(t)$. It is obvious that the probability $\alpha(K)$ is given by

$$\begin{aligned} \alpha(0) &= \Pr[t_c \leq r_1], \;\; K = 0, \qquad (2) \\ \alpha(K) &= \Pr[r_1 + t_2 + \cdots + t_K < t_c \leq \\ &\quad \leq r_1 + t_2 + \cdots + t_{K+1}], \;\; K \geq 1. \qquad (3) \end{aligned}$$

Theorem 1 ([6]) If the probability density function of the inter-service time has only finite possible isolated poles (which is the case when it has a rational Laplace transform), then the probability $\alpha(K)$ that a mobile terminal moves across K RAs during the inter-service time is given by

$$\begin{aligned}
\alpha(0) &= \frac{1}{2\pi j}\int_{\sigma-j\infty}^{\sigma+j\infty}\frac{1-f_r^*(s)}{s}f_c^*(-s)ds\\
\alpha(K) &= \frac{1}{2\pi j}\\
&\times\int_{\sigma-j\infty}^{\sigma+j\infty}\frac{f_r^*(s)[1-f^*(s)][f^*(s)]^{K-1}}{s}f_c^*(-s)ds
\end{aligned} \tag{4}$$

where σ is a sufficiently small positive number.

B. Cost Analysis for IS-41

As a baseline comparative study, we present the cost analysis for IS-41 first. Let M and F denote the total cost for *basic moves* during the inter-service time and the total cost for *basic find*, respectively (i.e., the costs incur in IS-41 scheme). Since all location management schemes will go through the *move* and *find* whenever a terminating call to a mobile $\mathcal{T}$ arrives, the inter-service time forms the fundamental regenerative period for cost analysis, thus we only need to consider the signaling traffic incurs during this period.

For IS-41 scheme, whenever the mobile crosses a RA boundary, a registration will be triggered. We assume that the unit cost for a basic registration (i.e., *basic move*) is m. From Theorem 1, M will be equal to the product of m and the average number of registrations incurred during the inter-service time, given by

$$\begin{aligned}
M &= m\sum_{K=0}^{\infty}K\alpha(K)\\
&= \frac{m}{2\pi j}\int_{\sigma-j\infty}^{\sigma+j\infty}\frac{f_r^*(s)[1-f^*(s)]}{s}\\
&\quad\times\left(\sum_{K=1}^{\infty}K(f^*(s))^{K-1}\right)f_c^*(-s)ds\\
&= \frac{m\lambda_m}{2\pi j}\int_{\sigma-j\infty}^{\sigma+j\infty}\frac{1}{s^2}f_c^*(-s)ds\\
&= m\lambda_m\int_0^{\infty}f_c(t)\left(\frac{1}{2\pi j}\int_{\sigma-j\infty}^{\sigma+j\infty}\frac{1}{s^2}e^{st}ds\right)dt\\
&= m\lambda_m\int_0^{\infty}f_c(t)tdt = \frac{m\lambda_m}{\lambda_c} = \frac{m}{\rho}
\end{aligned}$$

where $\rho = \lambda_c/\lambda_m$, which is called *call-to-mobility ratio*.

The *basic find* operation consists of two parts. The first part includes the interactions between the originating switch and the HLR while the second part includes the interactions between the HLR, the VLR, the MSC (terminating switch) and the mobile. Without loss of generality, we can assume that *basic find* unit cost is 1, and the unit cost of first part is δ ($0 \le \delta \le 1$), hence the second part will be $1-\delta$. We observe that the message exchanges in the first part of *basic find* are almost identical to those in the *basic move*, hence we have $m = \delta$. During one inter-service time, we only need one *find* operation. In summary, we obtain the total cost for IS-41 during the inter-service time is

$$\begin{aligned}
C_{IS-41} &= M + F\\
&= -\delta\sum_{p\in\sigma_c}\operatorname*{Res}_{s=p}\frac{f_r^*(s)}{s[1-f^*(s)]}f_c^*(-s)+1 = \frac{\delta}{\rho}+1.
\end{aligned} \tag{5}$$

C. Cost Analysis for Pointer Forwarding

In this subsection, we develop more general model to evaluate the performance of pointer forwarding scheme. Let M' and F' denote the corresponding costs for the pointer forwarding scheme, in which every K moves will trigger a new registration. Let S denote the cost of setting up a forwarding pointer between VLRs during a pointer forwarding *move* and let T denote the cost of traversing a forwarding pointer between VLRs during a pointer forwarding *find*. We first derive M' and F'.

Suppose that a mobile $\mathcal{T}$ crosses i RA boundaries, then there are $i - \lfloor i/K \rfloor$ pointer creations (every K moves require $K-1$ pointer creations) and the HLR is updated $\lfloor i/K \rfloor$ times (with pointer forwarding, the mobile $\mathcal{T}$ registers every Kth move). Thus, we have

$$\begin{aligned}
M' &= \sum_{i=0}^{\infty}\left[\left(i-\left\lfloor\frac{i}{K}\right\rfloor\right)S+\left\lfloor\frac{i}{K}\right\rfloor m\right]\alpha(i)\\
&= S\sum_{i=0}^{\infty}i\alpha(i)+(m-S)\sum_{i=0}^{\infty}\left\lfloor\frac{i}{K}\right\rfloor\alpha(i)\\
&= S\sum_{i=0}^{\infty}i\alpha(i)+(m-S)\sum_{r=0}^{\infty}r\left(\sum_{i=rK}^{(r+1)K-1}\alpha(i)\right)
\end{aligned} \tag{6}$$

Let

$$\begin{aligned}
X(K) &= \sum_{i=1}^{\infty}r\left(\sum_{i=rK}^{(r+1)K-1}\alpha(i)\right)\\
S(n) &= \sum_{k=1}^{n-1}\alpha(k)
\end{aligned}$$

then, from Theorem 1, we obtain

$$\begin{aligned}
S(n) &= \sum_{i=1}^{n-1}\frac{1}{2\pi j}\\
&\times\int_{\sigma-j\infty}^{\sigma+j\infty}\frac{f_r^*(s)[1-f^*(s)][f^*(s)]^{i-1}}{s}f_c^*(-s)ds\\
&= \frac{1}{2\pi j}\int_{\sigma-j\infty}^{\sigma+j\infty}\frac{f_r^*(s)[1-f^*(s)]}{s}\\
&\times\left(\sum_{i=1}^{n-1}[f^*(s)]^{i-1}\right)f_c^*(-s)ds
\end{aligned}$$

$$= \frac{1}{2\pi j}\int_{\sigma-j\infty}^{\sigma+j\infty} \frac{f_r^*(s)[1-(f^*(s))^{n-1}]}{s} f_c^*(-s)ds \tag{7}$$

Moreover, we have

$$\begin{aligned}
\sum_{i=1}^{N} s(iK) &= \sum_{i=1}^{N} \frac{1}{2\pi j} \\
&\times \int_{\sigma-j\infty}^{\sigma+j\infty} \frac{f_r^*(s)[1-(f^*(s))^{iK-1}]}{s} f_c^*(-s)ds \\
&= \frac{1}{2\pi j}\int_{\sigma-j\infty}^{\sigma+j\infty} \frac{f_r^*(s)}{s} \\
&\times \left\{ N - (f^*(s))^{K-1} \sum_{i=1}^{N} \left[(f^*(s))^K\right]^{i-1} \right\} f_c^*(-s)ds \\
&= \frac{1}{2\pi j}\int_{\sigma-j\infty}^{\sigma+j\infty} \frac{f_r^*(s)}{s} \\
&\times \left\{ N - \frac{(f^*(s))^{K-1}[1-(f^*(s))^{NK}]}{1-(f^*(s))^K} \right\} f_c^*(-s)ds
\end{aligned} \tag{8}$$

Thus, from (7) and (8), after some mathematical manipulations, we obtain

$$\begin{aligned}
X(K) &= \sum_{r=1}^{\infty} r\left[S((r+1)K) - S(rK)\right] \\
&= \lim_{N\to\infty} \left\{ \sum_{r=1}^{N} r\left[S((r+1)K) - S(rK)\right] \right\} \\
&= \lim_{N\to\infty} \left\{ NS((N+1)K) - \sum_{r=1}^{N} S(rK) \right\} \\
&= \frac{1}{2\pi j}\int_{\sigma-j\infty}^{\sigma+j\infty} \frac{f_r^*(s)(f^*(s))^{K-1}}{s[1-(f^*(s))^K]} f_c^*(-s) \\
&- \lim_{N\to\infty} \frac{1}{2\pi j} \left\{ \int_{\sigma-j\infty}^{\sigma+j\infty} f_c^*(-s) \right. \\
&\times \left. \frac{f_r^*(s)[N+1-N(f^*(s))^K]}{s[1-(f^*(s))^K]} [f^*(s)]^{(N+1)K-1} ds \right\} \\
&= \frac{1}{2\pi j}\int_{\sigma-j\infty}^{\sigma+j\infty} \frac{f_r^*(s)(f^*(s))^{K-1}}{s[1-(f^*(s))^K]} f_c^*(-s)ds
\end{aligned} \tag{9}$$

Noticing that $X(1) = \sum_{i=0}^{\infty} i\alpha(i)$, from (6), we obtain

$$\begin{aligned}
M' &= SX(1) + (m-S)X(K) \\
&= \frac{1}{2\pi j}\int_{\sigma-j\infty}^{\sigma+j\infty} \left[\frac{Sf_r^*(s)}{s[1-f^*(s)]} \right. \\
&\quad \left. + \frac{(m-S)f_r^*(s)(f^*(s))^{K-1}}{s[1-(f^*(s))^K]} \right] f_c^*(-s)ds
\end{aligned} \tag{10}$$

Next, we derive F'. After last *basic move* operation (if any), the mobile $\mathcal{T}$ crosses $n = i - K\lfloor i/K \rfloor$ RA boundaries. Let $\Theta(n)$ denote the number of pointers to be traced in order to find the mobile $\mathcal{T}$ in the pointer forwarding *find* operation. If the mobile visits a RA more than once ("loop" exists among n moves), then $\Theta(n)$ may not need to trace n pointers, i.e., $\Theta(n) \le n$. From this argument and applying Theorem 1, after some mathematical manipulations, we obtain

$$\begin{aligned}
F' &= \sum_{i=0}^{\infty} T\Theta\left(i - K\lfloor i \rfloor\right)\alpha(i) + F \\
&= T\sum_{r=0}^{\infty}\sum_{k=0}^{K-1} \Theta(k)\alpha(rK+k) + F \\
&= T\sum_{k=0}^{K-1}\Theta(k)\left(\sum_{r=0}^{\infty}\alpha(rK+k)\right) + F \\
&= \frac{T}{2\pi j}\int_{\sigma-j\infty}^{\sigma+j\infty} \frac{f_r^*(s)[1-f^*(s)]}{s[1-(f^*(s))^K]} \\
&\quad \times \left(\sum_{k=0}^{K-1}\Theta(k)(f^*(s))^{k-1}\right) f_c^*(-s)ds + F
\end{aligned}$$

In summary and applying the Residue Theorem, we finally arrive at

Theorem 2. If the inter-service time $f_c^*(s)$ has a finite number of poles (such as a proper rational function), then we have

$$\begin{aligned}
M' &= \frac{1}{2\pi j}\int_{\sigma-j\infty}^{\sigma+j\infty} \left[\frac{Sf_r^*(s)}{s[1-f^*(s)]} \right. \\
&\quad \left. + \frac{(m-S)f_r^*(s)(f^*(s))^{K-1}}{s[1-(f^*(s))^K]} \right] f_c^*(-s)ds \\
&= -\sum_{p\in\sigma_c} \operatorname*{Res}_{s=p} \left[\frac{Sf_r^*(s)}{s[1-f^*(s)]} \right. \\
&\quad \left. + \frac{(m-S)f_r^*(s)(f^*(s))^{K-1}}{s[1-(f^*(s))^K]} \right] f_c^*(-s)
\end{aligned} \tag{11}$$

$$\begin{aligned}
F' &= F + \frac{T}{2\pi j}\int_{\sigma-j\infty}^{\sigma+j\infty} \frac{f_r^*(s)[1-f^*(s)]}{s[1-(f^*(s))^K]} \\
&\quad \times \left(\sum_{k=0}^{K-1}\Theta(k)(f^*(s))^{k-1}\right) f_c^*(-s)ds \\
&= F - \sum_{p\in\sigma_c} \operatorname*{Res}_{s=p} \frac{f_r^*(s)[1-f^*(s)]}{s[1-(f^*(s))^K]} \\
&\quad \times \left(\sum_{k=0}^{K-1}\Theta(k)(f^*(s))^{k-1}\right) f_c^*(-s)
\end{aligned} \tag{12}$$

where σ_c denote the set of poles of $f_c^*(-s)$. ☐

As we mentioned in the previous subsection, we can choose $F = 1$. Thus, the total cost for TLA during the inter-service time can be computed as

$$C_{PFS} = M' + F' = 1 + \frac{1}{2\pi j}\int_{\sigma-j\infty}^{\sigma+j\infty} g(s)f_c^*(-s)ds$$

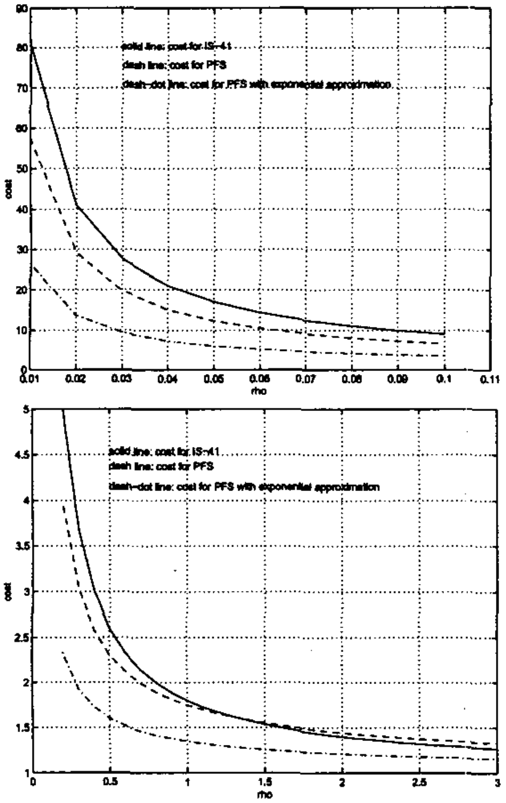

Fig. 1. Comparison results for PFS and IS-41: solid line is for IS-41, dash line is for PFS, dash-dot line is for PFS using exponential approximation for the inter-service time

$$= 1 - \sum_{p \in \sigma_c} \operatorname*{Res}_{s=p} g(s) f_c^*(-s) \tag{13}$$

where

$$\begin{aligned} g(s) &= \frac{S f_r^*(s)}{s[1 - f^*(s)]} + \frac{(m - S) f_r^*(s)(f^*(s))^{K-1}}{s[1 - (f^*(s))^K]} \\ &\quad + \frac{T f_r^*(s)[1 - f^*(s)]}{s[1 - (f^*(s))^K]} \left(\sum_{k=0}^{K-1} \Theta(k) \right). \end{aligned}$$

IV. NUMERICAL RESULTS

For illustration purpose, we choose the hyper-exponential distribution model for the inter-service time and choose the Gamma distribution model for the RA residence time. We also use the distribution model with the same average inter-service time to approximately model the inter-service time and study whether the exponential model is enough for the cost analysis.

Figures 1 shows the results for PFS. In this figure, we use the hyper-exponential distribution with the following parameters: $M = 2, p_1 = p_2 = 0.5, \eta_1 = 1$, and $\eta_2 = 0.5$, its average is $1/\lambda_c = p_1/\eta_1 + p_2/\eta_2 = 1.5$. We choose the Gamma distribution with the parameters: $\gamma = 0.1$, λ_m varies. Other parameters are given as follows: $K = 10, \delta = 0.8, S = 0.1$ and $T = 0.05$. We also consider the worst case scenario for PFS: we assume $\Theta(n) = n$, i.e., there are no loops in the pointer chain, which gives the highest pointer tracing cost. From Figure 1, we observe that there are significant differences between the total cost of PFS with the actual distribution for inter-service time and the total cost of PFS with the exponential approximation. Particularly, we observe that the crossing points of cost curves with the cost curve for IS-41 are different, which implies that wrong decision in the tradeoff analysis can be drawn if the exponential distribution model is used. For example, when $\rho = 2$, the cost curves show that IS-41 works better, however, if we use the exponential approximation, we conclude that PFS is still better than the IS-41, a wrong conclusion is drawn!

V. CONCLUSIONS

In this paper, we have developed a new approach to carrying out cost analysis for location management in wireless mobile networks. We focus on pointer forwarding scheme and present analytical results for the signaling cost under very general assumption. These results can be used to investigate how to choose the design parameters in the location management.

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