Modeling and Performance Analysis for Wireless Mobile Networks: A New Analytical Approach

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***Abstract*—In wireless mobile networks, quantities such as call blocking probability, call dropping probability, handoff probability, handoff rate, and the actual call holding times for both complete and incomplete calls are very important performance parameters in the network performance evaluation and design. In the past, their analytical computations are given only when the classical exponential assumptions for all involved time variables are imposed. In this paper, we relax the exponential assumptions for the involved time variables and, under independence assumption on the cell residence times, derive analytical formulae for these parameters using a novel unifying analytical approach. It turns out that the computation of many performance parameters is boiled down to computing a certain type of probability, and the obtained analytical results can be easily applied when the Laplace transform of probability density function of call holding time is a rational function. Thus, easily computable results can be obtained when the call holding time is distributed with the mixed-Erlang distribution, a distribution model having universal approximation capability. More importantly, this paper develops a new analytical approach to performance evaluation for wireless networks and mobile computing systems.**

***Index Terms*—Call blocking probability, call dropping probability, handoff probability, handoff rate, mobile computing, PCS, wireless cellular networks.**

NOMENCLATURE

t_c	Call holding time.
t_i	Cell residence time.
r	Residual cell residence time.
H	Number of handoffs in the life of a call.
$f(t), f^*(s)$	Probability density function and its Laplace transform of t_i.
$f_r(t)$, $f_r^*(s)$	Probability density function and its Laplace transform of r.
$f_c(t), f_c^*(s)$	Probability density function and its Laplace transform of t_c.
$f_k(t)$, $f_k^*(s)$	Probability density function and its Laplace transform of $r + t_2 + \cdots + t_k$.
$g_c(t), g_c^*(z)$	Probability density function and its Laplace transform of actual call holding time for a complete call.
$g_d(t), g_d^*(z)$	Probability density function and its Laplace transform of actual call holding time for an incomplete call.
T_c	Average actual call holding time for a complete call.
T_d	Average actual call holding time for an incomplete call.
λ	New call arrival rate.
λ_h	Handoff call arrival rate or handoff traffic arrival rate.
μ	Average call holding time.
η	Average cell residence time.
p_o	Call blocking probability.
p_f	Handoff blocking probability or forced termination probability.
p_c	Call completion probability.
p_d	Call dropping probability.
P_n	Handoff probability for a new call.
$P_h(k)$	Handoff probability for a call after kth handoff.
$\mathrm{Res}_{s=p}$	Residue operator at pole $s = p$.
σ_p	Set of poles of $f_c^*(-s)$.
$\mathcal{D}_\sigma$	$= \{s \mid \Re(s) \geq \sigma\}$ where $\Re$ indicates the real part.

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I. INTRODUCTION

WIRELESS networks and mobile computing systems have evolved into one of the most exciting areas in telecommunications industries [6], [9], [32], [36]. Future wireless networks will support a wide variety of services such as voice, data, and image/audio/video to the users on the move. Mobile customers can make a phone call as in wired telephony or make an Internet connection to retrieve information messages such as emails or stock quotes, to surf the Internet, or to do business over the Internet (electronic commerce over the air or m-commerce) while listening to one's favorite music online. To achieve this goal, wireless networks will have to be designed with desired quality-of-service (QoS) requirements.

In a wireless mobile network, call blocking probability and handoff blocking probability are most important QoS parameters. Usually, these two parameters are specified in the design. For example, in second-generation cellular systems, the call blocking probability is lower than 5% while the handoff blocking probability is lower than 2% for voice service. For the third-generation networks and networks, where data or multimedia services are dominant, these two blocking probabilities can be used to characterize the quality of call connections, which are then used for the general quality of service characterization. To evaluate the performance of a wireless network, the following performance metrics are of great importance: call dropping probability, handoff probability, handoff rate, and the actual call holding times for a complete call and an incomplete call (a call which is prematurely terminated due to the lack of resource when it roams). Call dropping probability, the probability that a call is immaturely terminated due to lack of resources (channels) in the network, is closely related to handoff blocking probability. The handoff rate is used to find the handoff traffic arrival rate, which is needed to find the call blocking probability and handoff blocking probability [14], [15]. The handoff probability can be used to design channel reservation schemes, and the actual call holding times can be used to design service charging rate or devise a reasonable billing plan [17], [27]. In the study of these quantities for the traditional cellular networks and PCS networks, the following assumptions are commonly used in order to obtain some analytical results: the interarrival time of cell traffic, the call holding time, and the channel holding time are all assumed to be exponentially distributed [11], [18], [19], [41] (for the convenience of our discussion, we call these assumptions the *classical assumptions*). However, field data and simulation study showed that these classical assumptions are not appropriate. In [3], [18], and [22]–[24], it has been shown that the channel holding time is not exponentially distributed for many wireless and cellular systems. In [15], under certain assumptions, we showed that channel holding time is exponentially distributed if and only if the cell residence time is exponentially distributed, where the cell residence time is the time a mobile user stays in a typical cell. The study for common-channel signaling (CCS) networks [5] demonstrated that the call holding time cannot be accurately modeled by exponential distribution and showed that the mixed-type probability distribution model is much more appropriate. In [34], the authors showed that the cell traffic is smooth (which implies that the interarrival times for the cell traffic cannot be modeled by Poisson process). Furthermore, the call holding time distribution will vary with the new applications (call holding times for data users may be significantly different from those for voice users), the interarrival time of cell traffic (a part of which is the handoff call traffic), and the channel holding times will depend on the mobility of the customers, the geographic situations, and the channel allocation schemes used; therefore, the classical assumptions will most likely fail, and more general distribution models for the time variables may be needed.

The salient feature in wireless mobile networks is the mobility, which complicates all design and analysis [7], [39]. In order to bring the mobility into the picture of performance evaluation of wireless networks, we have to quantify the mobility factors in the modeling. In most wireless network performance study, we often focus on the homogeneous wireless networks: all cells in the networks are statistically identical in terms of resource dimensioning and network traffic, thus the network performance evaluation can be reduced to the study of one single cell, where a queueing model for the cell can be used to find the aforementioned performance metrics such as call blocking probability and handoff blocking probability (the probability that a handoff call is blocked, also called the forced termination probability) [19]. A careful observation shows that in the homogeneous wireless networks, we can model the cell as the following queueing system (Fig. 1). In this model,

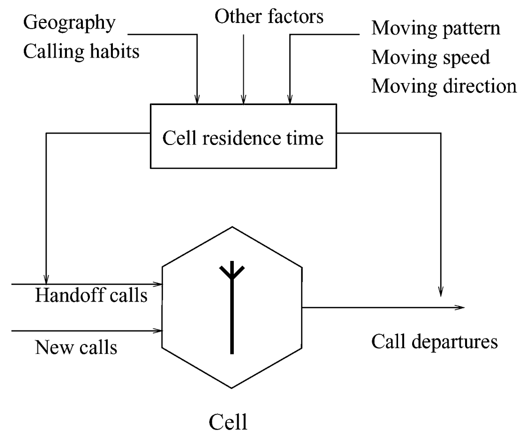

Fig. 1. Queueing model for a typical cell.

the cell traffic consists of two traffic streams: new calls and handoff calls, the channel holding time is determined by the cell residence time and the call holding time, and both the handoff traffic and channel holding time are determined by the cell residence time. Since, in homogeneous networks, each departed call, if not finished, will be handed off to the next cell with equal probability ($1/6$ if hexagonal cell layout is used for analysis), the users' mobility is completely characterized by the cell residence time (i.e., the mobility model is characterized by a semi-Markov process). The cell residence time is determined by the geography, mobile moving speed, and direction (or other factors such as fading) [39]. In many studies, the cell residence time distribution has been derived based on some assumption on the cell shape, moving speed, and moving direction, mostly following the classical work by Hong and Rappaport [19]. Xie and Goodman [39] compared three mobility models and pointed out that the probability density function (pdf) of terminal speeds should be characterized by the biased sampling formula. In this paper, we adopt a different approach: we use a general probability distribution to directly model the cell residence time. In this way, we can embed all mobility factors into the cell residence time distribution. In fact, we can regard our modeling as the second phase of the two-phase modeling: the first phase is to derive the cell residence time distribution from mobiles' movement characteristics and cell shape, and the second phase studies the effect of such distribution on the performance metrics. What we need now is to find an appropriate distribution model for cell residence time (mobility) and call holding time.

Distribution models, such as the exponential distribution, the lognormal distribution, the Erlang distribution, and the (generalized) Gamma distribution have been used to approximate the distributions of the channel holding times in the past [14]–[17], [22], [29], [30], [42]. It is well known that exponential distribution can be used for one-parameter approximation of the measured data, while the Gamma distribution can be used for two-parameter approximation. Although the exponential and Erlang distribution models have simple good properties for queueing analysis, however, they are not general enough to fit the field data. The (generalized) Gamma and log-normal distributions are more general, however, application of these model will lead to the loss of the Markov property required in the queueing analysis [25]. Recently, two new models are proposed for the mobility modeling for wireless and cellular networks. One is the so-called Sum of Hyper-exponential (SOHYP) model [33], which has been used to model the channel holding time for cellular systems with mixed platforms and various mobility. The other model, called the *Hyper-Erlang* model [14] (we will call it mixed-Erlang distribution more appropriately in this paper), is used to model the cell residence time for PCS networks and mobile computing systems. It has been demonstrated that the mixed-Erlang models and SOHYP models can approximate any distribution of nonnegative random variables [1], [14], [33]. Notice that the Laplace transforms of the SOHYP models and the mixed-Erlang model are rational functions. More importantly, applying the distribution models with rational Laplace transforms results in the preservation of the Markov property required for analytical queueing analysis. Hence, we can use these two models to model the call holding time and the cell residence time for the performance evaluation.

In this paper, we relax the classical exponential assumption for the call holding time and cell residence time and develop an analytical approach for the study of the following performance metrics: call dropping probability, handoff probability, handoff rate, and the actual call holding times for a complete call and an incomplete call. It turns out that many interesting performance quantities including the aforementioned performance metrics can be derived in a unifying approach: they can be completely determined by a single probability result. We will present analytical formulas for the above performance metrics for the cases when the Laplace transforms of pdfs of call holding time and cell residence time are rational functions. These results will lead to some simple computational algorithms for the SOHYP models and mixed-Erlang models.

As a final remark, we want to point out that, although we have relaxed the assumptions on the distribution models for some time variables such as cell residence time in this paper, we still impose the independence assumption on the cell residence time [i.e., we assume that cell residence times are independent and identically distributed (i.i.d.)]. This assumption is indeed valid under some mobility models. For example, the Hong and Rappaport Model ([19] or model B in [39]) will give the i.i.d. cell residence time because the moving speed and moving direction are independently generated whenever a mobile crosses a cell boundary. However, for some other mobility models (such as Model A and Model C in [39]), the cell residence times may be dependent, which may pose a serious challenge in obtaining analytical results. For example, what is the dependence relationship among the cell residence times? How does the dependence relationship affect the analytical performance metrics? We will investigate these issues in the future.

II. Preliminaries

In this section, we present some preliminary results which will be frequently used in the subsequent development.

Many analytical results for the evaluation of wireless network performance are boiled down to the calculation of the following type of probability $\Pr(\xi_1 \leq \xi_2)$ for random variables ξ_1 and ξ_2. This probability can be further reduced to the computation of the following integral:

$$C = \frac{A}{2\pi j}\int_{\sigma-j\infty}^{\sigma+j\infty} X(s)Y(-s)\,ds \tag{1}$$

where A is a constant, and $X(s)$ and $Y(s)$ are analytic over the set $\mathcal{D}_\sigma = \{s \,|\, \Re(s) \geq \sigma\}$ in the complex plane ($\Re$ denotes the real part of a complex number). If $X(s)$ and $Y(s)$ are known, then the techniques used to find the inverse Laplace transforms [28] can be used to find C. In particular, if $X(s)$ and $Y(s)$ are rational functions in s, then the well-known Residue Theorem [28] can be applied to find C, in which case, the partial fractional expansion technique [25], [28] can be used to obtain easily computable formula. Let σ_p denote the poles of $Y(-s)$ and let $\mathrm{Res}_{s=p}$ denote the residue at pole $s = p$. Then we can easily obtain the following.

Fact 1: If $X(s)$ and $Y(s)$ are proper rational functions and σ_p is the set of poles of $Y(-s)$, then we have

$$\begin{aligned} C &= \frac{A}{2\pi j}\int_{\sigma-j\infty}^{\sigma+j\infty} X(s)Y(-s)\,ds \\ &= -A\sum_{p\in\sigma_p} \operatorname*{Res}_{s=p}[X(s)Y(-s)]. \end{aligned} \tag{2}$$

The mixed-Erlang distributions and SOHYP distributions all have rational Laplace transforms, hence Fact 1 can be applied when $X(s)$ and $Y(s)$ are mixed-Erlang distributions and SOHYP distributions. Since the mixed-Erlang distributions are the simplest among many distributions, we will focus on the mixed-Erlang distributions.

The *mixed-Erlang* distribution has the following pdf and the corresponding Laplace transform:

$$\begin{aligned} f_{me}(t) &= \sum_{i=1}^{M} \alpha_i \frac{(m_i\eta_i)^{m_i} t^{m_i-1}}{(m_i-1)!} e^{-m_i\eta_i t} (t \geq 0), \\ f_{me}^*(s) &= \sum_{i=1}^{M} \alpha_i \left(\frac{m_i\eta_i}{s+m_i\eta_i}\right)^{m_i} \end{aligned} \tag{3}$$

where

$$\alpha_i \geq 0, \quad \sum_{i=1}^{M} \alpha_i = 1$$

and $M, m_1, m_2, \ldots, m_M$ are nonnegative integers, $\eta_1, \eta_2, \ldots, \eta_M$ are positive numbers, and mixed-Erlang distribution models contain the exponential distribution, the Erlang distribution, and the hyper-exponential distribution as special cases. This distribution has been used in queueing systems and stochastic modeling in the past [26], [38]. It has been shown (see [1]) that any distribution of a nonnegative random variable can be approximated by the mixed-Erlang distributions. In [1], a rigorous proof of the universal approximation capability of mixed-Erlang distributions is given, and statistical fitting methods have been proposed. In [14], a physical interpretation of the mixed-Erlang approximation from the point of the Sampling Theorem has been provided. In [38], the two-term mixed Erlang distribution (called generalized Erlangian distribution) is shown to have various coefficient-of-variation (CoV) values and is easier to work with than the Gamma distribution.

If $Y(s)$ is the Laplace transform of the mixed-Erlang distribution in (3), applying Fact 1, we can easily obtain the following corollary.

Corollary 1: Assume that $X(s)$ and $Y(s)$ are analytic over $\mathcal{D}_\sigma$ and $Y(s)$ is the Laplace transform of an mixed-Erlang distribution in (3). Then we have

$$C = \frac{A}{2\pi j}\int_{\sigma-j\infty}^{\sigma+j\infty} X(s)Y(-s)\,ds = -A\sum_{i=1}^{M}\alpha_i\frac{(-1)^{m_i}(m_i\eta_i)^{m_i}}{(m_i-1)!}X^{(m_i-1)}(m_i\eta_i) \quad (4)$$

where $X^{(k)}(a)$ denotes the kth derivative of $X(s)$ at the point $s=a$.

In the subsequent development, we often encounter the probability expression $\Pr(X_0+X_1+X_2+\cdots+X_k \le X)$, where X_0 and X are random variables whose pdfs have Laplace transforms $f_{X_0}^*(s)$ and $f_X^*(s)$, respectively, and $X_1, X_2, \ldots, X_k$ are random variables, i.i.d., whose pdf has a Laplace transform $f_{X_i}^*(s)$. The following result gives a method to compute the aforementioned probability.

Fact 2: Assume that the random variables X_0, X_1, $X_2, \ldots, X_k$, X are independent. If $f_{X_0}^*(s)$, $f_{X_i}^*(s)$, and $f_X^*(s)$ are analytic in $\mathcal{D}_\sigma$ for a real number σ, then

$$\Pr(X_0+X_1+X_2+\cdots+X_k \le X) = \frac{1}{2\pi j}\int_{\sigma-j\infty}^{\sigma+j\infty}\frac{f_{X_0}^*(s)\left[f_{X_i}^*(s)\right]^k}{s}f_X^*(-s)\,ds. \quad (5)$$

Proof: Let $\xi = X_0+X_1+X_2+\cdots+X_k$. Let $f_\xi(t)$ and $f_\xi^*(s)$ denote the pdf and the Laplace transform of ξ, respectively. From the independence of $X_0, X_1, X_2, \ldots, X_k$, we have

$$f_\xi^*(s) = E[e^{-s\xi}] = E[e^{-sX_0}]\prod_{i=1}^{k}E[e^{-sX_i}] = f_{X_0}^*(s)(f_{X_i}^*(s))^k.$$

Thus, the pdf of ξ is given by

$$f_\xi(t) = \frac{1}{2\pi j}\int_{\sigma-j\infty}^{\sigma+j\infty} f_{X_0}^*(s)(f_{X_i}^*(s))^k e^{st}\,ds.$$

Notice that the Laplace transform of $\Pr(\xi \le t)$ (the distribution function) is $f_\xi^*(s)/s$. Thus, we have ($f_X(t)$ is the pdf of X)

$$\begin{aligned}\Pr(X_0+X_1+X_2+\cdots+X_k \le X) &= \int_0^\infty \Pr(\xi \le X|X=t)f_X(t)\,dt\\ &= \int_0^\infty \frac{1}{2\pi j}\int_{\sigma-j\infty}^{\sigma+j\infty}\frac{f_{X_0}^*(s)[f_{X_i}^*(s)]^k}{s}e^{st}\,ds f_X(t)\,dt\\ &= \frac{1}{2\pi j}\int_{\sigma-j\infty}^{\sigma+j\infty}\frac{f_{X_0}^*(s)[f_{X_i}^*(s)]^k}{s}f_X^*(-s)\,ds.\end{aligned}$$

This completes the proof. □

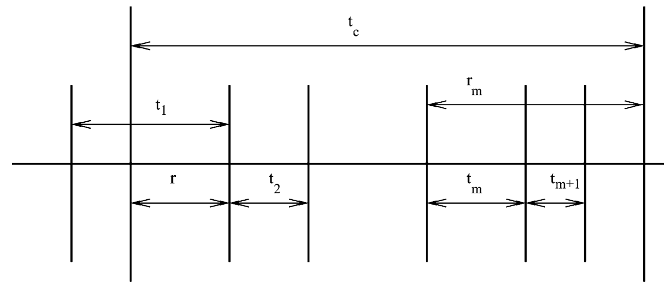

Fig. 2. Time diagram for call holding time and cell residence time.

Remark: In this result, we show how the probability may be obtained by evaluating an integral.

III. Analytical Formulas for Performance Metrics

Before we undertake the investigation on the performance metrics we mentioned earlier, we present the notation we will use in the subsequent development. In a wireless mobile network, a mobile user moves from cell to cell and engages call services when he/she moves. Fig. 2 shows the time diagram for a typical mobile user. Let t_c be the *call holding time* (the time of the requested connection to a wireless network, also known as *unencumbered call holding time*) for a typical new call with the mean value $1/\mu$. In the mobile computing systems, t_c can be regarded as the session time. Let t_m be the *cell residence time* in the mth cell a mobile user travels during a call life with the mean value $1/\eta$. Let r be the time between the time instant the new call is initiated at and the instant the new call moves out of the cell if the new call is not completed (we call it the *residual cell residence time*); let r_m $(m>1)$ be the *residual call holding time* when the call finishes the mth handoff successfully. Let λ and λ_h denote the arrival rates for new calls and handoff calls, respectively. Let $f_c(t)$, $f(t)$, and $f_r(t)$ denote, respectively, the probability density functions of t_c, t_m, and r with their corresponding Laplace transforms $f_c^*(s)$, $f^*(s)$ and $f_r^*(s)$, respectively. We assume throughout the paper that all distributions are nonlattice, i.e., they do not contain the discrete singular components. In what follows, we will use $h^{(i)}(s)$ to denote the ith derivative of a function $h(s)$ at the point s, when $i=0$, it gives the function itself.

In the current literature, t_c is assumed to be exponentially distributed, $t_2, t_3, \ldots$, are assumed to be independent and identically exponentially distributed [19], [21], [29]–[31], and, hence, from the memoryless property of exponential distribution, r is also exponentially distributed. From these assumptions, we conclude that the channel holding time is exponentially distributed (see [15] and references therein). However, as we mentioned before, field study showed that channel holding time is not exponentially distributed, thus the above exponential assumption will not be valid in general. Moreover, the independence assumption for the cell residence times $t_2, t_3, \ldots$, is also in question; the dependence effect has been touched upon in [39], in which Xie and Goodman demonstrated that the probability density function of terminal speeds follows the biased sampling formula. In real cellular systems, the dependence of cell residence times can also be observed in many scenarios, for example, in the highway cellular models. However, it is not known what effect this assumption would have on the performance metrics. In this paper, we focus on relaxing the first assumption, and we relax the exponential assumption and invoke the following more general conditions: the call holding time, cell residence time, and the interarrival time for both new calls and handoff calls are all independent. Specifically, we assume that $r, t_c, t_2, t_3, \ldots$, are independent, and $t_2, t_3, \ldots$, are identically distributed with the pdf $f(t)$. We will postpone the independence issue for future research.

Next, based on the above general assumptions, we will derive analytical results for the aforementioned performance metrics: handoff probability, handoff rate, call dropping probability, and actual call holding times for complete calls and incomplete calls.

A. Handoff Probability

Handoff probability is defined as the probability that a call needs at least one more handoff during its remaining lifetime. Depending on whether a call is a new call or a handoff call, we call the probability the *handoff probability for a new call* or the *handoff probability for a handoff call*. Handoff probabilities have been used in the past in handoff scheme design [10], [42], in the computation of handoff rates [42] under specific assumptions for cell residence time and for channel reservation schemes [20]. These quantities have been investigated in the past only when cell residence time and call holding time are exponentially distributed. In this section, we study these quantities under general cell residence time and general call holding time distribution assumptions.

We first study the handoff probability for a new call. Let P_n denote the handoff probability for a new call. We observe that a new call needs at least one handoff if and only if the call holding time t_c is greater than the residual cell residence time r. From Fact 2 and Corollary 1, we obtain

$$P_n = \Pr(r \le t_c) = \frac{1}{2\pi j}\int_{\sigma-j\infty}^{\sigma+j\infty} \frac{f_r^*(s)}{s} f_c^*(-s)\,ds = -\sum_{p\in\sigma_p} \operatorname*{Res}_{s=p} \frac{f_r^*(s)}{s} f_c^*(-s) \quad (6)$$

where σ_p is the set of poles of $f_c^*(-s)$. When t_c is generally distributed with certain property (e.g., its Laplace transform is a proper rational function), some easily computable results can be obtained. We observe that, when t_c is exponentially distributed with parameter μ, we can obtain the following simple formula: $P_n = f_r^*(\mu)$.

Next we derive the handoff probability for a handoff call. This quantity is important as it allows us to monitor a call in progress and plan ahead for the next handoff of the call.

Let $P_h(k)$ denote the probability that a handoff call needs at least one more handoff in its remaining life time after the kth handoff. From the time diagram in Fig. 2, we observe that this quantity can be expressed as the following conditional probability:

$$P_h(k) = \Pr(r + t_2 + \cdots + t_k + t_{k+1} \le t_c \,|\, r + t_2 + \cdots + t_k \le t_c). \quad (7)$$

Since $r, t_2, \ldots, t_{k+1}, t_c$ satisfy all of the assumptions in Fact 2, from Fact 2 and Corollary 1, we obtain the equation shown at the bottom of the page.

When the call holding time t_c is exponentially distributed, $f_c^*(-s) = \mu/(-s+\mu)$, we can easily obtain

$$P_h(k) = \frac{f_r^*(\mu)[f^*(\mu)]^k}{f_r^*(\mu)[f^*(\mu)]^{k-1}} = f^*(\mu).$$

In other words, when the call holding time t_c is exponentially distributed, the handoff probability for a handoff call after the kth handoff is independent of k, we can simply call this quantity *the handoff probability for a handoff call*. The independence of k in $P_h(k)$ when the call holding time is exponentially distributed is due to the memoryless property of the exponential distribution: the remaining call life (residual call holding time) after k handoffs is still exponentially distributed with the same distribution as that for the call holding time!

Remark: When the call holding time is not exponentially distributed, the handoff probability for a handoff call is not defined in the literature because of the lack of memoryless property of the call holding time distribution. Our definition for handoff probability for a handoff call represents a new concept, which coincides with the handoff probability concept when the call holding time is exponentially distributed [10], [42].

In summary, we obtain the following result.

Theorem 1: Let $f_c^*(s)$, $f_r^*(s)$, and $f^*(s)$ be the Laplace transforms of the pdf $f_c(t)$, $f_r(t)$, and $f(t)$, respectively, for

$$P_h(k) = \frac{\Pr(r + t_2 + \cdots + t_k + t_{k+1} \le t_c, r + t_2 + \cdots + t_k \le t_c)}{\Pr(r + t_2 + \cdots + t_k \le t_c)} = \frac{\Pr(r + t_2 + \cdots + t_k + t_{k+1} \le t_c)}{\Pr(r + t_2 + \cdots + t_k \le t_c)} = \frac{\frac{1}{2\pi j}\int_{\sigma-j\infty}^{\sigma+j\infty} \frac{f_r^*(s)[f^*(s)]^k}{s} f_c^*(-s)\,ds}{\frac{1}{2\pi j}\int_{\sigma-j\infty}^{\sigma+j\infty} \frac{f_r^*(s)[f^*(s)]^{k-1}}{s} f_c^*(-s)\,ds} = \frac{\sum_{p\in\sigma_p} \operatorname{Res}_{s=p} \frac{f_r^*(s)[f^*(s)]^k}{s} f_c^*(-s)}{\sum_{p\in\sigma_p} \operatorname{Res}_{s=p} \frac{f_r^*(s)[f^*(s)]^{k-1}}{s} f_c^*(-s)}$$

the call holding time, the residual life of cell residence time and cell residence time, then we have

$$P_n = \frac{1}{2\pi j}\int_{\sigma-j\infty}^{\sigma+j\infty}\frac{f_r^*(s)}{s}f_c^*(-s)\,ds \tag{8}$$

$$P_h(k) = \frac{\int_{\sigma-j\infty}^{\sigma+j\infty}\frac{f_r^*(s)[f^*(s)]^k}{s}f_c^*(-s)ds}{\int_{\sigma-j\infty}^{\sigma+j\infty}\frac{f_r^*(s)[f^*(s)]^{k-1}}{s}f_c^*(-s)ds} \tag{9}$$

where σ is a sufficiently small positive number. If the call holding time and cell residence time are distributed with rational Laplace transforms $f^*(s)$ and $f_c^*(s)$, then the handoff probabilities are given by

$$P_n = -\sum_{p\in\sigma_p}\operatorname*{Res}_{s=p}\frac{f_r^*(s)}{s}f_c^*(-s) \tag{10}$$

$$P_h(k) = \frac{\sum_{p\in\sigma_p}\mathrm{Res}_{s=p}\frac{f_r^*(s)[f^*(s)]^k}{s}f_c^*(-s)}{\sum_{p\in\sigma_p}\mathrm{Res}_{s=p}\frac{f_r^*(s)[f^*(s)]^{k-1}}{s}f_c^*(-s)} \tag{11}$$

where σ_p is the set of poles of $f_c^*(-s)$. In particular, when the call holding time is exponentially distributed with parameter μ, we have

$$\begin{aligned} P_n &= f_r^*(\mu)\\ P_h(k) &= f^*(\mu). \end{aligned} \tag{12}$$

When the call holding time t_c is mixed-Erlang distributed with distribution in (3), we have

$$P_n = \sum_{i=1}^{M}\alpha_i\sum_{j=0}^{m_i-1}\frac{f_r^{*(j)}(m_i\eta_i)}{j!}(-m_i\eta_i)^j \tag{13}$$

$$P_h(k) = \frac{\sum_{i=1}^M\alpha_i\sum_{j=0}^{m_i-1}\frac{\{f_r^*(s)[f^*(s)]^k\}^{(j)}\big|_{s=m_i\eta_i}}{j!}(-m_i\eta_i)^i}{\sum_{i=1}^M\alpha_i\sum_{j=0}^{m_i-1}\frac{\{f_r^*(s)[f^*(s)]^{k-1}\}^{(j)}\big|_{s=m_i\eta_i}}{j!}(-m_i\eta_i)^i}. \tag{14}$$

Proof: We only need to show (13) and (14), which can be derived from the special case when t_c is Erlang distributed. The Erlang distribution has the following density function and Laplace transform:

$$\begin{aligned} f_c(t) &= \frac{(m\beta)^m t^{m-1}}{(m-1)!}e^{-m\beta t}\\ f_c^*(s) &= \left(\frac{m\beta}{s+m\beta}\right)^m. \end{aligned} \tag{15}$$

If t_c is distributed with this distribution, taking it into (10) and using the differentiation formula

$$(uv)^{(p)} = \sum_{i=0}^{p}\binom{p}{i}u^{(i)}v^{(p-i)}$$

we obtain

$$\begin{aligned} P_n &= -\operatorname*{Res}_{s=m\beta}\frac{f_r^*(s)}{s}\cdot\left(\frac{m\beta}{-s+m\beta}\right)^m\\ &= (-1)^{m+1}\frac{(m\beta)^m}{(m-1)!}\left(\frac{1}{s}\cdot f_r^*(s)\right)^{(m-1)}\Bigg|_{s=m\beta}\\ &= \sum_{i=0}^{m-1}\frac{(-m\beta)^{m-i-1}}{(m-i-1)!}f_r^{*(m-i-1)}(m\beta)\\ &= \sum_{i=0}^{m-1}\frac{f_r^{*(i)}(m\beta)}{i!}(-m\beta)^i. \end{aligned}$$

From this, we can easily obtain (13). Equation (14) can be proved in a similar fashion. □

Remark: If we assume that the call initiation occurs randomly at a cell (i.e., the new call arrivals form a Poisson process), then r can be regarded as the residual life of the cell residence time in the initiating cell; the Residual Life Theorem [25] can be used to relate $f_r^*(s)$ to $f^*(s)$, i.e.,

$$\begin{aligned} f_r(t) &= \eta[1-F(t)]\\ f_r^*(s) &= \frac{\eta[1-f^*(s)]}{s} \end{aligned} \tag{16}$$

where $F(t)$ is the cumulative distribution of the cell residence time and $1/\eta$ is its mean value. In what follows, we will use $f_r^*(s)$ for simplicity.

B. Handoff Rate

Handoff rate, i.e., the average number of handoffs undertaken during the actual call connection in the wireless network, is very important parameter for network design and traffic characterization. Nanda [31] presented an analytic result of handoff rate for the case when the call holding time is exponentially distributed and no handoff failure occurs (which is equivalent to the case where each cell has an infinite number of channels available). Lin *et al.* [29] considered the more practical case where handoff failure was taken into consideration and presented a formula for the case when call holding time is exponentially distributed. There are no results for handoff rate when the call holding time is not exponentially distributed in the open literature except our prior works. In this section, we present a formula for general cases where the call holding time and cell residence time are generally distributed and for which handoff failures are accounted. In fact, we have derived the probability distribution of the number of handoffs experienced by a typical call, which may be of great interest in wireless network performance analysis.

From the definition of handoff rate, we know that the handoff rate is the average number of i.i.d. time intervals (cell residence times) falling into another random interval (call holding time) under the constraint that, whenever we add one interval, we may have failure. In order to find this average number, we need to compute the distribution of the number of intervals fitted into the given random interval. Let H be the number of handoffs of a typical admitted call (either completed or forced to terminate) during the call connection. We first study the distribution of H

under general call holding time and cell residence time distributions. Fig. 2 shows the time diagram. We observe the following: $H=0$ if and only if the call is not blocked and the call holding time t_c is shorter than the residual life r, i.e., the call completes before the mobile moves out of the cell; $H=1$ if and only if the call is not blocked initially, and then it either makes a successful handoff and completes successfully in the new cell or is forced to terminate because of the first handoff failure, $H=k$ (an admitted call experiences k handoffs during its call life) if and only if the call is either successfully having k handoffs and finishing its service in the following cell without any forced termination or successfully having $(k-1)$ handoffs and failed at the kth handoff. If the blocking probability for a new call is p_o (call blocking probability) and the blocking probability for a handoff call (the handoff blocking probability) is p_f, then we can easily obtain

$$\begin{aligned}\Pr(H=0) &= (1-p_o)\Pr(r\geq t_c)\\ \Pr(H=1) &= (1-p_o)\Pr(r<t_c\leq r+t_2)(1-p_f)\\ &\quad+(1-p_o)\Pr(t_c\geq r)p_f\\ &\ \ \vdots\\ \Pr(H=k) &= (1-p_o)\Pr(r+t_2+\cdots+t_k<t_c\\ &\quad\leq r+t_2+\cdots+t_{k+1})(1-p_f)^k\\ &\quad+(1-p_o)\Pr(t_c\geq r+t_2+\cdots+t_k)\\ &\quad\times(1-p_f)^{k-1}p_f\\ &\ \ \vdots\end{aligned} \tag{17}$$

When $k=0$, we notice that $\Pr(H=0)$ is closely related to the handoff probability for a new call. From the previous subsection, we obtain

$$\begin{aligned}\Pr(H=0) &= (1-p_o)(1-P_n)\\ &= (1-p_o)\left[1-\frac{1}{2\pi j}\int_{\sigma-j\infty}^{\sigma+j\infty}\frac{f_r^*(s)}{s}f_c^*(-s)\,ds\right]\\ &= (1-p_o)\left[1+\sum_{p\in\sigma_p}\operatorname*{Res}_{s=p}\frac{f_r^*(s)}{s}f_c^*(-s)\right].\end{aligned} \tag{18}$$

When $k>0$, applying Fact 2 in (17), we obtain

$$\begin{aligned}&\Pr(H=k)\\ &= (1-p_o)\Pr(t_c\geq r+t_2+\cdots+t_k)(1-p_f)^{k-1}\\ &\quad-(1-p_o)\Pr(t_c\geq r+t_2+\cdots+t_{k+1})(1-p_f)^k\\ &= \frac{(1-p_o)(1-p_f)^k}{2\pi j}\\ &\quad\times\int_{\sigma-j\infty}^{\sigma+j\infty}\frac{f_r^*(s)[f^*(s)]^{k-1}[1-f^*(s)]}{s}f_c^*(-s)\,ds\\ &\quad+\frac{(1-p_o)(1-p_f)^{k-1}p_f}{2\pi j}\\ &\quad\times\int_{\sigma-j\infty}^{\sigma+j\infty}\frac{f_r^*(s)[f^*(s)]^{k-1}}{s}f_c^*(-s)\,ds\\ &= \frac{(1-p_o)(1-p_f)^{k-1}}{2\pi j}\\ &\quad\times\int_{\sigma-j\infty}^{\sigma+j\infty}\frac{f_r^*(s)[1-(1-p_f)f^*(s)][f^*(s)]^{k-1}}{s}\\ &\quad\times f_c^*(-s)\,ds.\end{aligned} \tag{19}$$

Applying the Residue Theorem, we obtain

$$\begin{aligned}&\Pr(H=k)\\ &= \frac{(1-p_o)(1-p_f)^{k-1}}{2\pi j}\\ &\quad\times\int_{\sigma-j\infty}^{\sigma+j\infty}\frac{f_r^*(s)[1-(1-p_f)f^*(s)][f^*(s)]^{k-1}}{s}f_c^*(-s)\,ds\\ &= -(1-p_o)(1-p_f)^{k-1}\\ &\quad\times\sum_{p\in\sigma_p}\operatorname*{Res}_{s=p}\frac{f_r^*(s)[1-(1-p_f)f^*(s)][f^*(s)]^{k-1}}{s}f_c^*(-s).\end{aligned} \tag{20}$$

From the distribution of H, we can obtain the handoff rate as follows:

$$\begin{aligned}E[H] &= \sum_{k=0}^{\infty}k\Pr(H=k)=\sum_{k=1}^{\infty}k\Pr(H=k)\\ &= \frac{(1-p_o)}{2\pi j}\int_{\sigma-j\infty}^{\sigma+j\infty}\frac{f_r^*(s)[1-(1-p_f)f^*(s)]}{s}\\ &\quad\times\left(\sum_{k=1}^{\infty}k[(1-p_f)f^*(s)]^{k-1}\right)f_c^*(-s)\,ds\\ &= \frac{1-p_o}{2\pi j}\int_{\sigma-j\infty}^{\sigma+j\infty}\frac{f_r^*(s)}{s[1-(1-p_f)f^*(s)]}f_c^*(-s)\,ds.\end{aligned} \tag{21}$$

It is obvious that the integrand without term $f_c^*(-s)$ is analytic on the right half open complex plane and hence is analytic in $\mathcal{D}_\sigma$ for sufficiently small positive number σ. If $f_c^*(-s)$ has no branch point and has only finite possible isolated singular points in the open right half plane, then the Residue Theorem can be applied to (21) using a semicircular contour in the right half plane. Therefore, we finally obtain the following theorem.

Theorem 2: Let $f_c^*(s)$, $f_r^*(s)$, and $f^*(s)$ be the Laplace transforms of the pdf $f_c(t)$, $f_r(t)$, and $f(t)$, respectively, for the call holding time, the residual life of cell residence time, and cell residence time. Then we have

$$E[H]=\frac{1-p_o}{2\pi j}\int_{\sigma-j\infty}^{\sigma+j\infty}\frac{f_r^*(s)}{s[1-(1-p_f)f^*(s)]}f_c^*(-s)\,ds \tag{22}$$

where σ is a sufficiently small positive number. If the Laplace transform of the density function of the calling holding time t_c is a rational function, then the expected number of handoffs for an admitted call (the handoff rate) is given by

$$E[H]=-(1-p_o)\sum_{p\in\sigma_p}\operatorname*{Res}_{s=p}\frac{f_r^*(s)}{s[1-(1-p_f)f^*(s)]}f_c^*(-s). \tag{23}$$

In particular, if t_c is mixed-Erlang distributed with distribution in (3), then we have

$$E[H]=-(1-p_o)\sum_{i=1}^{M}\alpha_i\frac{(-1)^{m_i}(m_i\eta_i)^{m_i}}{(m_i-1)!}g^{(m_i-1)}(m_i\eta_i) \tag{24}$$

where

$$g(s)=\frac{f_r^*(s)}{s[1-(1-p_f)f^*(s)]}. \tag{25}$$

□

If the call holding time is exponentially distributed with parameter μ, from Theorem 2, we obtain

$$E[H] = (1-p_o)\frac{f_r^*(\mu)}{1-(1-p_f)f^*(\mu)}. \tag{26}$$

If there is no blocking and no forced termination, i.e., $p_o = p_f = 0$, and from (26) $E[H] = \eta/\mu$, which is obtained in [31]. In fact, this result is even valid when the call holding time is generally distributed. Indeed, from Theorem 2 and (16), if $p_o = p_f = 0$, we obtain

$$\begin{aligned} E[H] &= \frac{1}{2\pi j}\int_{\sigma-j\infty}^{\sigma+j\infty} \frac{f_r^*(s)}{s[1-f^*(s)]} f_c^*(-s)\,ds \\ &= \eta\int_0^\infty f_c(t)\left[\frac{1}{2\pi j}\int_{\sigma-j\infty}^{\sigma+j\infty}\frac{1}{s^2}e^{st}ds\right]dt \\ &= \eta\int_0^\infty t f_c(t)\,dt = \frac{\eta}{\mu}. \end{aligned}$$

This relationship can be explained intuitively as follows: the handoff rate is defined as the average number of handoffs. If there is no blocking and no forced termination (i.e., no handoff failure), the handoff rate is equivalent to the average number of cell residence time intervals fitting into a call holding time interval, which is given by $(1/\mu)/(1/\eta) = \eta/\mu$.

However, in reality, due to limited resources, calls do experience blocking, handoff failures do occur, and hence the handoff rate is different from the one given by Nanda [31]. Next, we want to analytically show that the handoff rate is no more than the one for the ideal case, which is intuitively true. In [15], we showed this when the call holding time is exponentially distributed. We now show that this is also true for the general case. First, we notice that

$$\begin{aligned} \Pr(H=k) &\le [\Pr(t_c \ge r + t_2 + \cdots + t_k) \\ &\quad - \Pr(t_c \ge r + t_2 + \cdots + t_{k+1})](1-p_f)^k \\ &\quad + \Pr(t_c \ge r + t_2 + \cdots + t_k)(1-p_f)^{k-1}p_f \\ &= \Pr(t_c \ge r + t_2 + \cdots + t_k)(1-p_f)^{k-1} \\ &\quad - \Pr(t_c \ge r + t_2 + \cdots + t_{k+1})(1-p_f)^k. \end{aligned}$$

Let $S_k = \Pr(t_c \ge r + t_2 + \cdots + t_k)(1-p_f)^{k-1}$. Then we have

$$\begin{aligned} E[H] &= \sum_{k=1}^\infty k\Pr(H=k) \le \sum_{k=1}^\infty k[S_k - S_{k+1}] \\ &= \lim_{N\to\infty}\left[\sum_{k=1}^N S_k - NS_{N+1}\right] \\ &\le \lim_{N\to\infty}\left[\sum_{k=1}^N \Pr(t_c \ge r + t_2 + \cdots + t_k)\right] \\ &= \lim_{N\to\infty}\left[\sum_{k=1}^N k\Pr(r + t_2 + \cdots + t_k \right. \\ &\quad \le t_c \le r + t_2 + \cdots + t_{k+1}) \\ &\quad \left. + N\Pr(t_c \ge r + t_2 + \cdots + t_{N+1})\right] \\ &= \sum_{k=1}^\infty k\Pr(r + t_2 + \cdots + t_k \\ &\quad \le t_c \le r + t_2 + \cdots + t_{k+1}) \\ &\quad + \lim_{N\to\infty} N\Pr(t_c \ge r + t_2 + \cdots + t_{N+1}). \end{aligned} \tag{27}$$

We notice that the first term on the right-hand side of the last equation in (27) is in fact the handoff rate for the ideal case, which is equal to η/μ, while the second term can be shown to be zero (using Fact 2 and noticing that $|f^*(s)| \le f^*(\sigma) < 1$ for sufficiently small positive number σ or applying Central Limit Theorem or the Large Deviation Theorem). In summary, from (27), we obtain $E[H] \le \eta/\mu$.

The handoff call arrival rate, a very important quantity for call blocking analysis, can be computed from the handoff rate for the homogeneous wireless mobile networks. We observe that, for each admitted new call, there will be on the average $E[H]$ number of handoff calls induced in the overall network, so the handoff call traffic will have arrival rate $\lambda_h = \lambda E[H]$. This is the major reason why we are interested in the handoff rate.

C. Call Dropping Probability

Call dropping probability is the probability that a call is prematurely terminated due to an unsuccessful handoff during the call life. Customers are more sensitive to call dropping than to call blocking at call initiation. Wireless service providers have to design the network to minimize the call dropping probability for customer care. This problem has been studied in [16], [17], and [29] for some special cases. In this subsection, we study the computation of the call dropping probability in the unifying framework.

We observe that a call is dropped if there is no available channel in the targeted cell during a handoff, i.e., a call is dropped when a handoff failure occurs during a call life. Fig. 2 can also be used to illustrate the timing diagram for a forced terminated call. As before, let p_o and p_f denote the call blocking probability and handoff blocking probability, respectively. Let p_c denote the probability that a call is completed (without blocking and forced termination). Then the call dropping probability $p_d = 1 - p_o - p_c$ is given by

$$\begin{aligned} p_d &= \Pr(\text{the call is not blocked, it is forced to} \\ &\quad \text{terminate due to an unsuccessful handoff}) \\ &= (1-p_o)\sum_{k=1}^\infty (1-p_f)^{k-1}p_f \\ &\quad \times \Pr(t_c \ge r + t_2 + \cdots + t_k) \\ &= \frac{(1-p_o)p_f}{2\pi j}\sum_{k=1}^\infty (1-p_f)^{k-1} \\ &\quad \times \int_{\sigma-j\infty}^{\sigma+j\infty}\frac{f_r^*(s)[f^*(s)]^{k-1}}{s}\cdot f_c^*(-s)\,ds \\ &= \frac{(1-p_o)p_f}{2\pi j} \\ &\quad \times \int_{\sigma-j\infty}^{\sigma+j\infty}\frac{f_r^*(s)\sum_{k=1}^\infty[(1-p_f)f^*(s)]^{k-1}}{s}\cdot f_c^*(-s)\,ds \\ &= \frac{(1-p_o)p_f}{2\pi j} \\ &\quad \times \int_{\sigma-j\infty}^{\sigma+j\infty}\frac{f_r^*(s)}{s[1-(1-p_f)f^*(s)]} f_c^*(-s)\,ds \end{aligned} \tag{28}$$

where we have again used Fact 2. Thus, we obtain the following theorem.

Theorem 3: Let $f_c^*(s)$, $f^*(s)$, and $f_r^*(s)$ be the Laplace transforms of the pdf of the call holding time, the cell residence time and the residual life of the cell residence time, respectively, then the call dropping probability is given by

$$\begin{aligned} p_d &= 1 - p_o - p_c \\ &= \frac{(1-p_o)p_f}{2\pi j} \int_{\sigma - j\infty}^{\sigma + j\infty} \frac{f_r^*(s)}{s[1-(1-p_f)f^*(s)]} f_c^*(-s)\, ds \\ &= p_f E[H] \end{aligned} \tag{29}$$

where σ is a sufficiently small positive number. When the call holding time t_c is mixed-Erlang distributed with the distribution in (3), we obtain the following:

$$\begin{aligned} p_d &= 1 - p_o - p_c \\ &= -(1-p_o)p_f \sum_{i=1}^{M} \alpha_i \frac{(-1)^{m_i}(m_i\eta_i)^{m_i}}{(m_i-1)!} g^{(m_i-1)}(m_i\eta_i) \end{aligned} \tag{30}$$

where

$$g(s) = \frac{f_r^*(s)}{s[1-(1-p_f)f^*(s)]}.$$

□

We observe that there is a close relationship between the call dropping probability and the handoff rate: $p_d = p_f E[H]$. This is very intuitive: recall that $E[H]$ is the average number of handoffs during the call life, each handoff has a probability p_f to fail, and hence the call dropping probability is then the summation of handoff failure probability for each handoff! Thus, if we can compute the handoff rate, then we can easily obtain the call dropping probability. Notice that we have $\lambda_h = \lambda E[H]$, and therefore, we have the following interesting result.

Corollary 2: The handoff rate, handoff call arrival rate, and call dropping probability have the following relationships in the homogeneous wireless networks:

$$p_d = p_f E[H] = \frac{\lambda_h}{\lambda} p_f. \tag{31}$$

□

This result tells us that, in homogeneous wireless networks, the call dropping probability, which is a networkwide quantity, can be completely determined by the call arrival rates for new calls and handoff calls and the handoff blocking probability in one single cell. This is consistent with the fact that a homogeneous wireless network can be completely characterized by a single cell in the wireless network.

D. Actual Call Holding Times

The actual call holding time (or actual call connection time) for a mobile user in a wireless network is a important quantity, which can be used to determine the charging rate for the services the user subscribes to. However, in a wireless network or a mobile computing system, calls may be prematurely terminated due to the limitation of finite resource. It is not fair to charge the same rate to an incomplete call as the one to a complete call. In order to obtain a fair billing rate planning, we need to determine the actual connection times for a complete call and an incomplete call, the expected actual connection times for the complete and the incomplete calls are called the *actual call holding times* for a complete call and an incomplete call, respectively.

We first consider the actual call holding time for an incomplete call. Let ξ denote the actual call connection time, let $G_d(t)$ denote the cumulative distribution function for an incomplete call, then we have

$$\begin{aligned} G_d(t) &= \Pr(\xi \le t \,|\, \text{the call is dropped}) \\ &= \frac{\Pr(\xi \le t, \text{the call is dropped})}{\Pr(\text{the call is dropped})} \\ &= \frac{1}{p_d} \sum_{k=1}^{\infty} \Pr(\xi \le t, \\ &\qquad \text{the call is dropped at the } k\text{th handoff}) \\ &= \frac{1}{p_d} \sum_{k=1}^{\infty} (1-p_o)(1-p_f)^{k-1} p_f \\ &\qquad \times \Pr(r + t_2 + \cdots + t_k \le t, r + t_2 + \cdots + t_k \le t_c) \\ &= \frac{(1-p_o)p_f}{p_d} \sum_{k=1}^{\infty} (1-p_f)^{k-1} \int_0^t f_k(t) \Pr(t_c \ge \tau)\, d\tau \end{aligned} \tag{32}$$

where $f_k(t)$ is the pdf of random variable $r + t_2 + \cdots + t_k$ and p_d is the call dropping probability. Let $f_k^*(s)$ denote the Laplace transform of $f_k(t)$, which is given by $f_k^*(s) = f_r^*(s)[f^*(s)]^{k-1}$. Let $g_d(t)$ denote the density function of the actual call holding time for an incomplete call, and then, from (32), we obtain

$$\begin{aligned} g_d(t) &= \frac{(1-p_o)p_f}{p_d} \sum_{k=1}^{\infty} (1-p_f)^{k-1} f_k(t) \Pr(t_c \ge t) \\ &= \frac{(1-p_o)p_f}{p_d} \sum_{k=1}^{\infty} (1-p_f)^{k-1} f_k(t) \int_t^{\infty} f_c(t_c) dt_c. \end{aligned} \tag{33}$$

Let $g_d^*(z)$ denote the Laplace transform of $g_d(t)$ and T_d the expected actual call holding time for an incomplete call. Applying Laplace transformation on both sides of (33) and using a similar procedure to the one used in the proof of Fact 2, we obtain

$$g_d^*(z) = \frac{(1-p_o)p_f}{2p_d\pi j} \int_{\sigma - j\infty}^{\sigma + j\infty} \frac{f_r^*(s)}{1-(1-p_f)f^*(s)} \cdot \frac{f_c^*(-s+z) - 1}{s - z}\, ds \tag{34}$$

where σ is a sufficiently small positive number. Since

$$\lim_{s \to z} \frac{f_c^*(-s+z) - 1}{s - z} = f_c^{*(1)}(0)$$

we conclude that $s = z$ is a removable singular point [28] of the integrand of (34). Thus, the poles of the integrand are those of $f_c^*(-s+z)$, i.e., $\{z + p \,|\, p \in \sigma_p\}$, where σ_p is the set of poles of $f_c^*(-s)$.

The expected actual call holding time for an incomplete call T_d is given by

$$\begin{aligned} T_d &= -g_d^{*(1)}(0) \\ &= -\frac{(1-p_o)p_f}{2p_d\pi j} \int_{\sigma - j\infty}^{\sigma + j\infty} \frac{f_r^*(s)}{1-(1-p_f)f^*(s)} \\ &\qquad \cdot \frac{s f_c^{*(1)}(-s) + f_c^*(-s) - 1}{s^2}\, ds. \end{aligned} \tag{35}$$

Notice that since (from L'Hospital's theorem)

$$\lim_{s\to 0}\frac{sf_c^{*(1)}(-s)+f_c^*(-s)-1}{s^2} = \lim_{s\to 0}\frac{f_c^{*(1)}(-s)-sf_c^{*(1)}-f_c^{*(1)}(-s)}{2s} = -\frac{1}{2}f_c^{*(2)}(0)$$

then $s=0$ is a removable singular point of the integrand. Because the derivative of an analytic function has the same set of poles as the function itself does (except the multiplicities), the integrand in (35) has the same set of poles as $f_c^*(-s)$ does, i.e., σ_p. In summary, we obtain the following theorem.

Theorem 4: The actual call holding time for an incomplete call can be characterized as follows:

$$g_d^*(z) = \frac{(1-p_o)p_f}{2p_d\pi j}\int_{\sigma-j\infty}^{\sigma+j\infty}\frac{f_r^*(s)}{1-(1-p_f)f^*(s)} \cdot \frac{f_c^*(-s+z)-1}{s-z}\,ds$$

$$T_d = -\frac{(1-p_o)p_f}{2p_d\pi j}\int_{\sigma-j\infty}^{\sigma+j\infty}\frac{f_r^*(s)}{1-(1-p_f)f^*(s)} \cdot \frac{sf_c^{*(1)}(-s)+f_c^*(-s)-1}{s^2}\,ds.$$

If $f_c^*(s)$ is a rational function in s, then

$$g_d^*(z) = -\frac{(1-p_o)p_f}{p_d} \times \sum_{p\in\sigma_p}\operatorname*{Res}_{s=z+p}\frac{f_r^*(s)f_c^*(-s+z)}{(s-z)[1-(1-p_f)f^*(s)]},$$

$$T_d = \frac{(1-p_o)p_f}{p_d}\sum_{p\in\sigma_p}\operatorname*{Res}_{s=p}\frac{f_r^*(s)}{1-(1-p_f)f^*(s)} \cdot \frac{sf_c^{*(1)}(-s)+f_c^*(-s)-1}{s^2}.$$

In particular, if the call holding time is mixed-Erlang distributed with the distribution in (3), then we have

$$g_d^*(z) = -\frac{(1-p_o)p_f}{p_d} \times \sum_{i=1}^{M}\alpha_i\frac{(-1)^{m_i}(m_i\eta_i)^{m_i}}{(m_i-1)!}\left.\frac{\partial^{m_i-1}g(s;z)}{\partial s^{m_i-1}}\right|_{s=m_i\eta_i}$$

$$T_d = \frac{(1-p_o)p_f}{p_d}\sum_{i=1}^{M}\alpha_i\frac{(-1)^{m_i}(m_i\eta_i)^{m_i}}{(m_i-1)!} \times\left[g^{(m_i)}(m_i\eta_i)+g_1^{(m_i-1)}(m_i\eta_i)\right],$$

where

$$g(s) = \frac{f_r^*(s)}{s[1-(1-p_f)f^*(s)]},$$

$$g_1(s) = \frac{f_r^*(s)}{s^2[1-(1-p_f)f^*(s)]},$$

$$g(s;z) = \frac{f_r^*(s+z)}{s[1-(1-p_f)f^*(s+z)]}.$$

Next, we study the actual holding time for a complete call. Suppose that a call is completed when the mobile is in cell k'. Let ξ denote the actual call holding time. If $k'=1$, then $0\le t_c\le r$ and $\xi=t_c$, while if $k'>1$, then $r+t_2+\cdots+t_{k'-1}\le t_c\le r+t_2+\cdots+t_{k'}$ and $\xi=t_c$. Let $k=k'-1$, then we have

$$\text{For } k=0,\quad 0\le t_c\le r \tag{36}$$

$$\text{For } k>0,\quad r+t_2+\cdots+t_k\le t_c\le r+t_2+\cdots+t_{k+1} \tag{37}$$

Let $g_c(t)$ denote the pdf of the actual call holding time. Using an argument similar to the one for the actual call holding time for an incomplete call, we obtain

$$g_c(t_c) = \left(\frac{1-p_o}{p_c}\right)\left[f_c(t_c)\int_{t_c}^{\infty}f_r(t_1)\,dt_1\right] + \left(\frac{1-p_o}{p_c}\right)\left[\sum_{k=1}^{\infty}(1-p_f)^k f_c(t_c) \times\int_0^{t_c}f_k(t)\int_{t_c-t}^{\infty}f(\tau)\,d\tau\,dt\right]. \tag{38}$$

Applying the similar technique we used for actual call holding time for an incomplete call, we can obtain the following theorem.

Theorem 5: The actual call holding time for a complete call can be characterized as follows:

$$g_c^*(z) = \frac{1-p_o}{2\pi p_c j} \times\int_{\sigma-j\infty}^{\sigma+j\infty}\frac{[1-(1-p_f)f^*(s)]-p_f f_r^*(s)}{s[1-(1-p_f)f^*(s)]} \times f_c^*(-s+z)\,ds,$$

$$T_c = -\frac{1-p_o}{2\pi p_c j} \times\int_{\sigma-j\infty}^{\sigma+j\infty}\frac{[1-(1-p_f)f^*(s)]-p_f f_r^*(s)}{s[1-(1-p_f)f^*(s)]} \times f_c^{*(1)}(-s)\,ds$$

where σ is a sufficiently small positive number. If the Laplace transform $f^*(s)$ is a rational function, then

$$g_c^*(z) = -\left(\frac{1-p_o}{p_c}\right)\left\{\sum_{p\in\sigma_p}\operatorname*{Res}_{s=z+p} \times\frac{[1-(1-p_f)f^*(s)]-p_f f_r^*(s)}{s[1-(1-p_f)f^*(s)]}f_c^*(-s)\right\}$$

$$T_c = \left(\frac{1-p_o}{p_c}\right)\left\{\sum_{p\in\sigma_p}\operatorname*{Res}_{s=p} \times\frac{[1-(1-p_f)f^*(s)]-p_f f_r^*(s)}{s[1-(1-p_f)f^*(s)]}f_c^{*(1)}(-s)\right\}$$

where σ_p is the set of poles of $f_c^*(-s)$. If the call holding time is mixed-Erlang distributed with distribution in (3), we have

$$g_c^*(z) = -\frac{1-p_o}{p_c}\sum_{i=1}^{M}\alpha_i\frac{(-1)^{m_i}(m_i\eta_i)^{m_i}}{(m_i-1)!} \times \left.\frac{\partial^{m_i-1}h(s;z)}{\partial s^{m_i-1}}\right|_{s=m_i\eta_i}$$

$$T_c = \frac{1-p_o}{p_c}\sum_{i=1}^{M}\alpha_i\frac{(-1)^{m_i}(m_i\eta_i)^{m_i}}{(m_i-1)!}h^{(m_i)}(m_i\eta_i) \tag{39}$$

where

$$h(s;z) = \frac{[1-(1-p_f)f^*(s+z)] - p_f f_r^*(s+z)}{(s+z)[1-(1-p_f)f^*(s+z)]}$$

$$h(s) = h(s;0) = \frac{[1-(1-p_f)f^*(s)] - p_f f_r^*(s)}{s[1-(1-p_f)f^*(s)]}.$$

□

When the call holding time is exponentially distributed with parameter μ as commonly assumed in the literature, Theorems 4 and 5 give

$$g_d^*(z) = \frac{(1-p_o)p_f f_r^*(z+\mu)}{p_d[1-(1-p_f)f^*(z+\mu)]}$$

$$g_c^*(z) = \frac{1-p_o}{p_c}\cdot\frac{[1-(1-p_f)f^*(z+\mu)] - p_f f_r^*(z+\mu)}{(z+\mu)[1-(1-p_f)f^*(z+\mu)]}.$$

It is interesting to observe that the trivial identities $g_d^*(0) = 1$ and $g_c^*(0) = 1$ give formulas for the computation of p_d and p_c; the resulting formulas are the same as what were obtained earlier.

IV. Discussions and Numerical Results

Up to now, we observe that all of analytical results we have developed are reduced to the computation of the following type of integral:

$$C = \frac{A}{2\pi j}\int_{\sigma-j\infty}^{\sigma+j\infty} X(s)Y(-s)\,ds \tag{40}$$

as we mentioned earlier. The general computation of this type of integral can be found in [2], where various rational approximations (Padé approximations) can be used. It has been shown that the rational approximations such as the mixed-Erlang and the SOHYP distributions can provide very good fits to sufficiently general functions. In practice, measurements are taken for call holding time and cell residence time, and thus the mixed-Erlang models or other models with rational Laplace transforms can be used to fit such field data. Using the resulting distribution model, we can easily compute the performance metrics of interest such as handoff probability, handoff rate, call dropping probability, and actual call holding times. We believe that many other time variables can be computed by our approach and that many other problems in wireless and mobile computing systems can be solved using the analytical approach we developed in this paper.

If we choose rational approximation (Padé approximation) for the probability distributions of the involved time variables, then all computations are reduced to finding the high-order derivatives of rational functions. We show that the high-order derivatives of a rational function can be computed recursively. Let $R(s) = P(s)/Q(s)$ denote a rational function, where $P(s)$ and $Q(s)$ are polynomials. Applying the differentiation formula $(uv)^{(m)} = \sum_{i=0}^{m}\binom{m}{i}u^{(i)}v^{(m-i)}$ to both sides of the identity $R(s)Q(s) = P(s)$, we obtain

$$P^{(m)}(s) = \sum_{i=0}^{m}\binom{m}{i}R^{(i)}(s)Q^{(m-i)}(s) = R^{(m)}(s)Q(s) + \sum_{i=0}^{m-1}\binom{m}{i}R^{(i)}(s)Q^{(m-i)}(s)$$

from which we obtain

$$R^{(m)}(s) = \frac{P^{(m)}(s) - \sum_{i=0}^{m-1}\binom{m}{i}R^{(i)}(s)Q^{(m-i)}(s)}{Q(s)}.$$

Thus, the computational complexity can be significantly reduced. In fact, compared with the complexity in using exponential assumption, the numerical computation burden in using our general analytical results will not increase significantly, and yet we can calculate the performance metrics more accurately.

Next, we present a few numerical examples to demonstrate how the performance metrics obtained from our analytical results deviate from those obtained under the exponential assumptions on some time variables. Our approach here is as follows: we choose some distributions, say, Erlang distributions, for some time variables, and we then use our analytical results to compute the performance metrics of interest. We then use the exponential distributions with the same average values to approximate the distributions for the corresponding time variables, and calculate the corresponding performance metrics. In this way, we can compare the final results and observe the deviations.

Fig. 3 shows the handoff probability for handoff calls, where we use exponential distribution to model call holding time and use the Erlang distribution with parameters (m, η) to model the cell residence time, the curve with $m = 1$ corresponds to the exponential approximation for cell residence time. We observe that there is a significant difference between the actual handoff probability for handoff calls $(m = 10)$ and the approximate handoff probability by exponential distribution for the cell residence time; this is particularly true when the mobility factor (η/μ) is low. For example, when $\eta/\mu = 0.36$, the deviation between the actual handoff probability and the approximate handoff probability is close to 18%. Intuitively, for the high mobility case (when mobility factor is high), the mobile user will have high probability to move into other cells, the first moment statistics (the mean) will determine the handoff probability, and hence there is no significant difference between the actual handoff probability and the approximated values. When the mobility is low (i.e., when the mobility factor is small), the

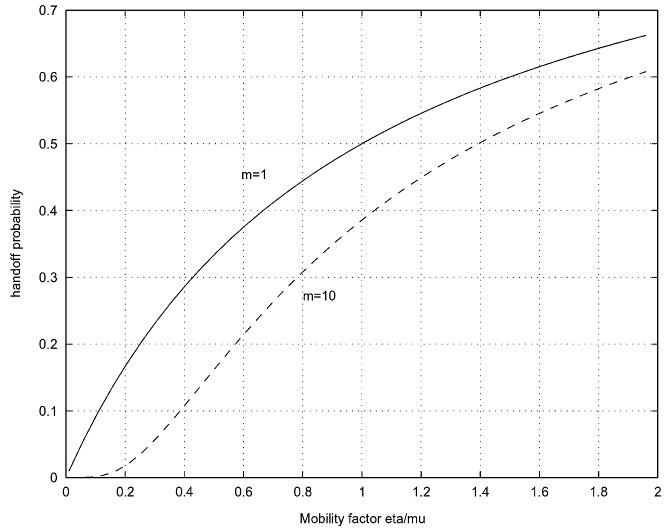

Fig. 3. Handoff probability for handoff calls.

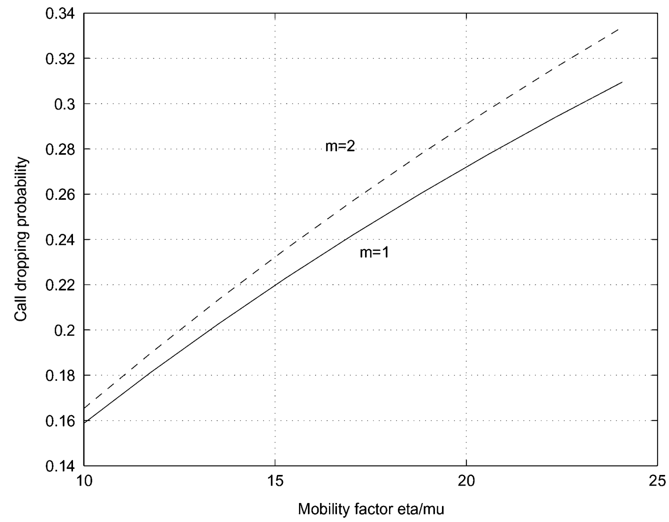

Fig. 5. Call dropping probability.

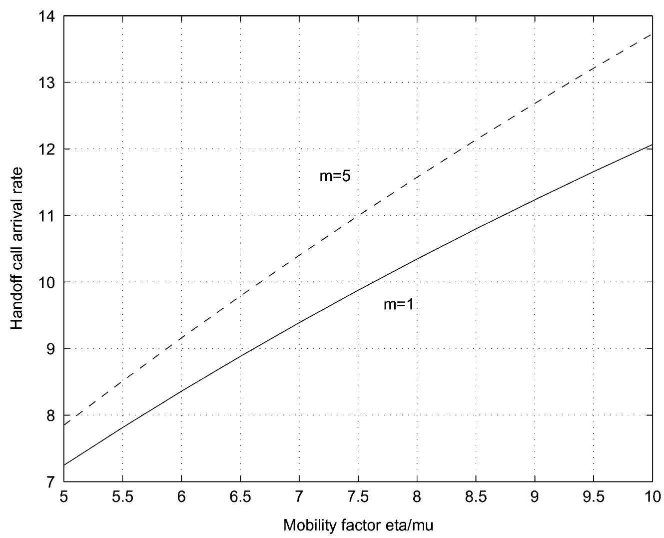

Fig. 4. Handoff traffic arrival rate.

probability distribution for cell residence time will play a significant role. When m is large, the cell residence time tends to be constant, and hence the mobility of the mobile user is much more predictable than the case when the cell residence time is exponentially distributed.

Fig. 4 gives the comparison result for the handoff traffic arrival rate, where we use a Gamma distribution to model the cell residence time and the Erlang distribution to model the call holding time. The curve with $m = 1$ corresponds to the case in which the exponential distribution is used to approximately model the call holding time. We observe that there is a significant deviation between the actual handoff traffic arrival rate and the approximate handoff traffic arrival rate. In this example, we assume that the new call arrival rate is $\lambda = 2$. When the new call arrival rate is higher, the difference will be more pronounced. The higher the mobility, the further the deviation. This is reasonable, when the mobility is higher and there is more handoff traffic, if the variance of the call holding time is low (i.e., m is large), the the call holding time is closer to the constant (i.e., $m = \infty$), thus it seems that we can fit more Gamma distributed random intervals into an constant interval than into an exponentially distributed interval. The exponential approximation model is likely to underestimate the handoff traffic.

Fig. 5 presents the result for the call dropping probability, where the cell residence time is again Gamma distributed and the call holding time is Erlang distributed. The case with $m = 1$ indicates the approximate result when the call holding time distribution is approximated by exponential distribution. We observe that, in quite a large mobility range (say, the mobility factor from 1 to 20), there is no significant difference between the actual call dropping probability and that obtained from the approximate model. The reason is that the design requires the handoff blocking probability to be less than $p_f = 0.02$. Since the call dropping probability $p_d = p_f E[H]$, although there might be a significant difference in the handoff rate $E[H]$ when the approximate model is used, the call dropping probability may not be significantly affected due to the smallness of p_f. Moreover, when the mobility is relatively low, the call dropping probability may not be high enough to be noticed; when the mobility is higher, the call dropping probability will be higher, and the difference between the actual call blocking probability and the approximate call dropping probability will not be significant compared to their call dropping probability value. This is obviously shown in the figure.

To sum up, our numerical results show that the traditional exponential modeling may not be appropriate for some performance metrics while they may do reasonably well for some other performance metrics. It is not clear when such modeling is valid and when such modeling fails. The contribution of this paper is the theoretical results: when cell residence time and call holding time are not exponentially distributed, we can use the analytical results developed in this paper and compute the performance metrics analytically without too much computational effort.

V. Conclusion

In this paper, we develop a new analytical method for the performance evaluation of wireless networks and mobile computing systems. Under a very general assumption on distributions of the call holding time and cell residence time, we derive analytical formulas for handoff probability, handoff rate, call dropping probability, and the actual call holding times for both complete and incomplete calls. This new analytical approach opens a new avenue for performance evaluation for wireless networks and mobile computing systems. In fact, we recently have used this approach to analytically evaluate a few mobility management schemes under fairly general assumptions [12], [13].

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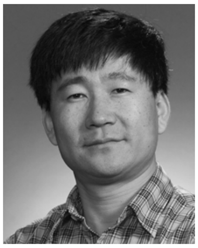

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