Portable Movement Modeling for PCS Networks

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***Abstract*—In this paper, we propose a new model for the portable movement in personal communications services (PCSs) networks. Based on this model with general interservice time and registration area residence time distributions, analytic expression for the probability that a portable moves across K registration areas (RAs) is obtained. Busy-line effect on this quantity is also studied and analytic expression is presented. The result given in this paper is very useful for the cost analysis for location updating and paging.**

***Index Terms*—Call holding time, cell residence times, location modeling, mobility, personal communications services (PCS).**

I. Introduction

PERSONAL Communications Services (PCS) networks are poised to provide integrated services such as voice, data and multimedia to mobile users anywhere, anytime [1], [11], in an uninterrupted and seamless way, using advanced microcellular and handoff concepts [8]. In such a network, the service area is populated with base stations which provide the radio links for communications. The radio coverage of each base station is called a *cell*. The base station is responsible for locating a mobile user or a portable through paging or some other location tracking strategies [17], [21], and delivers calls from and to the portable. The service of a PCS network is also divided into registration areas (RAs), each of which consists of an aggregation of cells, forming a contiguous geographical region. For a call from or to a roaming user, the location of the roaming user has to be determined for the call delivery. Two-level hierarchies which maintain a system of a home database (called home location register or HLR) and a visited database (called visitor location register or VLR) are commonly used for mobility management. When a user subscribes to a service from a PCS network, the user will first register at HLR where the user's information profile is stored. When the user requests a service in a visited RA, it will contact the VLR associated with the RA, the VLR will contact the HLR of the user for authentication, the user's record will be temporarily stored in the VLR. The VLR acts as an agent for the roaming user in the RA it is visiting.

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One of the most important issues in PCS networks is the location tracking. The location of a called portable must be determined before the connection can be established. Paging and location updating are schemes to locate a mobile user in a PCS network. Fewer location updates will lead to more paging traffic, while more location updates will result in less paging traffic, hence there is a tradeoff between the signaling traffic from mobile users and from the base stations. Thus, cost analysis will be needed to find the best location update and paging scheme. In order to carry out this task, an appropriate movement model for a portable needs to be constructed. From [13], we observe that one critical quantity in the cost analysis is the probability of the number of RA crossings, that is, the probability that a portable moves K RA between the two consecutive served calls (i.e., during the interservice time). For example, in IS-41, each RA crossing will incur at least one signaling message (for registration), the average number of signaling messages for a call life, which can be found from the probability distribution of RA crossings, will be used in the tradeoff analysis [13]. However, the cost analysis carried out in [13] is valid only for the cases when the interservice time is exponentially distributed, moreover, the busy-line effect is not considered. In general, this assumption is not valid, which was also observed in the same paper. The difficulty in carrying out the same cost analysis for general situation lies in the lack of analytical result for the probability of the number of RA crossings under general interservice time. As long as we find the computational procedure for the probability of the number of RA crossings, the same cost analysis in [13] can be carried out in a similar fashion. We also observe that the probability distribution of RA crossings is also signifying the portable movements in PCS networks.

In this paper, under the assumptions that the interservice times and the RA residence times are generally distributed, we derive some analytical results for the probability of the number of RA crossings. The results presented in this paper are very useful for cost analysis in finding a best tradeoff between location updating and paging for tracking mobile users in PCS networks.

II. Probability of the Number of RA Crossings

In this section, we study the patterns of the incoming calls and the portable movement. Assume that the incoming calls to a portable form a Poisson process, the time the portable stays in an RA (called the RA residence time) has a general distribution. We will derive the probability $\alpha(K)$ that a portable moves across K RAs between two phone calls. The time between the start of a call served and the start of the following call served by the portable is called the interservice time. The interservice time is of interest because it can be used to characterize the mobility of the portable. It is possible that a new call arrives while

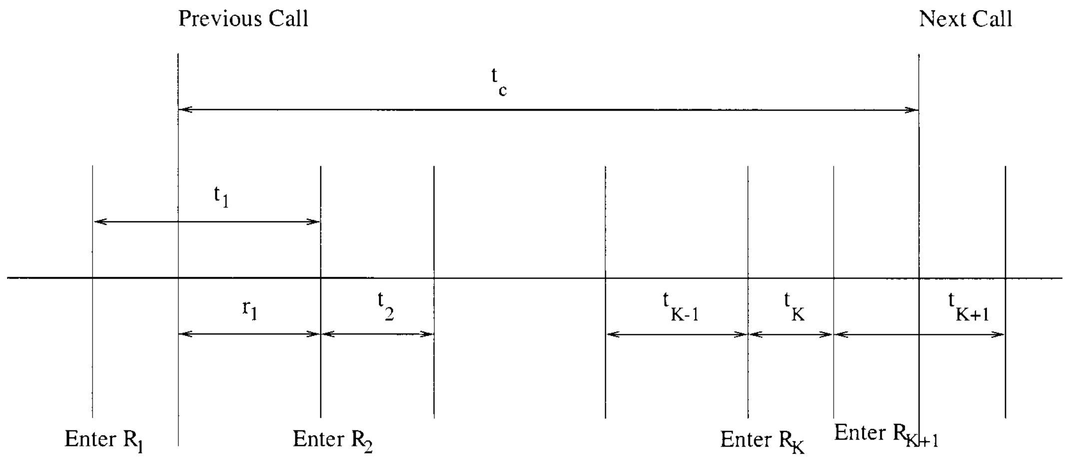

Fig. 1. The time diagram for K RA crossings.

the previous call served is still in progress [13]. In this case, the portable cannot initiate/accept the new call. In this analysis, we ignore call waiting service, and this new call is rejected. Thus, the interarrival (inter-call) times are different from the interservice times. This phenomenon is called the *busy line* effect. Although the incoming calls form a Poisson process (i.e., the interarrival times are exponentially distributed), the interservice times may not be exponentially distributed. By ignoring the busy line effect, Lin [13] is able to give analysis for the model. In this section, we assume that the interservice times are generally distributed and derive an analytic expression for $\alpha(K)$.

Before we give the analytical result for $\alpha(K)$ we first demonstrate the use of $\alpha(K)$ in cost analysis. We take the IS-41 system for illustration purpose. In IS-41, each RA crossing incurs at least one signaling message, i.e., the registration message. The signaling cost for atypical call will be directly proportional to the average number of signaling message, which can be found from the following formula:

$$n_{\text{IS-41}} = \sum_{K=0}^{\infty} K\alpha(K).$$

Thus, we have to find the probability distribution $\alpha(K)$. In [13], simple formula can be found for $n_{\text{IS-41}}$ [and other quantities which are functions of $\alpha(K)$] under the exponential assumption on the interservice time. However, when the interservice time is not exponentially distributed, which is the case in practice, we must found viable computational procedure to calculate $\alpha(K)$. This is the motivation of the current paper. Next, we present an analytical result for $\alpha(K)$.

Let $t_1, t_2, \cdots, t_{K+1}$ denote the RA residence times and r_1 denote the residual life of the previous call served in the initiating RA (i.e., the time interval between when the call is served and when the portable exits the RA). Let t_c denote the interservice time between two consecutive served calls to a portable P (i.e., the time interval between the instant the previous call is served and the instant the next call is served). Notice that the consecutive served calls may not be necessarily the consecutive arriving calls because some calls may be blocked when the portable is busy. This implies that the interservice time is different from the interarrival time. Fig. 1 shows the time diagram for K RA crossings. Suppose that the portable is in an RA R_1 when the previous call arrives and is served, it then moves K RA's during the interservice time, and P resides in the jth RA for a period t_j $(1 \leq j \leq K+1)$. Let $t_1, t_2, \cdots$ be independent and identically distributed (iid) with a general density function $f(t)$, let t_c be generally distributed with density function $f_c(t)$, and let $f_r(t)$ be the density function of r_1. Let $f^*(s)$, $f_c^*(s)$ and $f_r^*(s)$ be the 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 random observer property [10], we have

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

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

$$\alpha(0) = \Pr[t_c \leq r_1], \qquad K = 0 \tag{2}$$

$$\alpha(K) = \Pr[r_1 + t_2 + \cdots + t_K \;<\; t_c \leq r_1 + t_2 + \cdots + t_{K+1}] \quad K \geq 1. \tag{3}$$

We first calculate $\alpha(0)$. Since the Laplace transform of $\int_t^{\infty} f_r(\tau)\, d\tau$ is $(1 - f_r^*(s))/s$, from (2), the inverse Laplace transform and the independence of r_1 and t_c, we have

$$\begin{aligned}\alpha(0) &= \int_0^{\infty} \Pr(r_1 \geq t) f_c(t)\, dt \\ &= \int_0^{\infty} \int_t^{\infty} f_r(\tau)\, d\tau f_c(t)\, dt \\ &= \int_0^{\infty} \frac{1}{2\pi j} \int_{\sigma - j\infty}^{\sigma + j\infty} \frac{1 - f_r^*(s)}{s}\, e^{st}\, ds\, f_c(t)\, dt \\ &= \frac{1}{2\pi j} \int_{\sigma - j\infty}^{\sigma + j\infty} \frac{1 - f_r^*(s)}{s} \int_0^{\infty} f_c(t) e^{st}\, dt\, ds \\ &= \frac{1}{2\pi j} \int_{\sigma - j\infty}^{\sigma + j\infty} \frac{1 - f_r^*(s)}{s}\, f_c^*(-s)\, ds \\ &= \frac{1}{2\pi j} \int_{\sigma - j\infty}^{\sigma + j\infty} \frac{s - \lambda_m(1 - f^*(s))}{s^2}\, f_c^*(-s)\, ds \end{aligned} \tag{4}$$

where σ is a sufficiently small positive number which is appropriately chosen for inverse Laplace transform. We want to remark that the choice of such σ is possible for the validity of the inverse Laplace transformation. Recall that for any density function, the Laplace transform is always analytic on the right half complex plane. Thus, if $f_c^*(s)$ has finite number of isolated poles (which is the case when it is a rational function), then $f_c^*(-s)$ will have finite number of isolated poles in the open right half complex plane, then we can choose σ to be less than the smallest of real parts of the poles of $f_c^*(-s)$. In this case, when we apply the Residue Theorem, we can use the semi-circle in the right half complex plane as the integration contour.

For $K > 0$, $\alpha(K)$ is computed as follows. First, we need to compute Pr$(r_1 + t_2 + \cdots + t_k \le t_c)$ for any $k > 0$. Let $\xi = r_1+t_2+\cdots+t_k$. Let $f_\xi(t)$ and $f_\xi^*(s)$ be the density function and the Laplace transform of ξ. From the independence of r_1, $t_2, t_3, \cdots$, we have

$$\begin{aligned} f_\xi^*(s) &= E[e^{-s\xi}] = E[e^{-sr_1}] \prod_{i=2}^{k} E[e^{-st_i}] \\ &= f_r^*(s)\,(f^*(s))^{k-1}. \end{aligned}$$

Thus, the density function is given by

$$f_\xi(t) = \frac{1}{2\pi j} \int_{\sigma-j\infty}^{\sigma+j\infty} f_r^*(s)\,(f^*(s))^{k-1} e^{st}\, ds.$$

Also, the Laplace transform of Pr$(\xi \le t)$ (the distribution function) is $f_\xi^*(s)/s$. We have

$$\begin{aligned} &\text{Pr}(r_1 + t_2 + \cdots + t_k \le t_c) \\ &\quad = \int_0^\infty \text{Pr}(\xi \le t) f_c(t)\, dt \\ &\quad = \int_0^\infty \frac{1}{2\pi j} \int_{\sigma-j\infty}^{\sigma+j\infty} \frac{f_r^*(s)\,[f^*(s)]^{k-1}}{s} e^{st}\, ds\, f_c(t)\, dt \\ &\quad = \frac{1}{2\pi j} \int_{\sigma-j\infty}^{\sigma+j\infty} \frac{f_r^*(s)\,[f^*(s)]^{k-1}}{s} f_c^*(-s)\, ds. \end{aligned}$$

Taking this into (3), we obtain

$$\begin{aligned} \alpha(K) =& \text{Pr}(t_c \ge r_1 + t_2 + \cdots + t_K) \\ &- \text{Pr}(t_c \ge r_1 + t_2 + \cdots + t_{K+1}) \\ =& \frac{1}{2\pi j} \int_{\sigma-j\infty}^{\sigma+j\infty} \frac{f_r^*(s)\,[f^*(s)]^{K-1}[1-f^*(s)]}{s} f_c^*(-s) ds \\ =& \frac{1}{2\pi j} \int_{\sigma-j\infty}^{\sigma+j\infty} \frac{\lambda_m [f^*(s)]^{K-1}[1-f^*(s)]^2}{s^2} f_c^*(-s)\, ds. \end{aligned} \tag{5}$$

It is obvious that the integrand without term $f_c^*(-s)$ in (4) and (5) is analytic on the right half open complex plane. If $f_c^*(-s)$ has no branch point and has only finite possible isolated poles in the right half plane (which is equivalent to saying that $f_c^*(s)$ has only finite number of isolated poles in the left half plane), then the Residue Theorem can be applied to (4) and (5) using a semi-circular contour in the right half plane. Indeed, if we use σ_c to denote the set of poles of $f_c^*(-s)$ in the right half complex plane, then from (4) and (5), and the Residue Theorem [12], we obtain the following.

Theorem 1: If the density function of interservice 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 portable moves across K RA's is given by

$$\begin{aligned} \alpha(0) &= -\sum_{p\in\sigma_c} \operatorname*{Res}_{s=p} \frac{s - \lambda_m(1-f^*(s))}{s^2} f_c^*(-s) \\ \alpha(K) &= -\sum_{p\in\sigma_c} \operatorname*{Res}_{s=p} \frac{\lambda_m(1-f^*(s))^2[f^*(s)]^{K-1}}{s^2} f_c^*(-s) \\ K &> 0 \end{aligned} \tag{6}$$

where $\text{Res}_{s=p}$ denotes the residue at poles $s = p$.

Proof: Choosing such σ that all poles of $f_c^*(-s)$ in the right half plane are on the right of vertical line $s = \sigma$, and choosing the contour enclosed by the semi-circle at center $s = \sigma + j0$ and with radius sufficiently large, then we can apply the Residue Theorem to complete the proof.

If the interservice times are exponentially distributed with parameter λ_c, then $f_c^*(-s) = \lambda_c/(-s+\lambda_c)$, which has a unique pole, and $\sigma_c = \{\lambda_c\}$. From Theorem 1, we can easily obtain

$$\begin{aligned} \alpha(0) &= 1 - \frac{1 - f^*(\lambda_c)}{\rho} \\ \alpha(K) &= \frac{1}{\rho} [1 - f^*(\lambda_c)]^2 [f^*(\lambda_c)]^{K-1}, \qquad K > 0 \end{aligned}$$

where $\rho = \lambda_c/\lambda_m$ is the *call-to-mobility ratio*. These equations have been obtained in [13] using a different approach.

One general distribution which is used often in many applications is the Gamma distribution [2] whose density function and its Laplace transform are given as follows:

$$f(t) = \frac{\alpha^\gamma t^{\gamma-1}}{\Gamma(\gamma)} e^{-\alpha t}, \quad f^*(s) = \left(\frac{\alpha}{s+\alpha}\right)^\gamma, \qquad \gamma > 0 \tag{7}$$

where γ is the shape parameter, $\alpha = \gamma\mu$ is the scale parameter, and $\Gamma(\gamma)$ is the Gamma function. When $\gamma = m$ is a positive integer, the Gamma becomes the Erlang distribution

$$f(t) = \frac{\alpha^m t^{m-1}}{(m-1)!} e^{-\alpha t}, \quad f^*(s) = \left(\frac{\alpha}{s+\alpha}\right)^m \tag{8}$$

where $\alpha = m\mu$. The gamma distribution applies to many applications. When $\gamma = 1$, it becomes the exponential distribution; When γ is sufficiently large, the distribution is asymptotically normal around μ [2].

Let us assume that the interservice times are iid with Erlang distribution as in (8), since its mean is $1/\mu$, hence we have $\mu = \lambda_c$, hence

$$f_c^*(-s) = \left(\frac{m\lambda_c}{-s + m\lambda_c}\right)^m.$$

Let

$$g_0 = \frac{s - \lambda_m[1 - f^*(s)]}{s^2} \tag{9}$$

$$g_K = \frac{\lambda_m[1 - f^*(s)]^2[f^*(s)]^{K-1}}{s^2}. \tag{10}$$

From Theorem 1, we can easily obtain

$$\alpha(0) = \frac{(-1)^{m+1}(m\lambda_c)^m}{(m-1)!}\, g_0^{(m-1)}(m\lambda_c) \tag{11}$$

$$\alpha(K) = \frac{(-1)^{m+1}(m\lambda_c)^m}{(m-1)!}\, g_K^{(m-1)}(m\lambda_c) \tag{12}$$

where $x^{(r)}(t)$ denotes the rth derivative of function $x(t)$.

In order to compute those quantities in (11) and (12), we need to find the $(m-1)$th derivative of certain functions, which may be complicated in general. Fortunately, we can have some recursive algorithms to compute them. We need the following identity:

$$(uv)^{(r)} = \sum_{i=0}^{r} \binom{r}{i} u^{(i)} v^{(r-i)}. \tag{13}$$

For fixed m, let $\alpha = m\lambda_c$. To compute $g_0^{(m-1)}(\alpha)$, we can use the following (applying (13) with $u = s - \lambda_m[1 - f^*(s)]$ and $1/s^2$)

$$g_0^{(0)}(\alpha) = \frac{\alpha - \lambda_m[1 - f^*(\alpha)]}{\alpha^2}$$
$$g_0^{(1)}(\alpha) = \frac{1 + \lambda_m f^{*(1)}(\alpha) - 2\alpha g_0^{(0)}(\alpha)}{\alpha^2}$$
$$g_0^{(r)}(\alpha) = \frac{\lambda_m f^{*(r)} - 2r\alpha g_0^{(r-1)}(\alpha) - r(r-1) g_0^{(r-2)}(\alpha)}{\alpha^2}$$
$$r = 2, 3, \cdots, m-1.$$

To compute $g_K^{(m-1)}(\alpha)$, we use (applying (13) with $u = \lambda_m[1 - f^*(s)]^2[f^*(s)]^{K-1}$ and $1/s^2$)

$$g_K^{(0)}(\alpha) = \frac{\lambda_m[h_{K-1}(\alpha) - 2h_K(\alpha) + h_{K+1}(\alpha)]}{\alpha^2}$$
$$g_K^{(1)}(\alpha) = \frac{\lambda_m[h_{K-1}^{(1)}(\alpha) - 2h_K^{(1)}(\alpha) + h_{K+1}^{(1)}(\alpha)] - 2\alpha g_K^{(0)}(\alpha)}{\alpha^2}$$

(see equation at the bottom of the page) where $h_K(s) = [f^*(s)]^K$.

It is known [9] that the weighted summation of Erlang distributions (the hyper-Erlang distributions) can approximate any distribution. For the cases when the interservice time t_c is distributed according to the weighted summation of Erlang distribution, using Theorem 1, we can also find simple analytical results. It has been shown [20] that the SOHYP (the sum of hyper-exponential distributions) is also a very general distribution to model the LA residence time (i.e., the dwell time), we observe that Theorem 1 is also applicable when the LA residence time is SOHYP distributed. In fact, as along as the Laplace transform of the density function of the interservice time t_c is rational function, our results can be applied to find the probability $\alpha(K)$.

III. Busy-Line Effect

As we mentioned earlier, the busy-line effect is the phenomenon when a new call to the portable arrives it finds the portable is busy, and hence it is rejected. In Lin [13], this effect is neglected for the purpose of analysis. Next, we show that our results can conveniently be used to study this effect.

As before, assume that the call arrivals to the portable form a Poisson process, i.e., the inter-call times are independent and exponentially distributed. Let p be the probability that a call to the portable finds the portable busy (i.e., busy-line). This probability will depend on the call arrival traffic and call holding times. In this analysis, we will use this probability to represent the total effect of call arrival traffic and call holding times. Let $E(t; m, \mu)$ denote the density function of Erlang distribution with shape parameter m and scale parameter $m\mu$ [see (8)]. It is well known [10] that this Erlang distribution is the distribution of the summation of m independent exponential distribution with parameter μ. A call to the portable finds the portable busy with probability p and finds the portable free and is served immediately with probability $1-p$, hence the conditional probability density function of the interservice time when $k-1$ calls find the portable busy while the kth call finds the portable free is given by

$$p^{k-1}(1-p)E(t; k, \mu/k).$$

Hence the probability density function of the interservice time is given by

$$f_c(t) = \sum_{k=1}^{\infty} p^{k-1}(1-p)E(t; m, \mu/k)$$
$$f_c^*(s) = \sum_{k=1}^{\infty} p^{k-1}(1-p)\left(\frac{\mu}{s+\mu}\right)^k. \tag{14}$$

Applying Theorem 1 with $\mu = \lambda_c$, (11) and (12), we obtain the following result.

Theorem 2: If p is the probability of busy-line, then

$$\alpha(0) = (1-p)\sum_{k=1}^{\infty} p^{k-1}\frac{(-1)^{k+1}\lambda_c^k}{(k-1)!}\, g_0^{(k-1)}(\lambda_c)$$
$$\alpha(K) = (1-p)\sum_{k=1}^{\infty} p^{k-1}\frac{(-1)^{k+1}\lambda_c^k}{(k-1)!}\, g_K^{(k-1)}(\lambda_c). \tag{15}$$

Notice that when the busy line effect is neglected, i.e., $p = 0$, Theorem 2 reduces to the case when the interservice time is exponentially distributed. We can not find simpler forms for the above formulae, however, the above formulae provide starting point for approximation. Considering that p is usually quite small, we can use finite number of terms in (15) for approximation.

$$g_K^{(r)}(\alpha) = \frac{\lambda_m[h_{K-1}^{(r)}(\alpha) - 2h_K^{(r)}(\alpha) + h_{K+1}^{(r)}(\alpha)] - 2r\alpha g_K^{(r-1)}(\alpha) - r(r-1)g_K^{(r-2)}(\alpha)}{\alpha^2}, \qquad r > 1$$

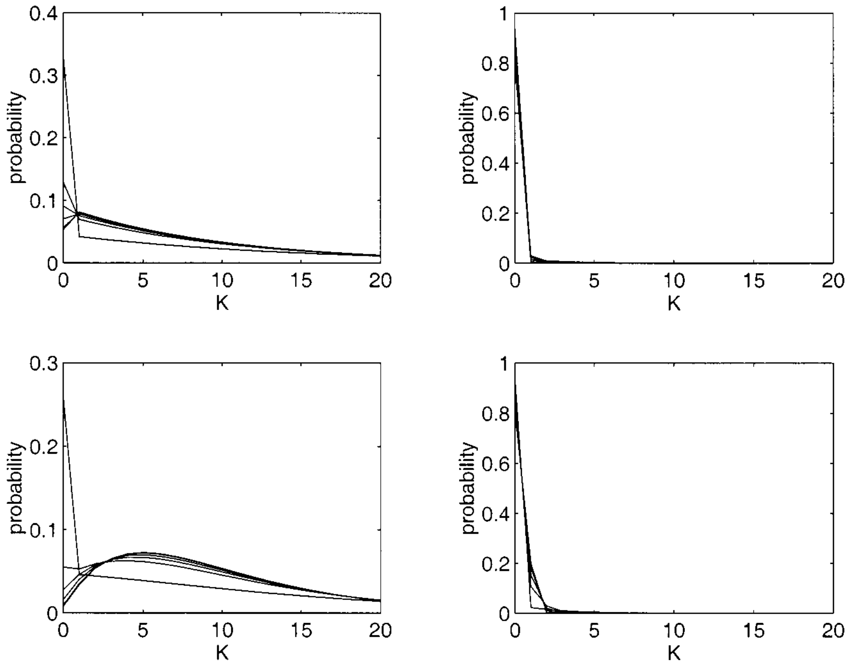

Fig. 2. Probability $\alpha(K)$: (a) and (b) for the cases when the interservice time is exponentially distributed and RA residence time is Gamma distributed; (c) and (d) for the case when the interservice time is Erlang distributed and RA residence time is Gamma distributed; γ = 0.1, 0.5, 1, 2, 6, 10, m = 2.

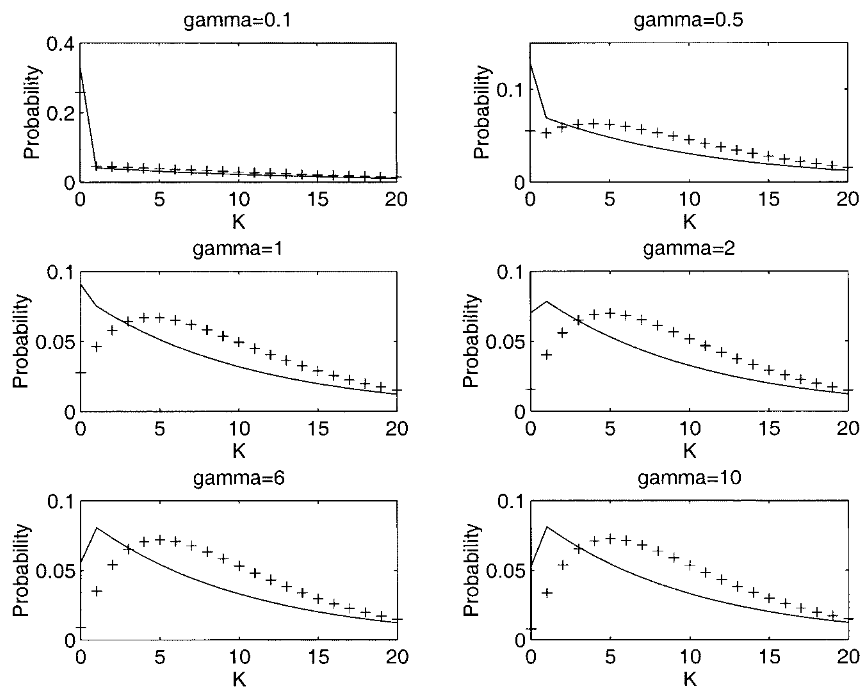

Fig. 3. Comparison of probability $\alpha(K)$ when the interservice time is exponentially distributed (solid line) and Erlang distributed (dashed line): call-to-mobility ratio is small (<1), m = 2.

IV. Discussions and Comments

In this section, we present a few examples to discuss our results. We assume that the interservice time t_c is Erlang distributed and the RA residence times t_i are Gamma distributed. Let t_c have the following Erlang density

$$f_c(t) = \frac{(m\lambda_c)^m t^{m-1}}{(m-1)!} e^{-mt}$$

whose mean is $1/\lambda_c$ and variance is $V(m) = 1/(m\lambda_c^2)$. When $m = 1$, it becomes the exponential distribution. Let t_i have the Gamma density function

$$f(t) = \frac{(\gamma\lambda_m)^\gamma t^{\gamma-1}}{\Gamma(\gamma)} e^{-\gamma\lambda_m t}$$

whose mean is $1/\lambda_m$ and variance is $V(\gamma) = 1/(\gamma\lambda_m^2)$. By varying value of m, we vary the variance of the interservice

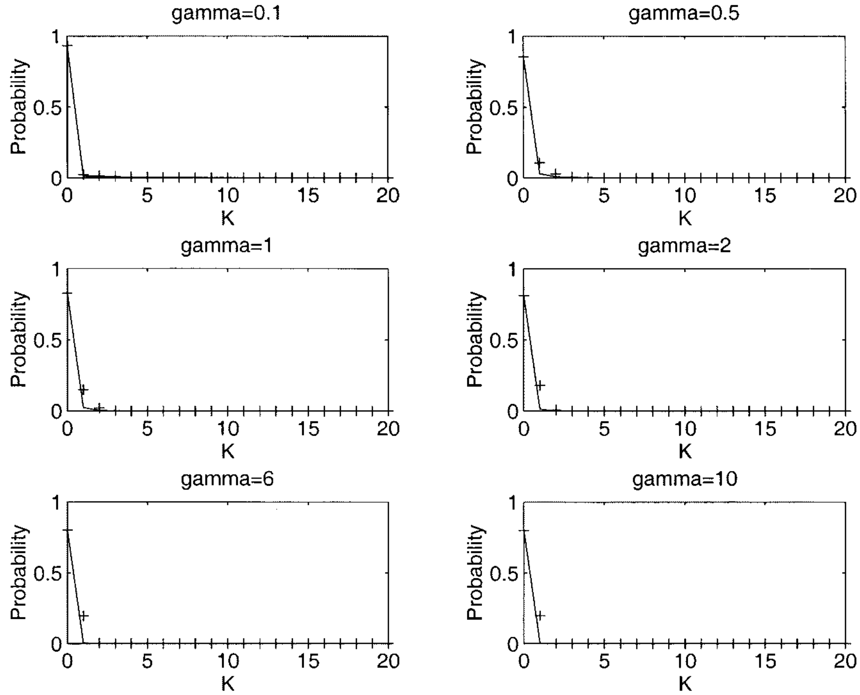

Fig. 4. Comparison of probability $\alpha(K)$ when the interservice time is exponentially distributed (solid line) and Erlang distributed (dashed line): call-to-mobility ratio is large (>1), m = 2.

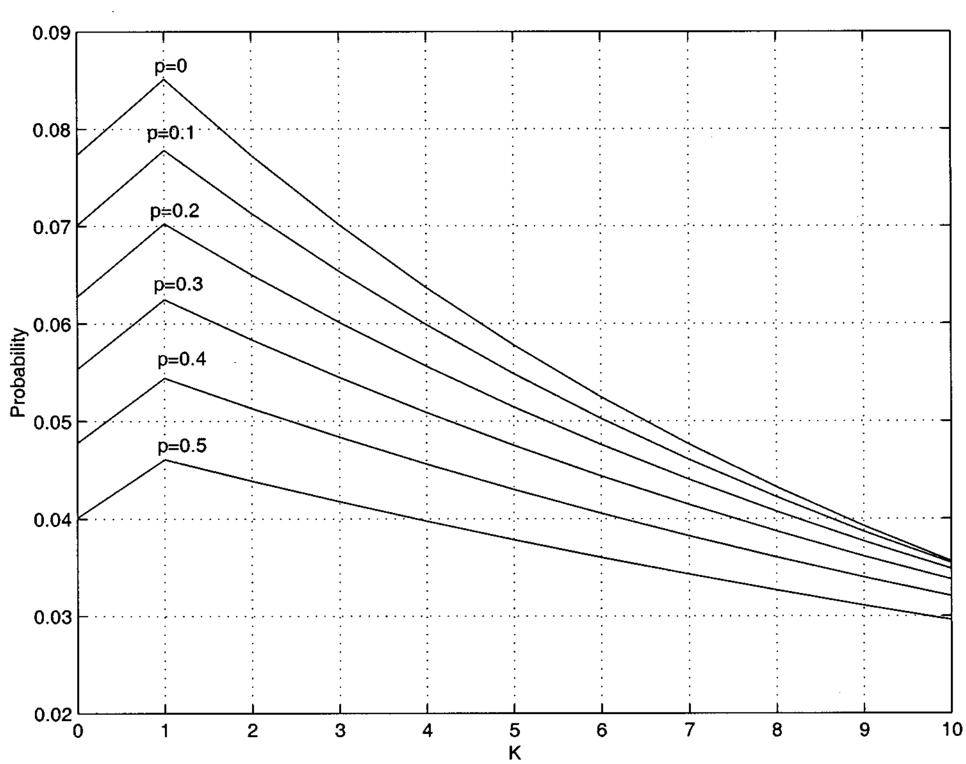

Fig. 5. Busy-line effect on the probability $\alpha(K)$ of K RA crossing, γ = 1.5.

time, in the same token, varying γ is equivalent to varying the variance of RA residence time. We study the effects on $\alpha(K)$ when the variances of the interservice time and the RA residence time vary.

Fig. 2 shows the probability $\alpha(K)$ when the RA residence time is Gamma distributed with various values of variance while the interservice time is exponentially distributed and Erlang distributed, respectively. It can be easily observed that when the variance of the RA residence time has significant effect on the probability $\alpha(K)$ for small K when call-to-mobility is small $(\rho < 1)$, and that hardly has any effect on the probability $\alpha(K)$ when call-to-mobility is large $(\rho > 1)$. The Erlang $(m = 2)$

distributed interservice time has more significant effect on the probability $\alpha(K)$ than the exponentially distributed interservice time does. The above observations are clearly shown in Figs. 3 and 4.

Next, we illustrate the busy-line effect. Fig. 5 shows the busy-line effect on the probability $\alpha(K)$ of K RA crossings where the call arrivals are Poissonian and the RA residence times are Gamma distributed. It is shown that as the probability p of busy-line effect increases, the probability $\alpha(K)$ with fewer RA crossings K is decreasing while that with higher RA crossings K is increasing. This is intuitive because for fixed call arrival process a larger probability of busy-line effect represents a longer interservice time, hence more RA crossings.

V. Conclusion

In this paper, we propose a new model for the portable movement in PCS networks. Previous work [13] investigated this issue by ignoring the busy-line effect. We relax this restriction by accommodating interservice times with general distribution. We apply the Residue Theorem to obtain analytical results for the probability of number of the RA crossings. Our new model can be applied to investigate the impact on busy-line effect on many location tracking strategies [13], [14], [21].

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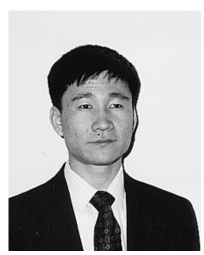

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