

Wireless network performance evaluation : link unreliability and parameter sensitivity

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Wireless Network Performance Evaluation: Link Unreliability and Parameter Sensitivity

Zhang Yan

School of Electrical & Electronic Engineering

A thesis submitted to the Nanyang Technological University
in fulfillment of the requirement for the degree of
Doctor of Philosophy

2005



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Statement of Originality

I hereby certify that the work embodied in this thesis is the result of original research done by me and has not been submitted for a higher degree to any other University or Institute.

8. Sep 2015
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Date


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ZHANG Yan

To all the people who have ever helped and encouraged me.

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Abstract

Numerous wireless mobile network standards have been proposed or are being drafted to meet the diverse demand in terms of the data rate, coverage and the multimedia service. However, the two basic features of any wireless system are unchangeable: limited capacity of the radio interface and the inherently time-varying nature of the wireless channel. While considerable papers have studied the performance of the wireless network constricted by the insufficient resource, few work has taken into account the limited bandwidth as well as the wireless link unreliability in evaluating the wireless network performance.

Two areas of interest in this thesis are wireless link unreliability and sensitivity in wireless network modeling. The wireless link unreliability means that the wireless network performance will be studied with the effects of the radio interface capacity bottleneck and the radio link impairment. Within the context of this thesis, the sensitivity refers to the generalization of the crucial tele-traffic parameters, such as the call holding time, the cell residence time and the handoff dwell time, in evaluating the network and call performance.

It is found that the ignorance of wireless channel unreliability will greatly overestimate the wireless network performance. In addition, the tele-parameters sensitivity holds true in both the single-tier and the multi-tier wireless networks. The results in the dissertation are helpful for designing more practical and efficient call admission control scheme taking into account the impaired wireless channel effect and for analyzing the reliability/availability characteristics of the wireless system.

List of Abbreviations and Symbols

Abbreviations

AMPS	Advanced Mobile Phone System
TACS	Total Access Communications Systems
GSM	Global System for Mobile Communications
GPRS	General Packet Radio Service
UMTS	Universal Mobile Telecommunications System
HIPERLAN	High Performance Radio Local Area Network
MS	Mobile Station
BS	Base Station
ITU	International Telecommunication Union
ETSI	European Telecommunications Standards Institute
IMT-2000	International Mobile Telecommunication-2000
BSC	Base Station Controller
MSC	Mobile Switching Center
CHT	Channel Holding Time
HDT	Handoff Dwell Time
CRT	Cell Resident Time
3G	Third Generation

4G	Fourth Generation
IP	Internet Protocol
WLAN	Wireless Local Area Network
CDMA	Code Division Multiple Access
WCDMA	Wideband Code Division Multiple Access
UTRA	Universal Terrestrial Radio Access
PCS	Personal Communications Service
QoS	Quality of Service
VoIP	Voice over IP
GSN	GPRS support node
SGSN	serving GPRS support node
GGSN	gateway GPRS support node
pdf	probability density function
cdf	cumulative distribution function

Symbols

t_c	call holding time
$f_{t_c}(t)$	call holding time probability density function
$F_{t_c}(t)$	call holding time cumulative distribution function
$f_{t_c}^*(s)$	LST of call holding time pdf
$1/\mu_c$	average value of call holding time
t_{crt}	cell residence time
$f_{t_{crt}}(t)$	cell residence time probability density function
$F_{t_{crt}}(t)$	cell residence time cumulative distribution function
$f_{t_{crt}}^*(s)$	LST of cell residence time pdf

P_{cc}	call complete probability
γ	call complete ratio
$t_{g,i}$	wireless channel good state duration in cycle i
$t_{b,i}$	wireless channel bad state duration in cycle i
P_s	link re-establishment successful probability
$E(\cdot)$	expected value of nonnegative random variable
P_n	new call blocking probability
P_h	handoff call blocking probability
Θ	handoff counting

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Chapter 1

Introduction

Over the years, a considerable number of wireless systems, such as IEEE802.11a/b/d/g [1], HIPERLAN [4], GSM [5], GPRS [5], UMTS [6], IS95 [7], CDMA2000 [7], Bluetooth [2] [3] have been standardized/deployed widely or are being drafted to meet the diverse requirements in the different scenarios with respect to the coverage, the large variety of the service type with a broad range of data rate.

As such, intensive research and development activities on a wide range of relevant aspects, e.g. network architecture and protocol design, are being carried out, and the tools for the analysis and modeling of the wireless network are becoming increasingly more complicated than the classical wireline network.

1.1 Wireless Mobile Network

Ever since the appearance of the cellular concept in the late 1960s [8], the wireless networks have evolved from voice-oriented, low capacity and low data rate to the system

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supporting multimedia services, high data rate and guaranteed Quality of Service (QoS).

Now, the second generation wireless network has matured and it is upon the turning point from the second or 2.5 generation wireless network to 3G.

GSM (Global System for Mobile Communications) developed in Europe and IS-54/IS-95 standardized in North American are two principle second generation wireless systems. Both of these two systems have higher capacity and higher QoS when compared with the preliminary analogous systems such as AMPS (Advanced Mobile Phone System) and TACS (Total Access Communications Systems).

Within the framework of 2G mobile systems, the central issue that is of the service provider's concern is the problem encountered during the wireless network planning, deployment and maintenance. In these systems, the call blocking probability is the fundamental QoS parameter and is controlled through the provision of sufficient frequencies to a given cell and adding new sites, if necessary.

Since 2G mobile systems are inherently designed for voice traffic, the data rate for mobile Internet service is not sufficiently high to support real-time multimedia traffic transmission. To further simplify and improve the wireless access to packet data networks, especially for the Internet, General Packet Radio Service (GPRS) network has been standardized and deployed on top of GSM network, acting as a new bearer service. When compared to the mobile data service in circuit-switched network, it has been demonstrated that GPRS subscribers benefit from shorter access time owing to the "always-on" property and higher data rates due to the multi-slot capability. From the infrastructure point of view, two GPRS support nodes (GSNs), serving GPRS support node (SGSN) and gateway GPRS support node (GGSN), are introduced in GPRS whereas the SGSN is responsible for transiting the packets to the MSs and the GGSN acts as a gateway between GPRS and the external data networks.

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The evolution of the end user needs towards multimedia applications has driven the wireless/mobile community to conceive the third generation (3G) systems. Third-generation mobile communication systems will bring a wide range of new services with diverse QoS requirements and will enable the system to exploit radio resource management to guarantee a certain target QoS, to maintain the planned coverage area and to offer a high capacity while efficiently using the radio resources. Universal Mobile Telecommunications System (UMTS), cdma2000 and TD-SCDMA are three major candidates in the framework of 3G, wherein UMTS is the successor of GSM, cdma2000 is the extended version of IS-95 and TD-SCDMA is the standard proposed by China. Wideband code-division multiple access (W-CDMA) is the predominant technology in UMTS and cdma2000. In contrast, TD-SCDMA employs CDMA as well as SDMA to efficiently eliminate the interface and provide higher multiplexing. The winner of the candidate standards depends on the market, the technology superiority, the implementation cost and the product maturity.

Alternatively, a gradually evolution for the transition from 2G to 3G is supported by a wide range of commercial and industrial policies and interests. During the development, mature wireless technologies that have been already deployed and covered different needs will be continuously used to avoid the investment waste. As far as coverage and the mobility are concerned, current wireless networks may be grouped into three classes: wireless LANs for local area, cellular network for wide area and satellite network for worldwide coverage.

The provision of wireless local area network connections in small environment represents one of the fastest growing business fields of the telecom market. To date, two of the most important wireless LAN standards are: IEEE 802.11 standard and ETSI HIPERLAN. IEEE 802.11 is based on Direct Sequence Spread Spectrum and Carrier Sense Multiple Access Collision Avoidance multiple access protocol. In its early stan-

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dard, the bit-rate operated by IEEE 802.11 was limited to 2Mb/s. An enhanced version, IEEE 802.11a, can offer transmission rates from 6 to 54 Mbit/s depending upon the distance.

ETSI also developed two standards for wireless LAN. The first one called HIPERLAN Type 1 works in the band of the 2.4 GHz and it allows a data transmission rate of up to 23.5 Mbit/s. This standard is based on an ad-hoc operating mode with an optional multi-hop routing. Recently, the ETSI has further developed a new standard called HIPERLAN/2, operating in the band of 5 GHz with transmission rates from 6 up to 54 Mbit/s. HIPERLAN/2 supports both infrastructure and ad-hoc modes.

Due to the diversity of wireless network standards and the various requirements in different environment, the future wireless network architecture infrastructure may be organized into a hierarchy on the basis of the technologies either already deployed or still under development (Fig. 1.1). The network infrastructure starts from the pico-net with the coverage in private buildings (e.g. house, office). In public "hot-spot" locations such as airport, train station and bus interchange, the technologies like IEEE802.11, HIPERLAN and Bluetooth may be used to provide the very high data rate but limited service coverage. In the national-wide service provision, the cellular technique such as 2G, 2.5G and 3G may provide wireless access up to microcell/macrocell. Finally, connectivity and mobility in satellite cells are provided via geosynchronous earth orbit(GEO), middle earth orbit (MEO), or low earth orbit (LEO) satellites.

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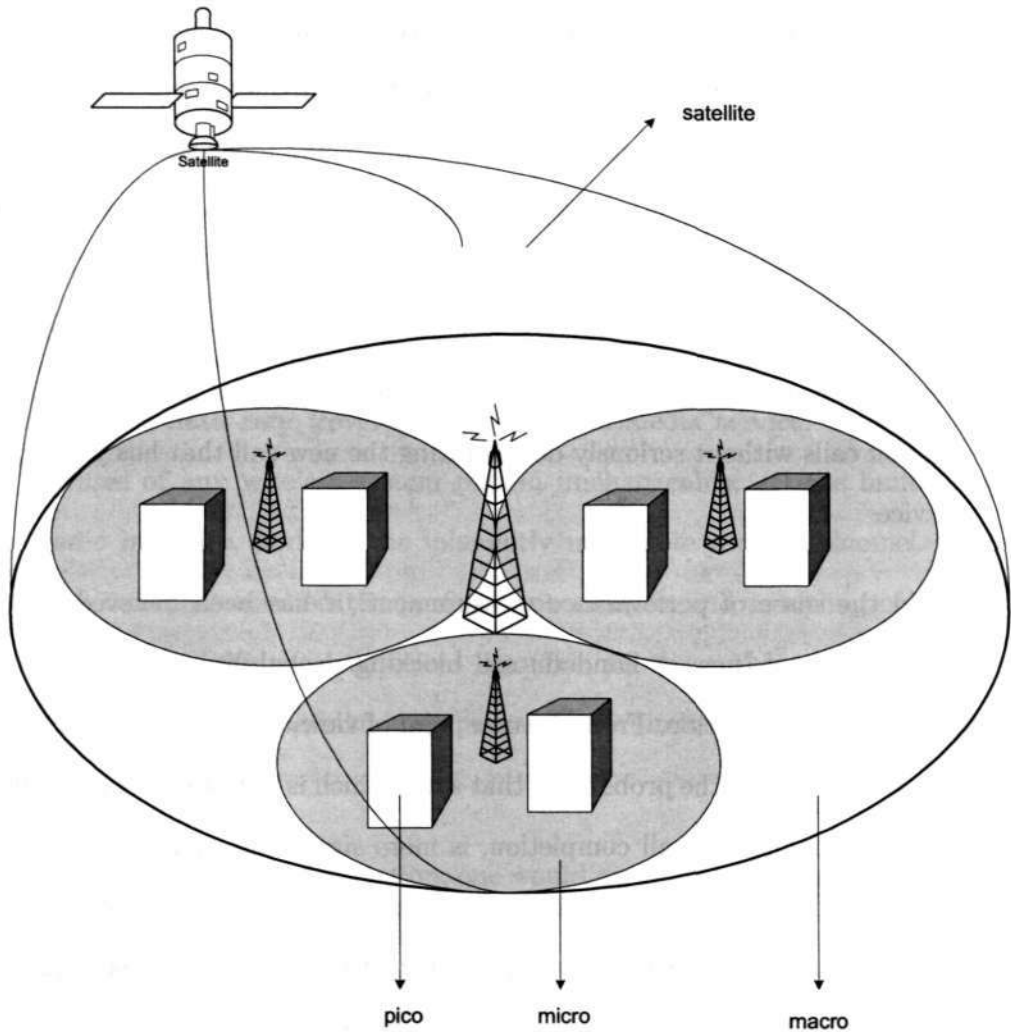


Figure 1.1: Hierarchical network architecture

1.2 Performance Modeling and Analysis Issues in Wireless Network

The increasing demand for high Quality of Service (QoS) provision and efficient radio resource utilization are the two major driving forces for the rapid development of wireless mobile network. In a wireless network, the whole service area is partitioned into smaller coverage areas, which are called *cells*. Each cell is equipped with a Base Station

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(BS) with a finite number of channels to provide the radio access and versatile services for the mobile users within the coverage of the cell. For a cell, there are two different types of call traffics with respect to the call starting location or channel request. The call originating from the cell is called as *new calls* and the call transferring from the immediate neighboring cell is termed as *handoff calls*. Since the dropping of a call in progress due to limited resources is more undesirable than rejecting a new call connection request, various priority strategies have been proposed to maintain the QoS for the handoff calls without seriously deteriorating the new call that has yet to gain access to services.

In the sense of performance measurement, it has been believed that only taking into account of (new or handoff) call blocking probability is not enough for network performance evaluation. From the user point of view, the forced termination probability, which is defined as the probability that a call which is not blocked is eventually forced to terminate before the call completion, is more significant and informative than merely the call blocking probability since this quantity expresses the experience that arises from the handoff characteristics from call starting to the abnormal termination due to unavailable channel. The property of the forced termination probability indicator is the relevance to the channel assignment scheme, call admission control algorithms and users roaming pattern. The call complete probability, defined as the probability that an unblocked call is completed, is nevertheless an important performance index. Note that forced termination probability is related to the call complete probability.

When evaluating the performance of mobile network, currently there are essentially two approaches. The first approach is from the cell point of view, where queueing theory is commonly applied to produce the desired performance measures in terms of a set of linear equations for the steady state probability distribution. From the steady state probability, we can further find the performance measures such as the new call

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blocking probability, handoff call blocking probability or the mean waiting time. The second perspective is to discuss the typical call behavior from the point the call begins to the call completion. From this, we can compute the important quantities such as the handoff rate, the call complete probability or call incomplete probability.

As stated, numerous wireless mobile network standards have been proposed or are being drafted to apply in different environments and can adapt to diverse requirements in terms of the data rate, coverage and the multimedia service. However, the two basic features of any wireless system remain unchangeable: (i) the limited capacity of the radio interface, and (ii) the inherently unreliable wireless channel. Although substantial work has studied the performance analysis and modeling of the wireless network constricted by the insufficient resource, to the authors best knowledge, no work has at the same time taken into account, the limited bandwidth as well as the wireless link unreliability.

Hence, in the author's dissertation, one would derive the following metrics to evaluate the performance of the wireless network in the presence of bandwidth insufficiency as well as the wireless link unreliability. Several of the important quantities will be defined as follows.

- *New call blocking probability* - the probability that a new call connection request is rejected.
- *Handoff call blocking probability* - the probability that a handoff call connection request is rejected.
- *Call complete probability* - a call is accepted and complete
- *Call incomplete probability* - a call is incomplete after the call is successfully accepted. Evidently, this probability is equal to one minus the call complete prob-

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ability.

- *Completed call holding time* - the actually completed time duration for a call connection.
- *Handoff counting* - the number of handoff an MS experienced.
- *Handoff rate* - the expected value of handoff counting.

Before proceeding on, we will introduce the significant concepts used in the thesis.

- *Call holding time* - the time duration for a call connection from the call initialization to the call completion.
- *Cell residence time* - the time duration for a call connection elapsed from the instant the mobile station enters the coverage of a cell to the moment the mobile station leaves the coverage of the serving cell.
- *Residual cell residence time* - the time duration for a call connection from the successful call origination to the moment the mobile station leaves the coverage of the serving cell.
- *Channel holding time* - the time duration an active call holds a channel in a cell.
- *Handoff dwell time* - the time duration an MS spends in the overlapped area of two cells.

1.3 Literature Survey

The wireless network tele-traffic modeling and performance evaluation has attracted the extensive research interest (see [11] [17] [35] and the reference therein). D.Hong

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and S.S.Rappaport [11] studied the guard channel (GC) scheme and the handoff call queueing priority scheme (QPS) and provided the basis for the extendable research in the area of traffic model and performance for wireless (cellular) network. S.S.Rappaport *et al.* [12] [13] [14] [15] subsequently reported the performance of wireless cellular systems supporting diverse services and mixed platforms. Yoon and Un [31] compared three call handling schemes and their performances under the assumption of Poisson arrival call process and Poisson departure process. Yum and Yueng [16] proposed the directed retry scheme to protect the handoff call from rejection and the results demonstrated that the performance in terms of blocking probabilities can be greatly increased. S. Tekinay and B. Jabbari [20] developed a measurement-based handoff call prioritization policy to re-order the waiting handoff call in the waiting buffer on the basis of the signal level. The simulation and the analytical results showed that the scheme can significantly decrease the handoff call blocking probability. Y.B.Lin *et al.* [17] proposed that the handoff call arrival rate is not an input parameter, but related to the other tele-traffic parameters such as new call arrival rate, call holding time distribution, the cell residence time distribution, and the blocking probability. Additionally, the closed-form formula for the handoff rate was given under the general cell residence time distribution function and an iterative algorithm is proposed due to the correlation of the call arrival rate and the significant performance metrics. The algorithm has been widely accepted and validated. Y.B.Lin *et al.* [18] presented and analyzed the sub-rate strategy (SRS) based on the observation that the data rate of an active call can be halved to tradeoff the blocking probabilities. The adaptive characteristics of the SRS was further applied in the wireless multimedia network [26] [27] [28] [29]. W. Zhuang *et al.* utilized the adaptive characteristics of data rate and analyzed the performance on the basis of classical exponential assumptions. C. Oliveira [28] applied the reasoning in the GSM network and also obtained the similar conclusion. Bong Dae Choi [29] generalized the bandwidth requirement for a call connection in SRS and

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applied the scheme into the UMTS multimedia network. In addition, the call-level as well as the packet-level performance were studied. The number of works by Li Wei and co-workers [21] [22] [23] [25] have studied the network performance as well as the call performance with the generalized tele-traffic parameters in the wireless network applying GC or QPS. The recent proposed channel allocation scheme or call admission control algorithm or the handoff call priority scheme are basically the mixture of the aforementioned policies [21] [22] [23] [25] [30] [32] [33] [34] [105] [108]. The studies [106] [107] [110] have contributed the wireless network performance from the perspective of network availability and system reliability.

The extensive experiments examining the exponential distribution for the critical tele-traffic parameters such as call inter-arrival time, call holding time or cell residence time in both the wireline, as well as the wireless systems [51] [52] [53] [54] [68] has driven the recent study for the wireless mobile network performance evaluation under the general assumptions for such crucial parameters [35] [64] [55] [66] [19] [46]. It has been popularly accepted that there is no universally valid function for the call holding time or cell residence time or channel holding time, and hence developing the general closed-form formula for the performance metrics of interest is much more significant than specifying a particular distribution function for the important tele-traffic parameters. Yuguang Fang *et al.* [35] [36] [37] [38] [39] [40] [41] [42] [43] [44] extensively investigated the sensitivity problem in wireless network performance evaluation. In particular, for the channel holding time [37] the exponential assumption was examined. The closed-form formula for the call complete probability [36], the call dropping probability and the handoff rate [37] were developed under the general call holding time and general cell residence time distribution function. The new Hyper-Erlang mobility model was also proposed to model the call holding time, which has been proven to be able to arbitrarily closely approximate to the distribution of any positive random variable

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as well as measured data [40] [64] [76]. P.V.Orlik and S.S.Rappaport [55] proposed a model called the SOHYP (the Sum of the Hyper-Exponential) distribution to model the channel holding time and cell dwell time (i.e., the cell residence time). By showing that the coefficient of variation (the ratio of square root of variance to mean) can be flexibly adjusted to be less than, equal and greater than unity, they showed the generality of the SOHYP models. The recent work [66] presented the performance analysis of hierarchical cellular system under the general call holding time and cell residence time assumption. For the sake of analytical tractability, the call duration distribution is approximated by a two-phase hyper-exponential distribution with the identical first and second moments based on the original general distribution. In essence, the analysis technique is based on Markovian assumptions as regards the traffic flows entering both microcells and macrocells, as well as an assumption of flow balance between handovers into and out of any cell. K. Yeo and C.-H. Jun [64] presented an analytic model for the performance evaluation of hierarchical cellular systems supporting the overflow strategy while the call time and the cell residence time are generally distributed. In particular, the Laplace transform of the channel occupancy time distribution for each call type is derived as a function of the Laplace transform of cell residence time based on the hyper-Erlang call connection time. The comparison shows that the distribution type of call connection time and cell residence time have significant influence on the performance measure and that the exponential case may severely underestimate the system performance. T.S.Dharmaraja *et.al.* [111] studies the cellular network performance with generalized inter-handoff arrival distribution. Y.-B Lin [19] utilized the Erlang distribution to model the call holding time and obtained the closed-form result for the call completion probability. Based on the expression, the effects of the mobility and the call holding time distribution were further discussed. I.F. Akyildiz and W.Y. Wang [46] generalized the sojourn time within the location area (LA) and employed the Gamma distribution modeling the cell residence time in the location management

cost evaluation. Yuguang Fang [43] obtained the closed-form formula for the location update and paging cost for the IS-41 [45], the pointer forwarding scheme (PFS) and the two location algorithm (TLA) under the general assumption of the residence time in a LA. The numerical results demonstrated and found that the classical exponential may result in wrong decision in cost evaluation. Furthermore, Yuguang Fang [44] derived the closed-form expression for the sum of the location update and paging in the movement-based location management scheme under the general assumption of the residence time in a LA. The tradeoff analysis and discussion show that the distribution plays a significant role in location update cost analysis.

1.4 Problem Formulation

In this section, we will present the motivation of our study and then restate the important problems still open to investigation or those need further research.

The common feature of the aforementioned studies related to wireless network performance evaluation is the attempt to analyze or simulate the effect of the limited capability in the radio interface based on the assumption that the link layer can reliably combat the signal degradation and thus the call level is not affected by the erroneous wireless channel. As a consequence, the wireless link unreliability adverse impact upon the network or call performance is ignored.

However, it is well-known that wireless mobile networks are quite error prone. Every wireless system has to combat the impaired environment during the transmission and propagation that are nonexistent in a wired companion. The critical technical bottlenecks and the two fundamental natures of a wireless link in any wireless network are the limited capacity of the radio channel, its vulnerability due to adverse time-varying,

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multi-path propagation and severe interference from other transmissions in the same or a neighboring cell. In particular, three mutually independent, multiplicative propagation phenomena can usually be distinguished: multi-path fading, shadowing and large-scale path loss [112].

Multi-path reception refers to the following phenomenon. The signal offered to the receiver contains not only a direct line-of-sight radio wave, but also a large number of reflected radio waves. These reflected waves will interfere with the direct wave, which may cause substantial degradation of the network performance. A wireless mobile network is required to be designed and implemented in such a way that the negative effect of these reflections is minimized. Usually the Rayleigh, Nakagami or Rician model is applied to address the channel behavior for multi-path reception. More specifically, channel impairments such as fading and multi-path dispersion are evaluated with respect to the Doppler spread, the time constants of fading, fade durations, level crossing rates, Rayleigh, Rician or Nakagami amplitude probability densities and the coherence bandwidth.

Shadowing is another inherent property of the wireless link and is characterized as a medium-scale effect, which means that the field strength variations occur if the antenna is located over distances larger than a few tens or hundreds of meters. Shadowing also introduces additional signal fluctuations. Hence, the received local-mean power, defined as the signal level averaged over a few tens of wavelengths, varies around the area-mean which denotes the power level averaged over an area of tens or hundreds of meters. The local propagation mechanisms is determined by terrain features in the immediate vicinity of the antennas.

The large-scale path loss causes the received power to vary gradually due to the signal attenuation between transmit and receive antenna as a function of the propaga-

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tion distance and other parameters. The attenuation is determined by the geometry of the path profile in its entirety and some models can exam many details of the terrain profile to estimate the signal attenuation. Experiments have showed that, for paths longer than a few hundred meters, the received power fluctuates with a log-normal distribution about the area-mean power. A rapid moving vehicle resulted in dramatic changes of the received field strength.

In short, the wireless/mobile system is notorious for the highly time-varying and unreliable wireless channel due to the propagation impairments such as multi-path fading, shadowing or path loss. The reason for a large part of dropped calls is due to the poor channel conditions. For instance, the main cause and criteria for handoff is essentially the weak signal power resulting from the severe channel degradation. Hence, it is more reasonable to study the wireless network performance by taking into consideration the effect of wireless channel impairment characteristics in the mobile network.

On the other hand, in investigating the wireless link unreliability impact on the call performance, the general assumption for the critical tele-traffic parameters should be employed to develop the generalized results in order to apply in the next generation wireless multimedia network. In addition, the sensitivity problems of the parameters needs further investigation in the highly promising hierarchical architecture network.

1.5 Contributions of the Thesis

Based upon the formulated problems in the previous section, we summarize the major contributions below:

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1. A novel analytical model is proposed to study the wireless link unreliability effect on the wireless mobile network performance with respect to the call complete probability and call complete ratio. The analysis result is validated by the simulation.
2. Both the wireless link unreliability and the resource insufficiency effects are taken into account in evaluating the wireless mobile network performance. The closed-form formula for the performance metrics call complete probability and the closed-form result for the probability density function of the completed call holding time under the general call holding time, general cell residence time and the typical wireless channel model. The analysis result is also validated by the extensive simulation. The comparison demonstrates that there is a considerable performance gap in applying different call holding time distribution. It is shown that the network performance will be substantially overestimated without integrating the unreliable wireless link impact.
3. The sensitivity of the handoff dwell time in the stand-alone wireless network, and the sensitivity of the critical tele-parameters such as call holding time or cell residence time or channel holding time in hierarchical cellular network are analyzed or simulated.

1.6 Thesis outline

This dissertation is organized as follows. In the next chapter, we study the call performance in the presence of the adverse wireless channel in terms of the call complete probability and the call complete ratio under the general call holding time and Gilbert-Elliott channel model. It is found that the wireless channel patterns have a significant

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effect upon the call performance and the call holding time sensitivity problem exists. In Chapter 3, we will study the call performance taking into account the limited bandwidth as well as the unreliable wireless link. The critical tele-traffic parameters such as the call holding time, the cell residence time and hence the channel holding time are assumed to follow the general distributions. In addition, the wireless channel model is also generalized with the general good/bad state distribution function due to the applicability of different channel model under diverse scenarios. The closed-form formula for the call complete probability and for the pdf of the completed call holding time are derived. The results show that the performance will be greatly overestimated with the absence of the wireless link. Again, the sensitivity problem with respect to the call holding time and the cell residence time still hold. Chapter 4 further presents the handoff dwell time sensitivity, which has not studied before. For this, the queueing priority scheme is adopted. Numerous extensive simulation and analytical results demonstrate that the handoff dwell time distribution function has a significant impact on the handoff call blocking probability, but negligible effect upon the new call blocking probability and the call complete probability. Chapter 5 studies the handoff counting in hierarchical cellular system supporting the overflow scheme. In Chapter 6, the characteristics of the channel holding time in hierarchical cellular system supporting both the overflow and the underflow scheme is developed in terms of the pdf and the expected value with the general call holding time and cell residence time, either in microcell or in macrocell. Chapter 7 presents the contribution of the novel resource management in GSM/GPRS network. Finally, chapter 8 concludes the thesis and provide a number of future research directions.

Chapter 2

The Effect of the Wireless Link Unreliability on Mobile Network Performance

2.1 Introduction

With the explosive demand and growing rate of the wireless/mobile network, considerable studies have discussed the problem when the call is blocked due to insufficient resources (time slot for TDMA, frequency for FDMA or code for CDMA) [11]-[41]. The mobile network performance evaluation as well as the call behavior characteristics is usually analyzed or simulated based on the assumption that the link layer can reliably combat the signal degradation at the lower layers and thus the call level is not affected by the erroneous wireless channel. However, it is known that wireless/mobile system is notorious for the highly time-varying and unreliable wireless channel due to the propagation impairments such as multi-path fading, shadowing and path loss. The reason

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for a large part of dropped calls is due to the poor channel conditions. For instance, the main cause and criteria for handoff is essentially the weak signal power resulting from the severe channel degradation. Hence, it is more reasonable to study the call-level performance and packet-level performance together with the effect of wireless physical channel impairment characteristics in the mobile network.

In this research direction, packet-level performance analysis or Quality of Service (QoS) provision with the effect of wireless channel have attracted extensive research interest[47]-[50]. By contrast, the characteristics of call behavior taking into account the effect of degraded channel has not attracted much attention. To reflect the impact of time-varying wireless channel on the call behavior, the usual QoS measures such as call blocking probability and the forced termination probability representing the resource insufficiency are inappropriate. Under such conditions, the critical questions are: i) the probability that a call can be completed successfully. After a call is originated, the physical link between Base Station(BS) and Mobile Station(MS) may become degraded during the conversation. Hence, the call may be terminated abnormally. From the perspective of user, it is undesirable to terminate a call connection during the communication. From the service provider's point of view, the probability can reflect the user's satisfaction and provide the statistical characteristics of wireless channel in order to design more reliable services. As a consequence, the probability is significant for both the users and the service providers. ii) how much of the requested call holding time is finished. If a call is forced to terminate due to the severely impaired wireless channel, the percentage of time that the call holding time has actually finished is important for the service provider since this quantity is informative to design a reasonable charging policy by compensating the terminated connection. In addition, if the completed percentage is small, the caller will redial the same callee more times to accomplish the call holding time. This gives rise to much heavier signalling burden on the network. Hence,

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for the network service provider, this quantity is crucial to plan the pricing policy and to implement a scheme to minimize the signalling cost.

Therefore, we introduce the corresponding performance metrics *call complete probability* and *call complete ratio*. The call complete probability is defined as the probability that the call connection can be completed successfully under the unreliable wireless environment. For instance, if the probability is 0.9, a call has 90% opportunity to complete without dropping. The call complete ratio is defined as the proportion between the actually completed call connection time and the requested call holding time. For example, if the call complete ratio is 0.5, the actually completed call connection duration is half of the required call holding time. The definitions imply that the former index focuses on the completed call while the latter one takes into account the successfully completed calls and the failed ones.

In the performance metrics derivation, the exponential call holding time distribution has been widely assumed for the sake of analysis simplicity and tractability [11]. However, some recent results have been presented showing that this assumption is not realistic [52] [53] [54]. In his study [52], V.-A. Bolotin stated that the exponential assumption may not be valid for modern telephone services and proposed the lognormal distribution [58] to approximate the wireline call holding time. E. Chlebus [53] applied the Anderson-Darling test to show that call duration in mobile telephony follows the same patterns as shown in [52] for fixed telephony. The long tailed nature of the call holding time was found in [54]. For wireless mobile network, besides the exponential assumption, Erlang call holding time is utilized to study the blocking phenomena caused by the limited bandwidth [19]. The sum of hyperexponential(SOHYP) distribution, which has the advantage of approximating the behavior of any positive random variable and preservation of the Markovian property, is applied to model the call holding time [55]. As a result, there is no universally valid function for the call holding time. In

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this chapter, the call holding time distribution is not dedicated to a specific function, but a general one to derive the proposed call performance metrics.

To summarize, the contributions of this chapter are to: i) present a new model to study the call performance taking into account the inherently unreliable wireless channel; ii) introduce the appropriate QoS parameters *call complete probability* and *call complete ratio* to show the impact of wireless channel error characteristics on call behavior; iii) provide the numerical tractable formula for the performance metrics with general call holding time distribution; iv) perform a numerical study evaluating the effect of impaired wireless link and the sensitivity problem with respect to the call holding time distribution.

The rest of the chapter is organized as follows. In Section 2.2, we describe the typical call trajectory with wireless channel model. The effect of link layer error protection and the performance measurements in terms of call complete ratio and call complete probability with general call holding time are analyzed in the Section 2.3. Numerical results are given in Section 2.4, followed by concluding remarks in Section 2.5.

2.2 System Model

2.2.1 Wireless Channel Model

Fig.2.1 illustrates the model of a typical trajectory of a MS roaming in a wireless mobile network with impaired channel. The notation t_c represents the call holding time.

For the time-varying channel, the Gilbert-Elliot model [9] [10] has been widely used to capture the periods of signal degradation [47]-[50]. In this two-state Markov Chain model, the state space of the wireless channel consists of $\Omega = \{good, bad\}$. The channel

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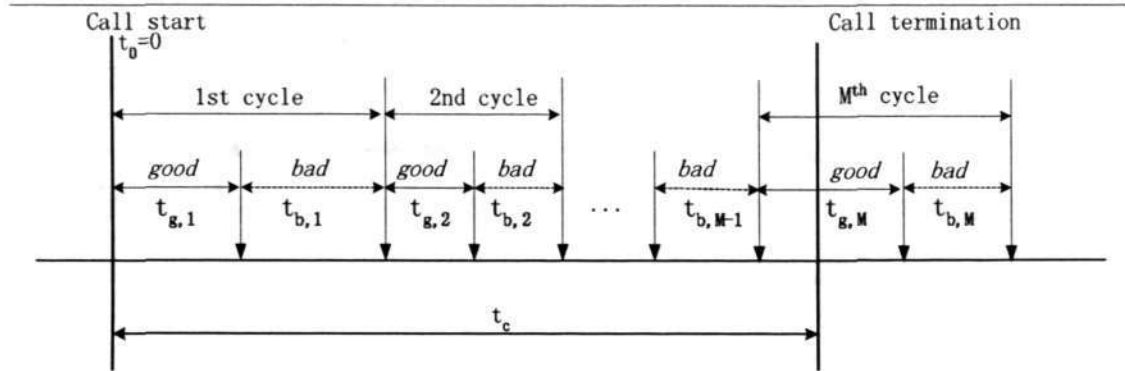


Figure 2.1: The time diagram for a call within a mobile network with unreliable wireless channel.

stays in good state for an exponentially distributed of time duration with a mean $1/\mu_g$. Then, it changes into the bad state and stays for an exponentially distributed period with a mean $1/\mu_b$. It is assumed that calls in good channel state can communicate with error free and those in bad channel state may, but not definitely, failed to complete the conversation owing to the broken link. Without loss of generality, we denote the time when a call is initialized as $t_0 = 0$. The call experiences the wireless channel the good state and bad state, alternatively. Define a *cycle* as the continuous good state and its next consecutive bad state. The time duration of good state during cycle i is denoted as $t_{g,i}$, where notation g represents good; and the interval in bad state during cycle i is denoted as $t_{b,i}$, where notation b stands for bad.

2.2.2 Link Re-establishment Procedure

The functionality of error handling is one of the key modules in BS software, wherein the component to handle the unreliable wireless channel is the core consideration. As the wireless channel associated with an ongoing call degrades, the BS should be able to monitor such degradation and notify the relevant module to deal with this condition, i.e. try to re-establish the impaired channel. Upon the time when the channel turns from a

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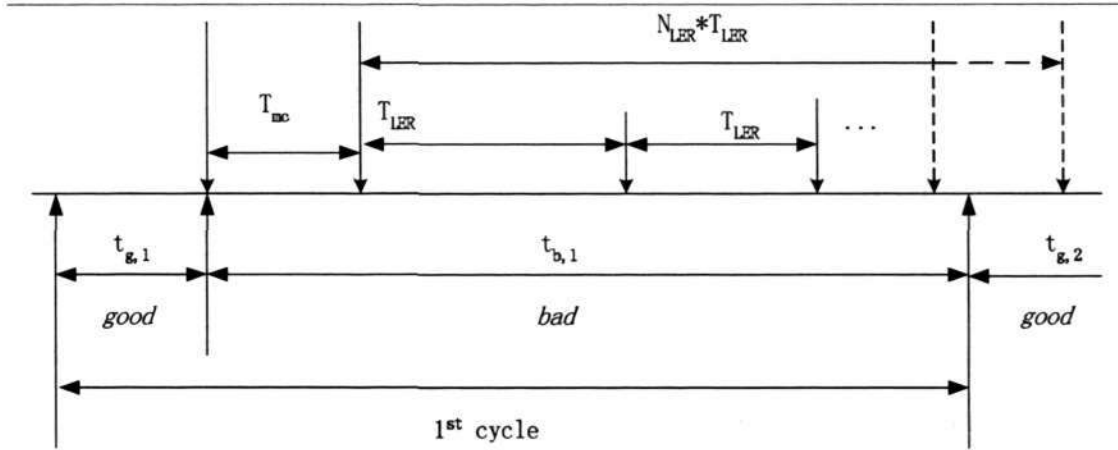


Figure 2.2: Link re-establishment procedure in the channel bad state.

good state into a bad state, the call may not be dropped immediately because of the link layer error protection scheme. Usually there is a timer, called as Monitoring Channel Timer(MCT) T_{mc} in this procedure as shown in Fig. 2.2, in link layer to monitor the channel state. As the channel becomes worse and no messages are exchanged between MS and BS during the duration T_{mc} , LINK-ReESTABLISH-REQUEST message is sent uplink from MS to BS or vice versa with the attempt to re-establish the physical link. Upon sending the message LINK-ReESTABLISH-REQUEST, the timer TIMER-LER with length T_{LER} is started to monitor the message transmission, if no acknowledgement LINK-ReESTABLISH-ACK is received in the duration T_{LER} , TIME-LER times out. Then, message LINK-ReESTABLISH-REQUEST is sent out again. If after N_{LER} times attempts and no message LINK-ReESTABLISH-ACK received, the voice channel is released and can be used by other users. Practically, T_{LER} is very small since its value is determined under good environment. In particular, in GSM system, Radio Link Protocol(RLP) uses a fixed retransmission timer recommended as 480 ms(full rate) or 780 ms(half rate), and the maximum number of retransmissions recommended as 6 [56]. In Universal Mobile Telecommunication System(UMTS), Radio Resource Control (RRC) protocol recommends the length of the retransmission timer T300 as 1000ms

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and the maximum number of retransmission $N_{300}=3$ [63]. On the other hand, the link re-establishment procedure is also related to the impatience characteristics of the users since too long re-establishment will usually make the user impatient and thus press the "Cancel" button on the phone. Hence, the result of link re-establishment procedure depends on the system configuration as well as on the user's behavior.

2.3 Performance Analysis

Let t_c be the call holding time with the probability density function (p.d.f.) $f_{t_c}(t)$ and cumulative distribution function (c.d.f.) $F_{t_c}(t)$. Denote the Laplace-Stieltjes Transform (LST) of the p.d.f. $f_{t_c}(t)$ as $f_{t_c}^*(s)$. Let $t_{g,i}(i = 1, 2, \dots)$ be exponentially independent and identical distributed (i.i.d.) random variables with the mean $1/\mu_g$, and $t_{b,i}(i = 1, 2, \dots)$ the i.i.d. exponentially distributed random variables with the average $1/\mu_b$. Hence, the p.d.f. of $t_{g,i}$ and $t_{b,i}(i = 1, 2, \dots)$ are, respectively, given by

$$f(t_{g,i}) = \mu_g e^{-\mu_g t_{g,i}}; \quad t_{g,i} \geq 0, \quad i = 1, 2, \dots \quad (2.1)$$

$$f(t_{b,i}) = \mu_b e^{-\mu_b t_{b,i}}; \quad t_{b,i} \geq 0, \quad i = 1, 2, \dots \quad (2.2)$$

2.3.1 Link Re-establishment Successful Probability

After the expiration of the timer MCT when the channel becomes worse and transits into a bad state, BS detects the link broken state and consequently a number of consecutive timer TIMER-LERs are probably started to try reestablishing the link with the MS. To present the attempt of the link re-establishment procedure, we define the link re-establishment successful probability as the probability that the physical link is successfully re-established during channel bad state.

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Let T_u be the user's impatience time. Let us denote its p.d.f. and LST of p.d.f. as $f_{T_u}(t)$ and $f_{T_u}^*(s)$, respectively. Due to i.i.d. property of random variables $t_{g,i}$ ($i = 1, 2, \dots$) and $t_{b,i}$ ($i = 1, 2, \dots$), the link re-establishment successful probabilities are the same during the channel bad state in any cycle, and therefore we will focus on the first cycle to derive the link re-establishment successful probability P_s .

A physical link may be failed to be re-established due to one of the following reasons.

1. Event \mathcal{B}_1 : user's impatience time T_u is less than $t_{b,1}$.
2. Event \mathcal{B}_2 : all the re-establishment attempts are failed. Namely, the wireless channel remains in the bad state after the maximum number N_{LER} of link re-establishment attempts.

Since the event \mathcal{B}_1 is solely related to mobile user's own behavior while the event \mathcal{B}_2 is only relevant to the system characteristics, these two events can be reasonably regarded independent. Hence, we have

$$P_s = 1 - Pr(\mathcal{B}_1 \text{ or } \mathcal{B}_2) = 1 - [Pr(\mathcal{B}_1) + Pr(\mathcal{B}_2) - Pr(\mathcal{B}_1\mathcal{B}_2)] \quad (2.3)$$

where

$$Pr(\mathcal{B}_1) = Pr(T_u < t_{b,1}) \quad (2.4)$$

$$Pr(\mathcal{B}_2) = Pr(T_{mc} + N_{LER}T_{LER} < t_{b,1}) \quad (2.5)$$

$$Pr(\mathcal{B}_1\mathcal{B}_2) = Pr(T_u < t_{b,1}, T_{mc} + N_{LER}T_{LER} < t_{b,1}) \quad (2.6)$$

Remark that the timer length T_{LER} for monitoring the message LINK-ReESTABLISH-REQUEST transmission has no essential difference from any other expiration verification which is used to monitor the message between BS and MS. In implementation,

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T_{LER} can be regarded as a fixed constant in BS software. The maximum number of re-transmitting message LINK-ReESTABLISH-REQUEST N_{LER} is also a fixed constant. Denote the p.d.f. and LST transform of the random variable T_{mc} as $f_{T_{mc}}(t)$ and $f_{T_{mc}}^*(s)$. Then, the probability for the event \mathcal{B}_1 is given by

$$\begin{aligned} Pr(\mathcal{B}_1) &= \int_0^\infty Pr(t_{b,1} > t) f_{T_u}(t) dt \\ &= f_{T_u}^*(\mu_b). \end{aligned} \quad (2.7)$$

Similarly, the probability for the event \mathcal{B}_2 is given by

$$\begin{aligned} Pr(\mathcal{B}_2) &= Pr(t_{b,1} > T_{mc} + N_{LER}T_{LER}) \\ &= f_{T_{mc}}^*(\mu_b) e^{-\mu_b N_{LER}T_{LER}} \end{aligned} \quad (2.8)$$

The probability for the simultaneous occurrence of the events \mathcal{B}_1 and \mathcal{B}_2 is given by

$$Pr(\mathcal{B}_1\mathcal{B}_2) = Pr(T_u < t_{b,1}, T_{mc} + N_{LER}T_{LER} < t_{b,1}) \quad (2.9)$$

$$= \int_0^\infty Pr(T_u < t) Pr(T_{mc} + N_{LER}T_{LER} < t) \mu_b e^{-\mu_b t} dt \quad (2.10)$$

$$= \int_{N_{LER}T_{LER}}^\infty Pr(T_u < t) Pr(T_{mc} + N_{LER}T_{LER} < t) \mu_b e^{-\mu_b t} dt \quad (2.11)$$

$$= \int_{N_{LER}T_{LER}}^\infty \int_0^t f_{T_u}(x) dx \int_0^{t-N_{LER}T_{LER}} f_{T_{mc}}(y) dy \mu_b e^{-\mu_b t} dt \quad (2.12)$$

where we have put the probability $Pr(T_{mc} + N_{LER}T_{LER} < t) = 0$ as $0 \leq t \leq N_{LER}T_{LER}$.

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By substituting (2.7) (2.8) (2.12) into (2.3), we obtain

$$P_s = 1 - f_{T_u}^*(\mu_b) - f_{T_{mc}}^*(\mu_b)e^{-\mu_b N_{LER} T_{LER}} + \int_{N_{LER} T_{LER}}^{\infty} \int_0^t f_{T_u}(x) dx \int_0^{t-N_{LER} T_{LER}} f_{T_{mc}}(y) dy \mu_b e^{-\mu_b t} dt \quad (2.13)$$

We assume that the timer length T_{mc} follows exponential distribution with average $1/\mu_{mc}$. The user's impatience duration is assumed to be exponentially distribution with mean $1/\mu_u$, and this has been popularly used in mobile network performance evaluation [57] [24]. In this case, after several manipulations, the probability for successful link re-establishment becomes

$$P_s = \frac{\mu_b}{\mu_b + \mu_u} + \mu_b e^{-(\mu_b + \mu_u) N_{LER} T_{LER}} \left[\frac{1}{\mu_{mc} + \mu_u + \mu_b} - \frac{1}{\mu_b + \mu_u} \right]. \quad (2.14)$$

2.3.2 Call Complete Probability Derivation

On the average, the duration elapsed from the instance the wireless channel turning into good state to the time the user continues the conversation (if the link is re-established successfully) is $T_{LER}/2$. Since this interval is very short compared with the call holding time, we ignore its effect and assume that if the call is not forced to block by the impaired channel, the user can continue his communication upon the instant as the channel changes to the good state. Let M denote the number of cycles needed for a user to complete the communication successfully without termination. Note that no messages are exchanged between MS and BS during the channel's bad state which is represented by the dashed line in Fig.2.1. Observing the time diagram in Fig.2.1, it is evident that: $M = 1$ if and only if the call holding time t_c is shorter than the wireless channel good state time duration $t_{g,1}$ in the first cycle; $M = 2$ if and only if

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the call holding time t_c is larger than $t_{g,1}$, but not longer than the summation of the channel good states during the first and second cycles, i.e. $t_{g,1} + t_{g,2}$, and so on. As a consequence, we develop the necessary and sufficient condition for $M = m$ given by the inequality

$$\sum_{i=1}^{m-1} t_{g,i} < t_c \leq \sum_{i=1}^m t_{g,i} \quad (2.15)$$

As stated, we can *not* use the expression below to determine $M = m$ since MS can not exchange messages with BS during channel bad state.

$$\sum_{i=1}^{m-1} t_{g,i} + \sum_{i=1}^{m-1} t_{b,i} < t_c \leq \sum_{i=1}^m t_{g,i} + \sum_{i=1}^{m-1} t_{b,i} \quad (2.16)$$

Denote

$$\xi_m = t_{g,1} + \cdots + t_{g,(m-1)} + t_{g,m} \quad (2.17)$$

Let $f_{\xi_m}(t)$, $F_{\xi_m}(t)$ and $f_{\xi_m}^*(s)$ denote the p.d.f., c.d.f. and the LST of p.d.f. for the nonnegative random variable ξ_m . The LST of ξ_m is given as

$$f_{\xi_m}^*(s) = \mathbb{E}[e^{-s\xi_m}] = \prod_{i=1}^m \mathbb{E}[e^{-st_{g,i}}] = \left(\frac{\mu_g}{s + \mu_g} \right)^m \quad (2.18)$$

where $\mathbb{E}(X)$ represents the expected value of random variable X . From the LST of ξ_m , the p.d.f. and the c.d.f. are thus given by

$$f_{\xi_m}(t) = \frac{\mu_g(\mu_g t)^{m-1}}{(m-1)!} e^{-\mu_g t}; \quad (2.19)$$

$$F_{\xi_m}(t) = \int_0^t f_{\xi_m}(x) dx = 1 - \sum_{k=0}^{m-1} \frac{(\mu_g t)^k}{k!} e^{-\mu_g t} \quad (2.20)$$

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It is known that the distribution of ξ_m is the Erlang distribution with parameter μ_g and m [59]. Hence, the probability $Pr(M = m)$ can be written as

$$Pr(M = m) = Pr(\xi_{m-1} < t_c \leq \xi_m) = \int_0^\infty (F_{\xi_{m-1}}(t) - F_{\xi_m}(t)) f_{t_c}(t) dt \quad (2.21)$$

$$= \frac{\mu_g^{m-1}}{(m-1)!} a_{m-1}(\mu_g) \quad (2.22)$$

where

$$a_k(x) = \int_0^\infty t^k e^{-xt} f_{t_c}(t) dt = (-1)^k \left(\frac{d^k f_{t_c}^*(s)}{ds^k} \right) \Big|_{s=x} \quad (2.23)$$

with $a_0(x) = f_{t_c}^*(x)$. After normalizing the probability $Pr(M = m)$, we have

$$Pr(M = m) = \frac{\frac{\mu_g^{m-1}}{(m-1)!} a_{m-1}(\mu_g)}{\sum_{i=1}^\infty \frac{\mu_g^{i-1}}{(i-1)!} a_{i-1}(\mu_g)} \quad (2.24)$$

Due to the unreliability of wireless channel, a call may be dropped without completing the required M cycles. Let \widehat{M} denote the actual number of cycles a user experienced. If the physical link is successfully re-established during all the bad channel states the user experiences, then \widehat{M} is equal to M and hence the call is normally completed. As a consequence, we have the following expression

$$Pr(\widehat{M} = m | M = m) = P_s^{m-1} \quad (2.25)$$

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Referring to the definition of call complete probability P_{cc} , we obtain

$$P_{cc} = \sum_{m=1}^{\infty} Pr(\widehat{M} = m, M = m) = \sum_{m=1}^{\infty} Pr(\widehat{M} = m | M = m) Pr(M = m) \quad (2.26)$$

$$= \frac{\sum_{m=1}^{\infty} \frac{\mu_g^{m-1}}{(m-1)!} a_{m-1}(\mu_g) \cdot P_s^{m-1}}{\sum_{i=1}^{\infty} \frac{\mu_g^{i-1}}{(i-1)!} a_{i-1}(\mu_g)} \quad (2.27)$$

Next, we have the following specific distributions cases for commonly used call holding time distribution.

- Exponential $f_{t_c}(t) = \mu_c e^{-\mu_c t}$

$$a_k(x) = \frac{k! \mu_c}{(\mu_c + x)^{k+1}} \quad (2.28)$$

$$\Rightarrow P_{cc} = \frac{\mu_c}{\mu_c + \mu_g - \mu_g P_s} \quad (2.29)$$

- n-order Hyperexponential $f_{t_c}(t) = \sum_{i=1}^n \alpha_i \eta_i e^{-\eta_i t}$, $\sum_{i=1}^n \alpha_i = 1$, ($n \in \mathcal{N}, 0 \leq \alpha_i \leq 1, \eta_i > 0$)

$$a_k(x) = \sum_{i=1}^n \alpha_i \frac{k! \eta_i}{(\eta_i + x)^{k+1}} \quad (2.30)$$

$$\Rightarrow P_{cc} = \frac{1}{n} \sum_{i=1}^n \alpha_i \frac{\eta_i}{\eta_i + \mu_g - \mu_g P_s} \quad (2.31)$$

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-
- n-stage Erlang $f_{t_c}(t) = \frac{(n\nu)^n t^{n-1}}{(n-1)!} e^{-n\nu t}$, ($n \in \mathcal{N}, \nu > 0$)
-

$$a_k(x) = \frac{n(n+1) \cdots (n+k-1)(n\nu)^n}{(n\nu+x)^{n+k}} \quad (2.32)$$

$$\Rightarrow P_{cc} = \frac{\sum_{i=1}^{\infty} \binom{n+i-2}{i-1} \left(\frac{\mu_g P_s}{n\nu+\mu_g} \right)^{i-1}}{\sum_{i=1}^{\infty} \binom{n+i-2}{i-1} \left(\frac{\mu_g}{n\nu+\mu_g} \right)^{i-1}} \quad (2.33)$$

where $\binom{x}{y} = \frac{x!}{y!(x-y)!}$ for non-negative integer x and y .

2.3.3 Call Complete Ratio Derivation

If the call connection duration is less than or equal to the length of the channel good state during the first cycle, then the required number of cycles $M = 1$, the user will not encounter degraded channel condition. In this case, the actual experienced number of cycles $\widehat{M} = M = 1$.

In case of $M = m \geq 2$, the MS will experience $m - 1$ channel bad state before the normal call completion(if available). \widehat{M} is equal to 1 if the call is dropped during the channel bad state in the first cycle. \widehat{M} can be 2 if the physical link is successfully re-established during the first cycle but failed in the second cycle. Similarly, \widehat{M} can be k ($k < m$) if the physical link is successfully re-established during the 1st, 2nd \dots , $(k-1)^{th}$ cycle but failed in the k^{th} cycle.

Recalling the probability P_s that a wireless link is successfully re-established, we obtain the conditional probability that the call has completed k cycles given the condition

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that the call is required to complete m cycles.

$$Pr(\widehat{M} = k | M = m) = \begin{cases} P_s^{k-1}(1 - P_s) & k = 1, 2 \dots m-1; \\ P_s^{m-1} & k = m; \end{cases} \quad (2.34)$$

Denote γ as the call complete ratio, which is defined as the proportion between the actual completed call length to the required call holding time. The call complete ratio γ is given by

$$\gamma = \begin{cases} \frac{t_{g,1}}{t_c}, & \widehat{M} = 1; \\ \frac{t_{g,1}+t_{g,2}}{t_c}, & \widehat{M} = 2; \\ \vdots & \\ \frac{t_{g,1}+t_{g,2}+\dots+t_{g,m-1}}{t_c}, & \widehat{M} = m-1; \\ 1, & \widehat{M} = m; \end{cases} \quad (2.35)$$

Denote

$$\gamma_k = \frac{t_{g,1} + t_{g,2} + \dots + t_{g,k}}{t_c} = \frac{\xi_k}{t_c}; \quad k = 1, 2 \dots m-1 \quad (2.36)$$

We have shown that ξ_k follows Erlang distribution. Hence, for $0 \leq t \leq 1$, the c.d.f. of γ_k is given by

$$\begin{aligned} F_{\gamma_k}(t) &= Pr(\gamma_k \leq t) = \int_0^\infty \int_0^{t\tau} f_{\xi_k}(u) du f_{t_c}(\tau) d\tau \\ &= 1 - \sum_{j=0}^{k-1} \frac{(\mu_g t)^j}{j!} \int_0^\infty \tau^j e^{-\mu_g t \tau} f_{t_c}(\tau) d\tau \\ &= 1 - \sum_{j=0}^{k-1} \frac{(\mu_g t)^j}{j!} a_j(\mu_g t) \end{aligned} \quad (2.37)$$

Specifically when $t < 0$, $F_{\gamma_k}(t) = 0$ and $t > 1$, $F_{\gamma_k}(t) = 1$. Thus, the probability density

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distribution of γ_k is calculated by taking derivative on the c.d.f. function

$$f_{\gamma_k}(t) = \frac{dPr(\gamma_k \leq t)}{dt} = - \sum_{j=0}^{k-1} \frac{\mu_g^j t^{j-1}}{j!} \left[j a_j(\mu_g t) + t \frac{da_j(\mu_g t)}{dt} \right]; \quad 0 \leq t \leq 1 \quad (2.38)$$

We further have

$$\frac{da_j(\mu_g t)}{dt} = \frac{d \left(\int_0^\infty \tau^j e^{-\mu_g t \tau} f_{t_c}(\tau) d\tau \right)}{dt} = -\mu_g a_{j+1}(\mu_g t) \quad (2.39)$$

Substituting (2.39) into (2.38), we obtain

$$f_{\gamma_k}(t) = - \sum_{j=0}^{k-1} \frac{\mu_g^j t^{j-1}}{j!} [j a_j(\mu_g t) - \mu_g t a_{j+1}(\mu_g t)] = \frac{\mu_g^k t^{k-1}}{(k-1)!} a_k(\mu_g t); \quad 0 \leq t \leq 1 \quad (2.40)$$

For $t < 0$ or $t > 1$, $f_{\gamma_k}(t) = 0$. Hence, the p.d.f. of γ_k is given by

$$f_{\gamma_k}(t) = (G_k)^{-1} \cdot \frac{\mu_g^k t^{k-1}}{(k-1)!} a_k(\mu_g t); \quad 0 \leq t \leq 1 \quad (2.41)$$

where the constant $G_k = \int_0^1 \frac{\mu_g^k t^{k-1}}{(k-1)!} a_k(\mu_g t) dt$ is determined by the normalization constraint $\int_0^1 f_{\gamma_k}(t) dt = 1$.

The expected value of γ_k is expressed as

$$\mathbb{E}(\gamma_k) = \int_0^1 t f_{\gamma_k}(t) dt = \frac{1}{G_k} \frac{\mu_g^k}{(k-1)!} \int_0^1 t^k a_k(\mu_g t) dt \quad (2.42)$$

Now, we will develop a recursive algorithm to efficiently calculate the average call

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complete ratio.

$$\begin{aligned}
 \mathbb{E}(\gamma_k) &= \frac{1}{G_k} \frac{1}{(k-1)! \mu_g} \int_0^{\mu_g} t^k a_k(t) dt \\
 &= \frac{1}{G_k} \frac{1}{(k-1)! \mu_g (k+1)} \left[t^{k+1} a_k(t) \Big|_0^{\mu_g} - \int_0^{\mu_g} t^{k+1} \frac{da_k(t)}{dt} dt \right] \\
 &= \frac{1}{G_k} \frac{1}{(k-1)! (k+1)} \left[\mu_g^k a_k(\mu_g) + k! G_{k+1} \mathbb{E}(\gamma_{k+1}) \right]
 \end{aligned} \tag{2.43}$$

As a consequence, the recursive algorithm is given by

$$\mathbb{E}(\gamma_k) = \frac{G_{k-1}}{G_k} \frac{k}{k-1} \mathbb{E}(\gamma_{k-1}) - \frac{1}{G_k} \frac{\mu_g^{k-1}}{(k-1)!} a_{k-1}(\mu_g); \quad k \geq 2 \tag{2.44}$$

with initial condition

$$\mathbb{E}(\gamma_1) = \frac{1}{G_1} \frac{1}{\mu_g} \int_0^{\mu_g} a_1(t) t dt \tag{2.45}$$

In addition, using the similar analysis, the recursive algorithm for G_k is given by

$$G_k = G_{k-1} - \frac{\mu_g^{k-1}}{(k-1)!} a_{k-1}(\mu_g); \quad k \geq 2 \tag{2.46}$$

with initial condition $G_1 = \int_0^{\mu_g} a_1(t) dt$.

Using the total probability theorem, the expected call complete ratio is described

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as

$$\begin{aligned}
 \mathbb{E}(\gamma) &= \sum_{m=1}^{\infty} \sum_{k=1}^m \mathbb{E}(\gamma_k) \cdot \Pr(\widehat{M} = k, M = m) \\
 &= \sum_{m=1}^{\infty} \left[\sum_{k=1}^m \mathbb{E}(\gamma_k) \cdot \Pr(\widehat{M} = k | M = m) \right] \Pr(M = m) \\
 &= \frac{\sum_{m=1}^{\infty} \left[\sum_{k=1}^{m-1} \mathbb{E}(\gamma_k) \cdot P_s^{k-1}(1 - P_s) + P_s^{m-1} \right] \cdot \frac{\mu_g^{m-1}}{(m-1)!} a_{m-1}(\mu_g)}{\sum_{i=1}^{\infty} \frac{\mu_g^{i-1}}{(i-1)!} a_{i-1}(\mu_g)} \quad (2.47)
 \end{aligned}$$

This expression suggests that the call complete ratio comprises of two components. One is from the incomplete calls represented by the item $\sum_{k=1}^{m-1} \mathbb{E}(\gamma_k) \cdot P_s^{k-1}(1 - P_s)$ and the other is from the successfully completed call reflected by the item P_s^{m-1} . Therefore, the metrics call complete ratio, unlike the call complete probability, can reflect the impact of wireless channel unreliability on the normally completed calls as well as the forced terminated calls.

2.4 Numerical Results

In this section, we present numerical examples to study the effect of wireless link error characteristics and system configuration parameters on call behavior. We choose $N_{LER} = 6, T_{LER} = 0.48\text{sec}$. Both T_{mc} and T_u are regarded as exponentially distributed random variables. The mean of call holding time is 180.0sec . In the following, we focus on two aspects. Firstly, the wireless channel unreliability effect on the call complete probability and call complete ratio is studied. Then, we will evaluate the impact of call holding time distribution on the performance metrics.

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We simulate the MS behavior with respect to its time duration relationship to obtain the simulation result. Each simulation point is the 100000-call-based average value. In the simulation program, the call complete probability and the average value of call complete ratio are expressed as

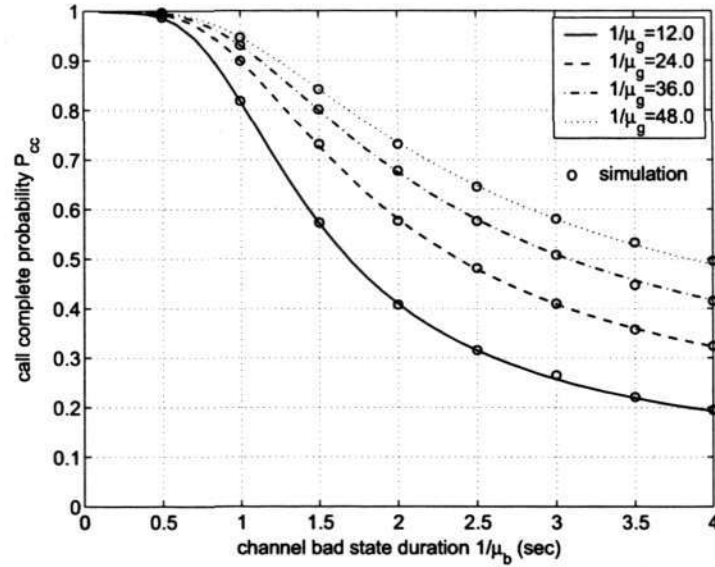
$$P_{cc} = 1 - \lim_{N \rightarrow \infty} \frac{N_{incomplete}}{N} \quad (2.48)$$

$$\mathbb{E}(\gamma) = \lim_{N \rightarrow \infty} \frac{\sum_{i=1}^N T_{cc,i}/t_{c,i}}{N} \quad (2.49)$$

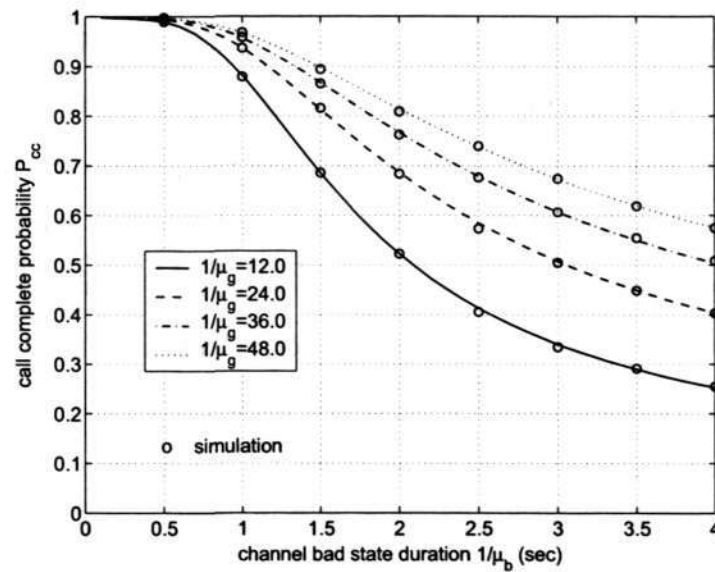
where $N_{incomplete}$ denotes the number of incomplete calls due to the failed link re-establishment during the channel's bad state and N represents the total number of generated calls. $T_{cc,i}$ and $t_{c,i}$ represent the actually completed call holding time and call holding time $t_{c,i}$ of the i^{th} ($i = 1, 2 \dots N$) call.

Fig.2.3 shows the impact of various channel conditions and system setting on the call complete probability with exponential call holding time. Simulation result is also provided for comparison purpose. It is evident that the analysis result matches the simulation result very well, which validates our analytical model. In this figure, we eliminate the effect of the user's impatience by setting the average impatience time, $1/\mu_u = 1000.0$ sec, much larger than the mean of channel bad state duration. It is seen that longer channel good state or shorter bad state duration will lead to higher call complete probability, which is expected. Comparison result of Fig.2.3(a) and Fig.2.3(b) shows that a slightly longer timer length T_{mc} can achieve distinct increase in call complete probability. This is because, with a longer T_{mc} , a call connection is able to tolerate a longer wireless channel bad state without breakdown and hence higher probability to successfully complete a call. Fig.2.4 illustrates a realistic condition by setting $1/\mu_u$ as 4.0 sec. It is shown that in this case P_{cc} is almost insensitive to the timer length due to the user's impatience time constraint. Hence, the suitable time length is highly

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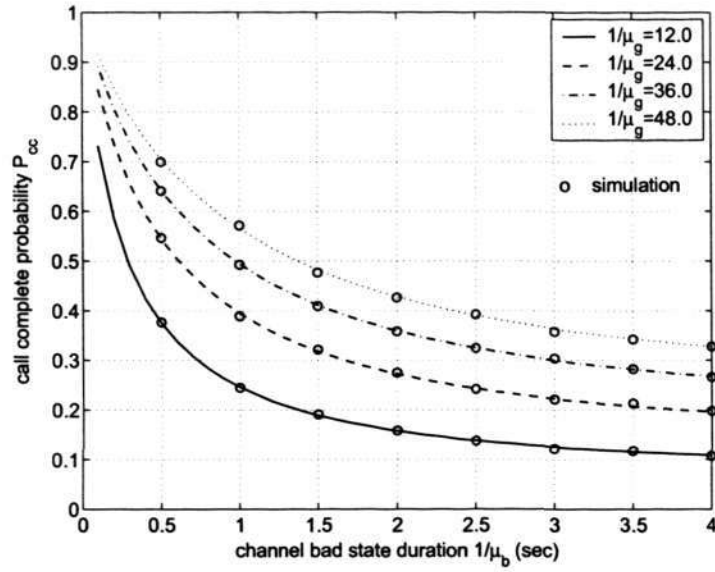
(a) $\mu_{mc} = 1/3.0, \mu_u = 1/1000.0$



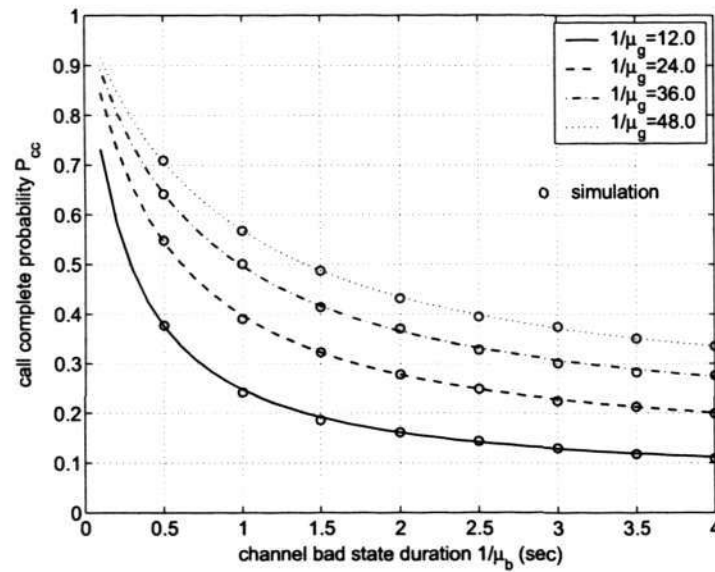
(b) $\mu_{mc} = 1/6.0, \mu_u = 1/1000.0$

Figure 2.3: Call complete probability P_{cc} v.s. the average channel bad state duration μ_b^{-1} .

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(a) $\mu_{mc} = 1/3.0, \mu_u = 1/4.0$



(b) $\mu_{mc} = 1/6.0, \mu_u = 1/4.0$

Figure 2.4: Call complete probability P_{cc} v.s. the average channel bad state duration μ_b^{-1} .

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dependent on the user's behavior in order to to satisfy a required QoS.

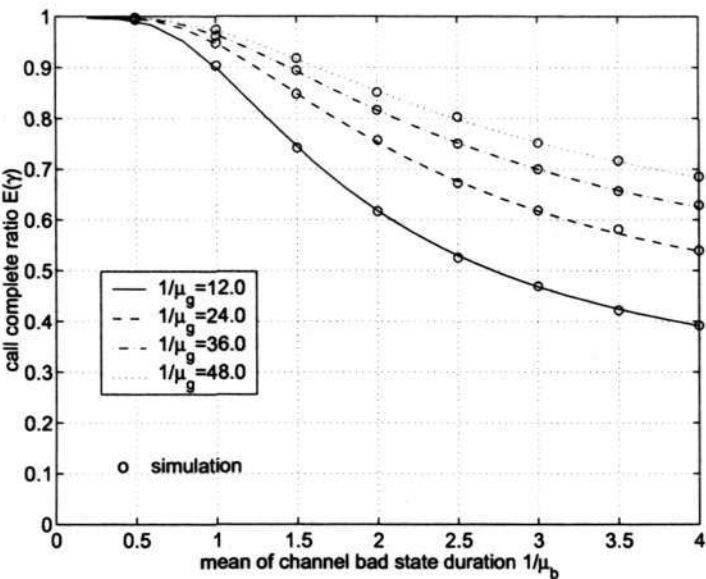
Fig.2.5 and Fig.2.6 illustrate the effect of various channel conditions on the call complete ratio with exponential call holding time. It is observed that the call complete ratio has similar variation as the call complete probability but less decreasing gradient due to the involvement of completed calls as well as the uncompleted calls. Hence, comparing with the call complete probability, the call complete ratio is less sensitive to the length of channel bad state.

Since the traditional exponential call holding time may not be universally valid in any system, it is necessary to exam the sensitivity problem, i.e. whether there is a significant performance gap while utilizing different call holding time function. We select the following different call holding time distributions having the fixed mean $1/\mu_c = 180.0\text{sec}$.

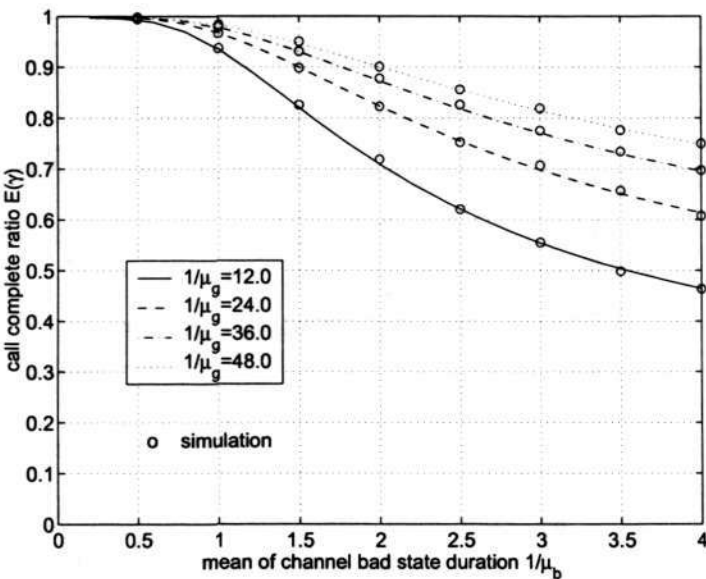
- exponential (EXP) distribution $\mu_c e^{-\mu_c t}$
- 2-order hyper-exponential (H_2) $0.2 \times 0.4\mu_c e^{-0.4\mu_c t} + 0.8 \times 1.6\mu_c e^{-1.6\mu_c t}$
- 4-state Erlang (E_4) $\frac{n\mu_c(n\mu_c t)^{n-1}}{(n-1)!} e^{-n\mu_c t}, (n = 4)$

Fig.2.7 depicts the call complete probability under various wireless channel environment with different call holding time distributions. It is shown that there is a considerable performance discrepancy between the results employing different call holding time distributions. The probability with exponential call holding time may overestimate or underestimate the quantity with other popular assumptions. This is because the exponentially distributed call holding time can only provide the information of mean-value analysis. From the expression of P_{cc} , we can see that P_{cc} is not only related to the average value of call holding time, but also related to the higher statistics moments (e.g. variance) and specific behavior of the call holding time distribution functions.

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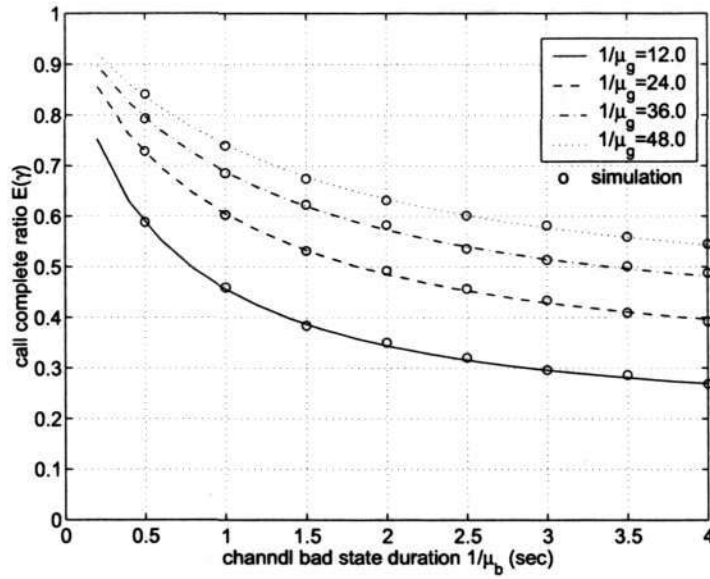
(a) $\mu_{mc} = 1/3.0, \mu_u = 1/1000.0$



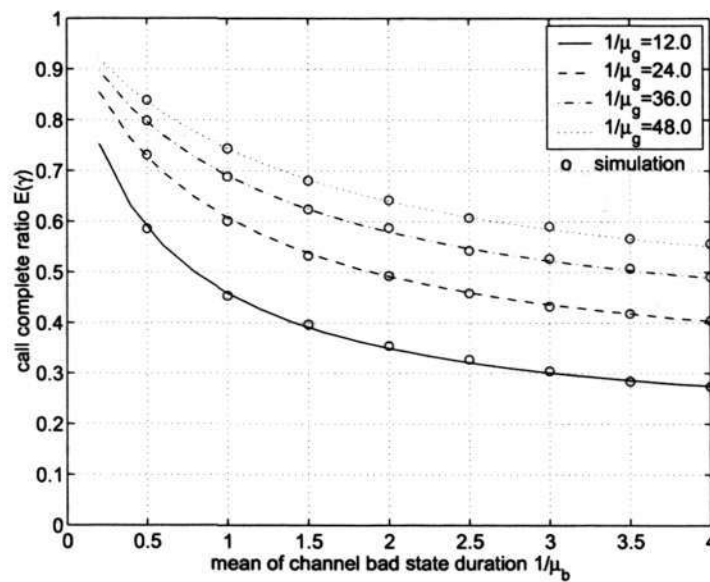
(b) $\mu_{mc} = 1/6.0, \mu_u = 1/1000.0$

Figure 2.5: Call complete ratio $E(\gamma)$ v.s. the average channel bad state duration μ_b^{-1} .

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(a) $\mu_{mc} = 1/3.0, \mu_u = 1/4.0$



(b) $\mu_{mc} = 1/6.0, \mu_u = 1/4.0$

Figure 2.6: Call complete ratio $E(\gamma)$ v.s. the average channel bad state duration μ_b^{-1} .

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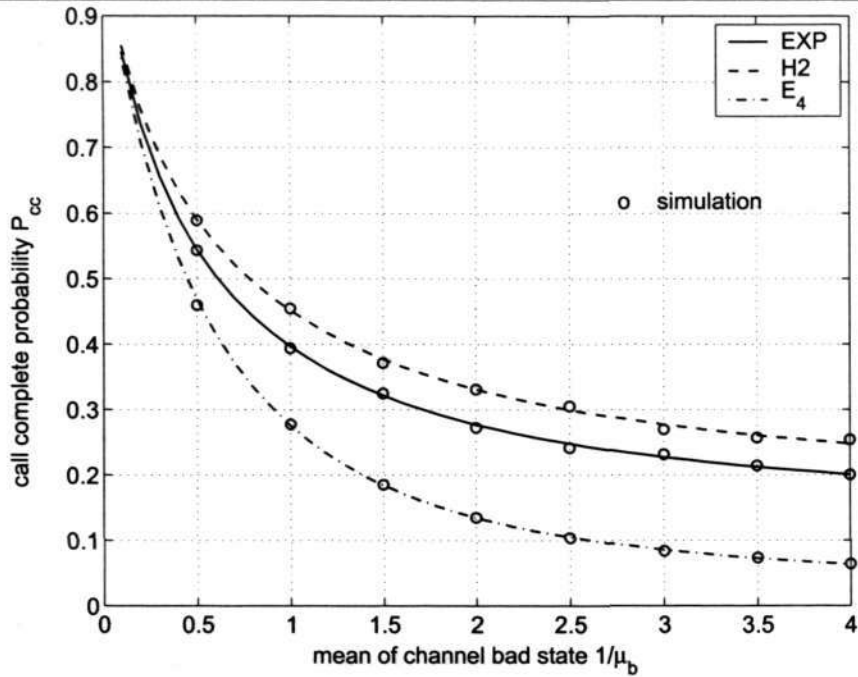


Figure 2.7: Call complete probability P_{cc} v.s. mean channel bad state μ_b^{-1} with different call holding time distributions ($1/\mu_{mc} = 6.0\text{sec}$, $1/\mu_u = 4.0\text{sec}$, $1/\mu_g = 24.0\text{sec}$).

Thereafter, although the employed distributions have the same mean, P_{cc} still shows a noticeable discrepancy. The sensitivity of the call holding time on the call complete ratio is shown in Fig.2.8. Similarly, significant performance gap exists with the usage of various call holding time distributions.

In this chapter, we concentrate on the problem when a call connection may be dropped due to the impaired channel and consequently neglect the blocking due to the insufficient resource/bandwidth. Generally speaking, the resource insufficiency and the wireless channel unreliability processes are not independent due to the common constraint of the call holding time. However, conditioning on a given specific call connection, the two factors independently affect the call behavior. Based on this point, the proposed analytical model in the present chapter can be extended to derive the performance metrics such as call complete probability by focusing on a typical call

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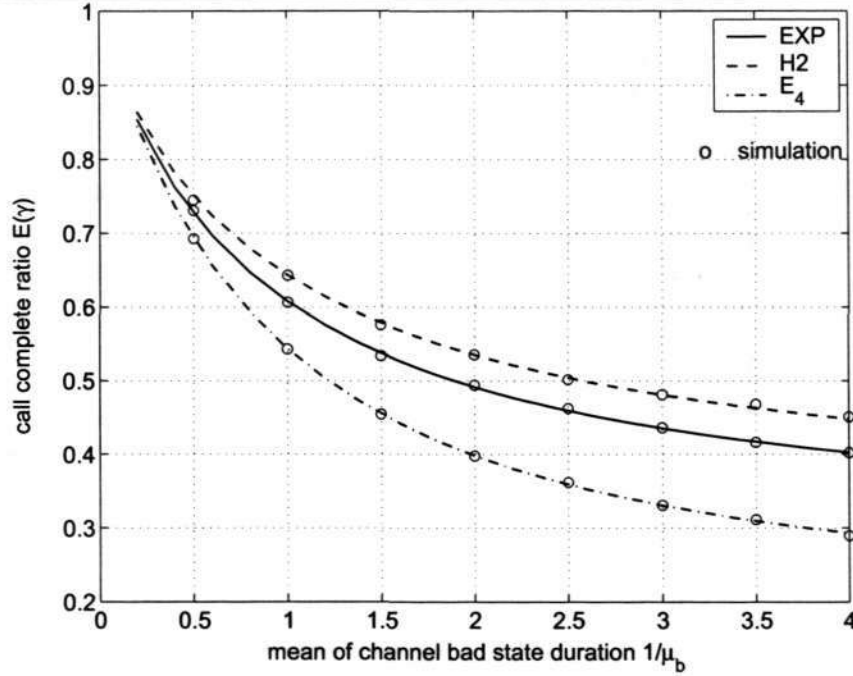


Figure 2.8: Call complete ratio γ v.s. mean channel bad state μ_b^{-1} with different call holding time distributions ($1/\mu_{mc} = 6.0\text{sec}$, $1/\mu_u = 4.0\text{sec}$, $1/\mu_g = 24.0\text{sec}$).

trajectory while taking account into the two independent processes for the specific call, instead of the single wireless channel impairment in the present scenario.

2.5 Conclusions

In this chapter, we have developed a novel analytical model to study the call performance taking into account the effect of unreliable wireless channel in mobile network. The call performance metrics with respect to call complete probability and call complete ratio are derived under the general call holding time. The analysis result is validated by the simulation. Numerical results demonstrate that the wireless channel error characteristics has a significant impact on the call performance and there exists a considerable performance gap while using different call holding time distribution. The

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results presented are helpful for designing more practical and efficient call admission control scheme integrating the impaired wireless channel effect and for analyzing the reliability/availability characteristics of the wireless system.

Chapter 3

Mobile Network Performance with the Wireless Link Unreliability and Resource Insufficiency

In the last chapter, we have studied the call performance under the simple two-state Markovian Gilbert-Elliott model in the presence of the unreliable wireless channel.

This chapter is the generalization and extension of those concepts of the Chapter 2. In this Chapter, we propose a general analytical model taking into account the unreliable wireless link and insufficient resource upon the mobile network performance. In particular, the call holding time, cell residence time and hence the channel holding time are assumed to follow a general assumption. The wireless channel model is also generalized with generally distributed channel good state time duration and bad state time duration.

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3.1 Introduction

Several extensive experiments examining the exponential distribution for the critical tele-traffic parameters such as call inter-arrival time, call holding time or cell residence time in both the wireline and the wireless systems [51]-[54] [68] have driven the recent study for the wireless mobile network performance evaluation under the general assumptions for such crucial parameters [35] [64] [55] [66] [19] [46]. It is popularly accepted that there is no universally valid function for the call holding time or cell residence time or channel holding time, and hence developing the general closed-form formula for interested performance metrics is much more significant than specifying a particular distribution function for the important tele-traffic parameters.

In wireless mobile network, the performance evaluation with respect to the significant metrics such as the call complete probability (or call incomplete probability) has attracted extensive research (see [35] [65] [103] [19] and the reference therein). In the aforementioned studies, the call complete probability is investigated under the single factor, i.e. the lack of the radio resource. It is well-known that wireless/mobile system is characterized by the unreliable physical link and is notorious for the inherent highly time-varying wireless link due to the propagation impairments such as multi-path fading, shadowing or path loss. Therefore, by investigating the network performance taking into account the physical link unreliability is the inherent requirement in wireless/mobile system. In the previous chapter and the study [3], the effect of the unreliable wireless channel on the call performance is presented under the general call holding time. It has been shown that the wireless link unreliability characteristics has a significant impact on the consequence of the probability of call completion.

In this chapter, we will derive the closed-form formula for the call complete probability while relaxing the exponential distributed assumption for the wireless link error-free

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state or the erroneous state duration into the general distribution. In addition, the result takes into account the effect of the unreliable wireless link as well as the insufficient radio resource under the general call holding time or cell residence time distribution. In addition, another important performance indicator is the completed call holding time (CCHT), defined as the actually completed call connection duration upon call termination or normal completion. This quantity is useful for the service provider to design flexible charging policy [39] in order to attracting the potential subscribers and maintaining the present customers. The closed-form probability density function for CCHT taking into account the resource unavailability during the handoff operation as well as the physical link unreliability will be presented. It is noteworthy that the two mentioned factors affecting the call behavior are correlated due to the common constraint of the call holding time length. In addition, the general distribution of the link state duration and the general call holding time or cell residence time will further complicate the performance analysis. Hence, this study is characterized by the correlation and the generalization compared with the work in the chapter 2.

We note that the "call level performance" is a broad terminology and is not limited to the previously deployed 2G or 2.5G telephony-oriented systems. In the packet network, the call-level is the synonym as the session, which shows the protocol performance in the higher layer while comparatively the packet delay or packet error rate exhibits performance of the lower link layer. For instance, a tele-conference service is characterized as a very long active session. During the service, the call/session may be forced to termination due to the wireless channel impairment or unavailable bandwidth owing to the user seamless mobility. Hence, it is believed that the "call-level" or "session-level" still plays an important role in evaluating the network performance and the signalling burden in the next generation wireless/cellular network. This belief can be validated by the standardized protocol recommending the timer length and the maximum number

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of re-transmission during the link re-establishment procedure in 3G network [63].

The remainder of the chapter is organized as follows. In Section II, we describe the typical call trajectory with wireless channel model. The call complete probability and the CCHT are derived accounting the degraded wireless link and the unavailable bandwidth are analyzed in the section III and IV, respectively. Numerical results are given in Section V, followed by concluding remarks in Section VI.

3.2 System Model

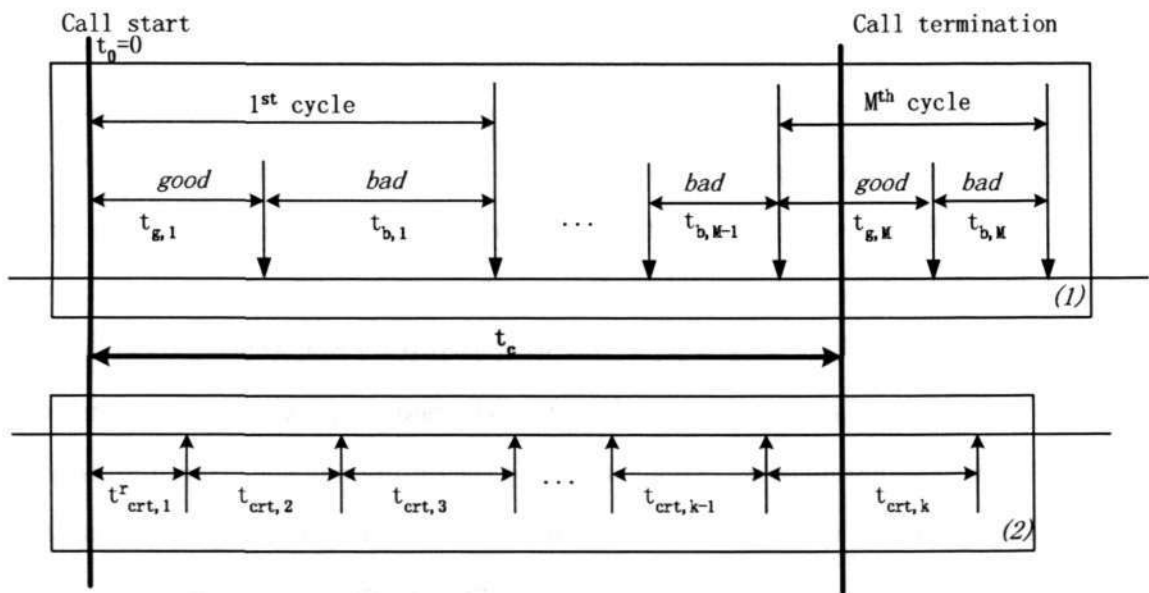


Figure 3.1: The time diagram for a typical call in mobile network with unreliable wireless channel and insufficient bandwidth.

Fig.3.1 shows the model of the typical trajectory of a MS roaming in a wireless mobile network with the unreliable wireless channel (upper block (1)) and resource insufficiency (lower block (2)). Specifically, the upper block (1) represents the effect of the impaired wireless link upon the MS behavior, and the lower block (2) represents the insufficient bandwidth effect. After initializing a call connection, the user will continue

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its conversation during its movement. Upon entering a new cell, the call may be blocked because of the limited bandwidth in the cell and hence leads to the failed handoff. This process will repeat until the call is successfully completed or forced to termination. t_c also denotes the call holding time.

3.2.1 Wireless Channel Model

The Gilbert-Elliott model [9] [10] has been commonly used to capture the periods of signal degradation (e.g. [47]). For this Markov Chain model, the state space of the wireless channel consists of two states $\Omega = \{good, bad\}$. The channel alternatively stays in good or bad state for an exponentially distributed duration. Motivated by the fact that the Gilbert-Elliott model is unable to capture the sharp change of signal, Fritchman [60] extended and generalized the Gilbert's wireless channel model as a Markov chain with a finite number of N_F states. Two classes are grouped in these N_F finite states. The first class is comprised of N_g error-free states while the second one consists of the remaining $N_b = N_F - N_g$ states with each state representing different error state. Fritchman has derived a model for which the period of the error-free state is expressed as the summation of N_g exponentials and the duration of the error state is given by the summation of N_b exponentials. Furthermore, a Finite State Markov Channel (FSMC) is proposed and studied in [61]. Other works including the Hidden Markov Chain [62] are also applied in modeling the fading wireless channel.

As a consequence, due to the diversity and the application of the various wireless channel model under different mobility environment, the duration in good (or error-free) or bad (or erroneous) state that follows a general distribution is the more reasonable manipulation than assuming a specific function for good or bad state duration. Generally, the call experiences the wireless channel the good state and bad state, alternatively.

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The time duration of good state during the i^{th} cycle is denoted as $t_{g,i}$ and $t_{b,i}$ for the interval of bad state during cycle i .

3.3 Call Complete Probability

Referring to Fig. 3.1, let t_c be the call holding time with the probability density function (p.d.f.) $f_{t_c}(t)$ and cumulative distribution function (c.d.f.) $F_{t_c}(t)$. Let \mathcal{N} represent the set of positive integer. Denote the Laplace-Stieltjes Transform (LST) of the p.d.f. $f_{t_c}(t)$ as $f_{t_c}^*(s)$. As we have stated in the section 3.2.1, $t_{g,i}(i \in \mathcal{N})$ are generally distributed i.i.d. random variables with the p.d.f. $g(t)$, the c.d.f. $G(t)$ and the average μ_g^{-1} , and $t_{b,i}(i \in \mathcal{N})$ are the generally i.i.d. distributed random variables with the p.d.f. $b(t)$, the c.d.f. $B(t)$ and the average μ_b^{-1} . The LST of $g(t)$ and $b(t)$ are denoted as $g^*(s)$ and $b^*(s)$, respectively.

3.3.1 Link Re-establishment Successful Probability with the Presence of the User's Impatience Time

From Chapter 2, with the reference to the result (2.13), the link re-establishment successful probability P_s is given by,

$$P_s = 1 - \int_0^\infty \int_0^t f_{T_u}(x) dx b(t) dt - \int_{N_{LER} T_{LER}}^\infty \int_0^{t - N_{LER} T_{LER}} f_{T_{mc}}(x) dx b(t) dt + \int_{N_{LER} T_{LER}}^\infty \int_0^t f_{T_u}(x) dx \int_0^{t - N_{LER} T_{LER}} f_{T_{mc}}(y) dy b(t) dt \quad (3.1)$$

We assume that the timer length T_{mc} follows exponential distribution with average $1/\mu_{mc}$. The user's impatience duration is assumed to be exponential distribution with

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mean $1/\mu_u$, which has been popularly used in mobile network performance evaluation [57] [24]. In this case, the probability for successful link re-establishment becomes

$$P_s = b^*(\mu_u) + \int_{N_{LER}T_{LER}}^{\infty} e^{-\mu_u t} b(t) dt - e^{\mu_{mc} N_{LER}T_{LER}} \int_{N_{LER}T_{LER}}^{\infty} e^{-\mu_{mc} t - \mu_u t} b(t) dt \quad (3.2)$$

With Gilbert-Elliott wireless model, the duration of good state and bad state are exponentially distributed, i.e.

$$g(t) = \mu_g e^{-\mu_g t} \quad (3.3)$$

$$b(t) = \mu_b e^{-\mu_b t} \quad (3.4)$$

Then, we have

$$P_s = \frac{\mu_b}{\mu_b + \mu_u} + \mu_b e^{-(\mu_b + \mu_u) N_{LER}T_{LER}} \left[\frac{1}{\mu_{mc} + \mu_u + \mu_b} - \frac{1}{\mu_b + \mu_u} \right] \quad (3.5)$$

For Fritchman channel model [60], we denote the duration of good state and the duration of bad state following the distribution function

$$g(t) = \sum_{i=1}^{N_g} \alpha_{g,i} \eta_{g,i} e^{-\eta_{g,i} t}, \quad \sum_{i=1}^{N_g} \alpha_{g,i} = 1, \quad (N_g \in \mathcal{N}, 0 \leq \alpha_{g,i} \leq 1, \eta_{g,i} > 0) \quad (3.6)$$

$$b(t) = \sum_{i=1}^{N_b} \alpha_{b,i} \eta_{b,i} e^{-\eta_{b,i} t}, \quad \sum_{i=1}^{N_b} \alpha_{b,i} = 1, \quad (N_b \in \mathcal{N}, 0 \leq \alpha_{b,i} \leq 1, \eta_{b,i} > 0) \quad (3.7)$$

Then, we obtain

$$P_s = \sum_{i=1}^{N_b} \frac{\alpha_{b,i} \eta_{b,i}}{\mu_u + \eta_{b,i}} + \sum_{i=1}^{N_b} \alpha_{b,i} \eta_{b,i} e^{-(\eta_{b,i} + \mu_u) N_{LER}T_{LER}} \left[\frac{1}{\mu_{mc} + \mu_u + \eta_{b,i}} - \frac{1}{\mu_u + \eta_{b,i}} \right] \quad (3.8)$$

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3.3.2 Link Re-establishment Successful Probability without the Presence of the User's Impatience Time

Following the similar reasoning leading to (2.13), we can obtain the link re-establishment successful probability without the user impatience time consideration.

$$\begin{aligned}
 P_s &= 1 - Pr(\text{all the re-establishment attempts are failed}) \\
 &= 1 - Pr(T_{mc} + N_{LER}T_{LER} < t_{b,1}) \\
 &= 1 - \int_{N_{LER}T_{LER}}^{\infty} \int_0^{t - N_{LER}T_{LER}} f_{T_{mc}}(x) dx b(t) dt
 \end{aligned} \tag{3.9}$$

Similarly we have substituted the probability $Pr(T_{mc} + N_{LER}T_{LER} < t) = 0$ as $0 \leq t \leq N_{LER}T_{LER}$.

3.3.3 Call Complete Probability

Define ξ_m as the summation of the number of m wireless channel good state time duration, i.e.

$$\xi_m = (t_{g,1} + \dots + t_{g,(m-1)} + t_{g,m}) \cdot \mathbf{1}_{m \geq 1} \tag{3.10}$$

where indicator function $\mathbf{1}_E$ equals 1 when the event E is true and zero otherwise. Let $f_{\xi_m}(t)$, $F_{\xi_m}(t)$ and $f_{\xi_m}^*(s)$ denote the p.d.f., c.d.f. and the LST of p.d.f. for the nonnegative random variable ξ_m . The LST of ξ_m is given as

$$f_{\xi_m}^*(s) = \mathbb{E}[e^{-s\xi_m}] = \prod_{i=1}^m \mathbb{E}[e^{-st_{g,i}}] = [g^*(s)]^m \tag{3.11}$$

Denote $t_{crt,k}$ ($k \in \mathcal{N}$) as the cell residence time an MS stays in cell k with the generic form t_{crt} and the average value $1/\eta_{crt}$. The p.d.f. of t_{crt} and its corresponding LST are

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denoted as $f_{t_{crt}}(t)$ and $f_{t_{crt}}^*(s)$, respectively. Let t_{crt}^r be the residual cell residence time in the first cell that the call initializes the connection request. Then, the p.d.f. of t_{crt}^r is given by [75, page 172]

$$f_{t_{crt}^r}(t) = \eta_{crt} \int_t^\infty f_{t_{crt}}(t) dt \quad (3.12)$$

with its LST

$$f_{t_{crt}^r}^*(s) = \frac{\eta_{crt}[1 - f_{t_{crt}}^*(s)]}{s} \quad (3.13)$$

In addition, we define

$$\chi_k = t_{crt,1}^r \cdot \mathbf{1}_{k=1} + \left(t_{crt,1}^r + \sum_{i=2}^k t_{crt,i} \right) \cdot \mathbf{1}_{k \geq 2} \quad (3.14)$$

Then, the LST of χ_k p.d.f. is given by

$$f_{\chi_k}^*(s) = f_{t_{crt}^r}^*(s)[f_{t_{crt}}^*(s)]^{k-1} = \frac{\eta_{crt}[1 - f_{t_{crt}}^*(s)][f_{t_{crt}}^*(s)]^{k-1}}{s}; \quad k \in \mathcal{N} \quad (3.15)$$

Let P_n and P_h denote the new call blocking probability and the handoff call blocking probability, respectively.

A call connection is normally completed when the following three events are valid.

1. Event S1: the originating call is accepted by the target Base Station, i.e. the new call connection request is not rejected.
2. Event S2: at each handoff operation during the active call connection, there are sufficient resource and the call connection is not blocked;
3. Event S3: during each wireless channel bad state, the wireless link is successfully

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re-established.

Note that the latter two events, S2 and S3, are not generally independent due to the common constraint by the call holding time. However, S2 and S3 are conditionally independent due to the nature that the wireless link and the resource on a particular call connection will be independent. As a consequence, we develop the equation for the call complete probability as,

$$P_{cc} \tag{3.16}$$

$$= (1 - P_n) \sum_{m=0}^{\infty} \sum_{k=0}^{\infty} Pr(\xi_m < t_c \leq \xi_{m+1}; \chi_k < t_c \leq \chi_{k+1}) P_s^m (1 - P_h)^k \tag{3.17}$$

$$= (1 - P_n) \sum_{m=0}^{\infty} \sum_{k=0}^{\infty} \int_0^{\infty} Pr(\xi_m < x \leq \xi_{m+1}) Pr(\chi_k < x \leq \chi_{k+1}) f_{t_c}(x) dx P_s^m (1 - P_h)^k \tag{3.18}$$

$$= (1 - P_n) \int_0^{\infty} \sum_{m=0}^{\infty} Pr(\xi_m < x \leq \xi_{m+1}) P_s^m \sum_{k=0}^{\infty} Pr(\chi_k < x \leq \chi_{k+1}) (1 - P_h)^k f_{t_c}(x) dx \tag{3.19}$$

In this equation, the index m represents the number of experienced channel bad states (if available) while k stands for the possible number of traversed cells during a call

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connection. Based on this equation, we define

$$a(m, x) = Pr(\xi_m < x \leq \xi_{m+1}) \quad (3.20)$$

$$a^{**}(z, s) = \sum_{m=0}^{\infty} \int_0^{\infty} a(m, x) e^{-sx} dx z^m \quad (3.21)$$

$$d(k, x) = Pr(\chi_k < x \leq \chi_{k+1}) \quad (3.22)$$

$$d^{**}(z, s) = \sum_{k=0}^{\infty} \int_0^{\infty} d(k, x) e^{-sx} dx z^k \quad (3.23)$$

$$A(x) = \sum_{m=0}^{\infty} Pr(\xi_m < x \leq \xi_{m+1}) P_s^m; \quad A^*(s) = \mathcal{L}(A(x)) \quad (3.24)$$

$$D(x) = \sum_{k=0}^{\infty} Pr(\chi_k < x \leq \chi_{k+1}) (1 - P_h)^k; \quad D^*(s) = \mathcal{L}(D(x)) \quad (3.25)$$

$$\phi(x) = A(x)D(x); \quad \phi^*(s) = \mathcal{L}(\phi(x)) \quad (3.26)$$

where the operator $\mathcal{L}(\cdot)$ represents the LST transform. The defined probabilities $a(m, x)$ and $d(k, x)$, given $t_c = x$, can be derived as

$$a(m, x) = \int_0^x f_{\xi_m}(u) [1 - G(x - u)] du \quad (3.27)$$

$$= F_{\xi_m}(x) - f_{\xi_m}(x) \otimes G(x) \quad (3.28)$$

$$d(0, x) = \int_x^{\infty} f_{\chi_1}(u) du \quad (3.29)$$

$$= 1 - F_{\chi_1}(x) \quad (3.30)$$

$$d(k, x) = \int_0^x f_{\chi_k}(u) [1 - F_{t_{crt}}(x - u)] du \quad (3.31)$$

$$= F_{\chi_k}(x) - f_{\chi_k}(x) \otimes F_{t_{crt}}(x); \quad k \geq 1 \quad (3.32)$$

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where the operator \otimes represents the convolution operation.

Then, from (3.28), we obtain the LST of $a(m, x)$ as

$$\mathcal{L}(a(m, x)) = \int_0^\infty a(m, x) e^{-sx} dx = \frac{[g^*(s)]^m [1 - g^*(s)]}{s} \quad (3.33)$$

For $|z| \leq 1$, from (3.20) (3.33), we have

$$a^{**}(z, s) = \sum_{m=0}^\infty \frac{[g^*(s)]^m [1 - g^*(s)]}{s} z^m = \frac{1 - g^*(s)}{s[1 - zg^*(s)]} \quad (3.34)$$

Similarly, based on (3.30) and (3.32), the LST of $d(0, x)$ and $d(k, x)$ are respectively given by

$$\mathcal{L}(d(0, x)) = \frac{s - \eta_{crt}[1 - f_{t_{crt}}^*(s)]}{s^2} \quad (3.35)$$

$$\mathcal{L}(d(k, x)) = \frac{\eta_{crt}[f_{t_{crt}}^*(s)]^{k-1}[1 - f_{t_{crt}}^*(s)]^2}{s^2}, \quad k \geq 1 \quad (3.36)$$

For $|z| \leq 1$, from (3.22) (3.35) and (3.36), we can express

$$d^{**}(z, s) = \sum_{k=0}^\infty \int_0^\infty d(k, x) e^{-sx} dx z^k \quad (3.37)$$

$$= \frac{s - \eta_{crt}[1 - f_{t_{crt}}^*(s)]}{s^2} + \frac{\eta_{crt}(1 - P_h)[1 - f_{t_{crt}}^*(s)]^2}{s^2[1 - zf_{t_{crt}}^*(s)]} \quad (3.38)$$

As a consequence, the LST for $A(x)$ and $D(x)$ are respectively given by

$$A^*(s) = \sum_{m=0}^\infty \mathcal{L}(a(m, x)) P_s^m = a^{**}(P_s, s) \quad (3.39)$$

$$= \frac{1 - g^*(s)}{s[1 - P_s g^*(s)]}; \quad (3.40)$$

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$$D^*(s) = \sum_{k=0}^{\infty} \mathcal{L}(d(k, x))(1 - P_h)^k \quad (3.41)$$

$$= d^{**}(1 - P_h, s) \quad (3.42)$$

$$= \frac{s - \eta_{crt}[1 - f_{t_{crt}}^*(s)]}{s^2} + \frac{\eta_{crt}(1 - P_h)[1 - f_{t_{crt}}^*(s)]^2}{s^2[1 - (1 - P_h)f_{t_{crt}}^*(s)]} \quad (3.43)$$

Applying the Residue Theorem [72] and following the similar technique in [35], the call complete probability (4.12) becomes

$$P_{cc} = (1 - P_n) \int_0^{\infty} \phi(x) f_{t_c}(x) dx \quad (3.44)$$

$$= (1 - P_n) \left[\frac{1}{2\pi j} \int_{\sigma - j\infty}^{\sigma + j\infty} \phi^*(s) \left(\int_0^{\infty} f_{t_c}(x) e^{sx} dx \right) ds \right] \quad (3.45)$$

$$= -(1 - P_n) \sum_{s_0 \in \sigma_c} \text{Res}_{s=s_0} [\phi^*(s) f_{t_c}^*(-s)] \quad (3.46)$$

where j is the imaginary unit ($j^2 = -1$) and σ is sufficiently small. σ_c denotes the set of the poles $f_{t_c}^*(-s)$ in the right half complex plane. $\text{Res}_{s=s_0}$ represents the residue at $s = s_0$.

In particularity, we have the following specific cases for commonly used call holding time distribution. For the exponential call holding time with p.d.f. $f_{t_c}(t) = \mu_c e^{-\mu_c t}$, the call complete probability is expressed as

$$P_{cc} = (1 - P_n) \mu_c \phi^*(\mu_c) \quad (3.47)$$

Although the exponential distribution function may be not exactly modelling the call holding time, it can provide the mean value and allow examination of the variation trend.

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In case of the hyper-exponential call holding time with p.d.f. [69] [70],

$$f_{t_c}(t) = \sum_{i=1}^H q_i \theta_i e^{-\theta_i t}; \quad \text{where } \sum_{i=1}^H q_i = 1, \quad (H \in \mathcal{N}, 0 \leq q_i \leq 1, \theta_i > 0) \quad (3.48)$$

we have

$$P_{cc} = (1 - P_n) \sum_{i=1}^H q_i \theta_i \phi^*(\theta_i) \quad (3.49)$$

For n -stage Erlang call holding time [19] [58] with mean $1/\mu_c = n/\nu$, variance $V_c = n/\nu^2$, and the probability density function

$$f_{t_c}(t) = \frac{\nu^n t^{n-1}}{(n-1)!} e^{-\nu t}, \quad (n \in \mathcal{N}, \nu > 0, t > 0) \quad (3.50)$$

Note that Erlang distribution can be easily extended into hyper-Erlang distribution [76], which has been proven to be able to arbitrarily closely approximate to the distribution of any positive random variable as well as measured data [40] [64].

One can obtain that

$$P_{cc} = \frac{(-1)^{n-1} \nu^n (1 - P_n)}{(n-1)!} \phi^{*(n-1)}(\nu) \quad (3.51)$$

where $\phi^{*(n-1)}(s)$ represents the $(n-1)^{th}$ order derivative of $\phi(s)$ with respect to s .

As the current trend is towards packet-based communications (such as Voice over IP and DiffServ for QoS) in the wireless mobile environment, it is critical to take account into the characteristics of the packet data traffic. It has been shown that the Pareto distribution can approximate the packet data traffic very well [94] [67]. Let us consider the Pareto p.d.f. and c.d.f. with shape parameter α and scale parameter β for the call

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holding time

$$f_{t_c}(t) = \frac{\alpha\beta^\alpha}{t^{\alpha+1}}; \quad F_{t_c}(t) = 1 - \left(\frac{\beta}{t}\right)^\alpha, \quad 1 < \alpha < 2, t \geq \beta > 0 \quad (3.52)$$

Taking the Laplace transform on the p.d.f. function, we have

$$f_{t_c}^*(s) = \int_0^\infty f_{t_c}(t)e^{-st}dt = \alpha\beta^\alpha(C + E_{\alpha+1}(s)), \quad \text{Re}(s) > 0 \quad (3.53)$$

where $C = \alpha\beta^\alpha \int_0^1 e^{-st}t^{\alpha+1}dt$, $E_{\alpha+1}(s) = \int_1^\infty e^{-st}t^{\alpha+1}dt$ is the generalized exponential integral [73] and can be written in terms of incomplete gamma or confluent hypergeometric functions [74]. Hence, it is clear that no closed-form or analytical LST exists for the Pareto call holding time. The closed-form formula for call complete probability maybe not applicable for the heavy-tailed call holding time. However, we can fit Pareto distribution via the distribution functions with the universal approximation property such as hyper-exponential [69] [70]. In addition, the hyper-exponential function is also called as truncated power tail(TPT) distribution [71] by setting

$$q_i = \frac{(1-q)q^i}{1-q^H}; \quad \theta_i = \omega/\delta^i \quad (3.54)$$

where q , ω and δ are positive real values. And the study [71] has shown that the TPT converges to a power tail distribution as $H \rightarrow \infty$. After either the fitting procedure or choosing the suitable parameters in (3.54), we can directly re-use the closed-form analytical results under the hyper-exponential call holding time.

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3.4 Normalized expected value of completed call holding time

The completed call holding time (CCHT), denoted as T , is defined as the time duration elapsed from the moment the call connection request to the instant when the call is normally completed or forced to termination either due to the wireless link failure or to the insufficient resource during handoff. Conditioning on the call characteristics, we introduce the notations

1. $\Gamma_c(t)$: the p.d.f. of CCHT under the condition that the call is normally completed. In this case, T equals t_c given that all exercised handoff are successful and the wireless link is successfully re-established during the bad state.
2. $\Gamma_f(t)$: the p.d.f. of CCHT under the condition that the call is forced to terminate either during the handoff or the failure in the wireless link bad state. If the reason behind the termination is the blocking at the k^{th} ($k \geq 1$) handoff, T is equal to χ_k provided that all experienced wireless channel bad state (if available) during the period χ_k are successful. On the other hand, T is equal to ξ_m due to the wireless link breakdown at the m^{th} bad state and all possible handoff requests are not rejected during the duration ξ_m .

Then, the p.d.f. of T is given by

$$f_T(t) = (1 - P_n)[\Gamma_f(t) + \Gamma_c(t)] \quad (3.55)$$

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We proceed in computing the two functions

$$\Gamma_c(t) = \sum_{m=0}^{\infty} \sum_{k=0}^{\infty} f_{t_c}(t) Pr(\xi_m < t_c < \xi_{m+1}, \chi_k < t_c < \chi_{k+1} | t_c = t) P_s^m (1 - P_h)^k \quad (3.56)$$

$$= \sum_{m=0}^{\infty} a(m, t) P_s^m \sum_{k=0}^{\infty} d(k, t) (1 - P_h)^k f_{t_c}(t) \quad (3.57)$$

$$= A(t) D(t) f_{t_c}(t) = \phi(t) f_{t_c}(t) \quad (3.58)$$

where $\phi(t) = A(t) D(t)$, and $A(t) = \sum_{m=0}^{\infty} a(m, t) P_s^m$; $D(t) = \sum_{k=0}^{\infty} d(k, t) (1 - P_h)^k$, and

$$\begin{aligned} \Gamma_f(t) &= \sum_{m=1}^{\infty} \sum_{k=0}^{\infty} f_{\xi_m}(t) Pr(t < t_c, \chi_k < t \leq \chi_{k+1} | \xi_m = t) P_s^{m-1} (1 - P_s) (1 - P_h)^k \\ &\quad + \sum_{k=1}^{\infty} \sum_{m=0}^{\infty} f_{\chi_k}(t) Pr(t < t_c, \xi_m < t \leq \xi_{m+1} | \chi_k = t) (1 - P_h)^{k-1} P_h P_s^m \end{aligned} \quad (3.59)$$

$$\begin{aligned} &= \sum_{m=1}^{\infty} \sum_{k=0}^{\infty} f_{\xi_m}(t) [1 - F_{t_c}(t)] d(k, t) P_s^{m-1} (1 - P_s) (1 - P_h)^k \\ &\quad + \sum_{k=1}^{\infty} \sum_{m=0}^{\infty} f_{\chi_k}(t) [1 - F_{t_c}(t)] a(m, t) (1 - P_h)^{k-1} P_h P_s^m \end{aligned} \quad (3.60)$$

$$\begin{aligned} &= [1 - F_{t_c}(t)] (1 - P_s) \sum_{m=1}^{\infty} f_{\xi_m}(t) P_s^{m-1} \sum_{k=0}^{\infty} d(k, t) (1 - P_h)^k \\ &\quad + [1 - F_{t_c}(t)] P_h \sum_{k=1}^{\infty} f_{\chi_k}(t) (1 - P_h)^{k-1} \sum_{m=0}^{\infty} a(m, t) P_s^m \end{aligned} \quad (3.61)$$

$$\begin{aligned} &= [1 - F_{t_c}(t)] (1 - P_s) D(t) \sum_{m=1}^{\infty} f_{\xi_m}(t) P_s^{m-1} \\ &\quad + [1 - F_{t_c}(t)] P_h A(t) \sum_{k=1}^{\infty} f_{\chi_k}(t) (1 - P_h)^{k-1} \end{aligned} \quad (3.62)$$

Furthermore, on the basis of (3.62), we define

$$u(t) = \sum_{m=1}^{\infty} f_{\xi_m}(t) P_s^{m-1}; \quad w(t) = \sum_{k=1}^{\infty} f_{\chi_k}(t) (1 - P_h)^{k-1} \quad (3.63)$$

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The LST of $u(t)$ and $w(t)$ are given by

$$u^*(s) = \int_0^\infty \sum_{m=1}^\infty f_{\xi_m}(t) P_s^{m-1} e^{-st} dt = \frac{g^*(s)}{1 - P_s g^*(s)} \quad (3.64)$$

$$w^*(s) = \frac{\eta_{crt}[1 - f_{t_{crt}}^*(s)]}{s[1 - (1 - P_h)f_{t_{crt}}^*(s)]} \quad (3.65)$$

respectively. Combining (3.55) (3.58) (3.62) and (3.63), the p.d.f. of T is rewritten as

$$f_T(t) = (1 - P_n) \{A(t)D(t)f_{t_c}(t) + [1 - F_{t_c}(t)][(1 - P_s)D(t)u(t) + P_h A(t)w(t)]\} \quad (3.66)$$

The statistical moments can be obtained following the formal definition. In particular, the expected value is given by $\mathbb{E}(T) = \int_0^\infty t f_T(t) dt$. The normalized expected value of the CCHT, ω_T , is defined as the proportion between the average value of CCHT to the mean of the required call holding time.

$$\omega_T = \mathbb{E}(T)/\mathbb{E}(t_c) \quad (3.67)$$

3.5 Numerical Result

In this section, we focus on the analytical model validation and the effect of wireless link error characteristics on call behavior with respect to the call complete probability and CCHT. We choose $N_{LER} = 3$, $T_{LER} = 1000$ ms [63]. Both T_{mc} and T_u are regarded as exponentially distributed random variables with the average 6.0sec and 6.0sec, respectively. The average duration of the channel good state is fixed as 24.0sec. The

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cell residence time follows the Gamma distribution [68] [59] [19] with average value $\eta_{crt}^{-1} = 120.0sec$ (if not specified) and the variance $V_{crt} = 0.5\eta_{crt}^{-2}$. The new call blocking probability $P_n = 0.05$ and the handoff call blocking probability $P_h = 0.02$. We employ the similar simulation program in Chapter 2 with minor revision to produce the results in this situation.

We select the following typical call holding time distributions having the fixed mean $1/\mu_c = 180.0sec$.

- exponential (EXP) distribution $\mu_c e^{-\mu_c t}$
- 2-order balanced hyper-exponential (H2) $0.2 \times 0.4\mu_c e^{-0.4\mu_c t} + 0.8 \times 1.6\mu_c e^{-1.6\mu_c t}$.
- 3-stage Erlang (E3) $\frac{n\mu_c(n\mu_c t)^{n-1}}{(n-1)!} e^{-n\mu_c t}, (n = 3)$
- Pareto $\frac{\alpha\beta^\alpha}{t^{\alpha+1}}, \alpha = 1.2$ [67], $\beta = \frac{\alpha-1}{\alpha\mu_c} = 30.0$

3.5.1 Validation with Gilbert-Elliott channel model

Fig. 3.2 depicts the call complete probability in terms of the average channel bad state duration with the Gilbert-Elliott wireless channel model under the different call holding time. Fig. 3.3 illustrates the case for the normalized expected value of the CCHT. It is clear that the analytical result and the simulation are in consistence, which validate the proposed analysis model as well as the simulation model. In addition, we can observe that P_{cc} or ω_T decreases quickly with the longer channel bad state duration. This shows that, besides the bandwidth resource insufficiency, the wireless link unreliability is another significant factor affecting the wireless network performance.

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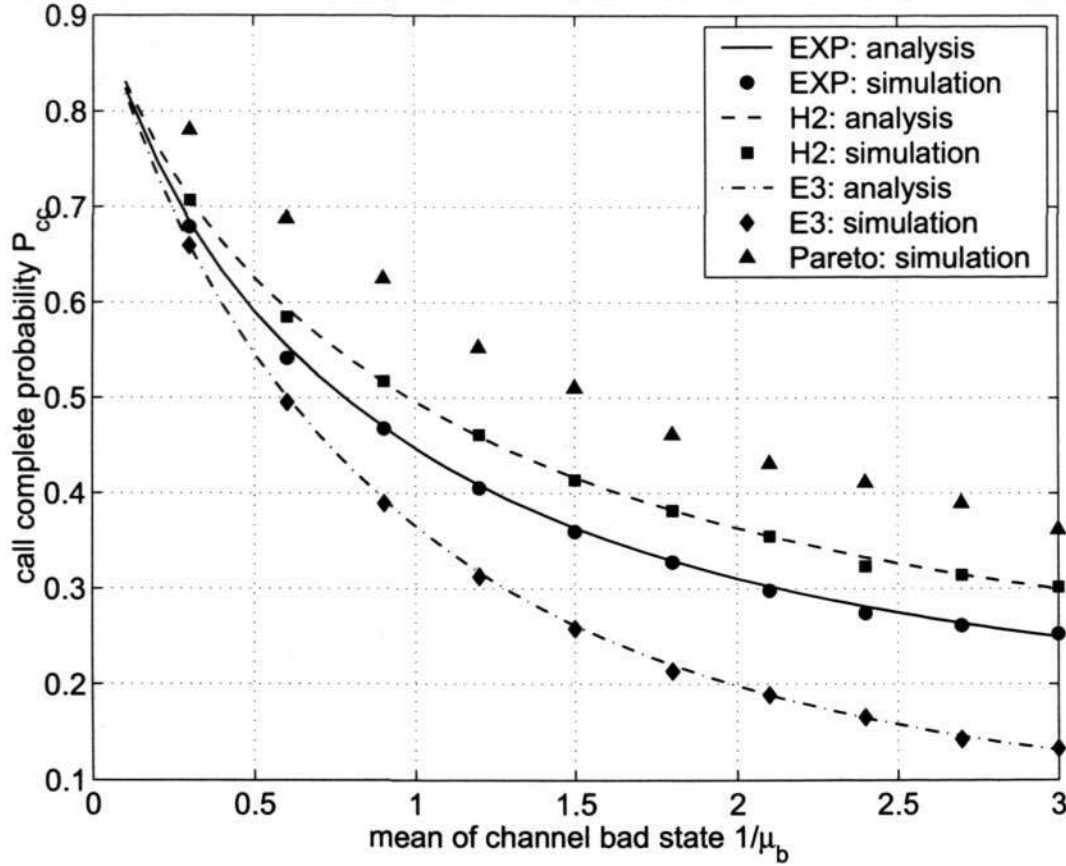


Figure 3.2: The call complete probability P_{cc} in terms of the average channel bad state duration μ_b^{-1} with Gilbert-Elliott wireless channel model under different call holding time distribution

3.5.2 Validation with Fritchman channel model

To further validate our analytical model, we present the comparison between the simulation result under the Fritchman channel model. In this case, we suppose the channel good state or bad state duration follows the 2-order hyper-exponential distribution with p.d.f.

$$g(t) = 0.2 \times 0.4\mu_g e^{-0.4\mu_g t} + 0.8 \times 1.6\mu_g e^{-1.6\mu_g t} \quad (3.68)$$

$$b(t) = 0.2 \times 0.4\mu_b e^{-0.4\mu_b t} + 0.8 \times 1.6\mu_b e^{-1.6\mu_b t} \quad (3.69)$$

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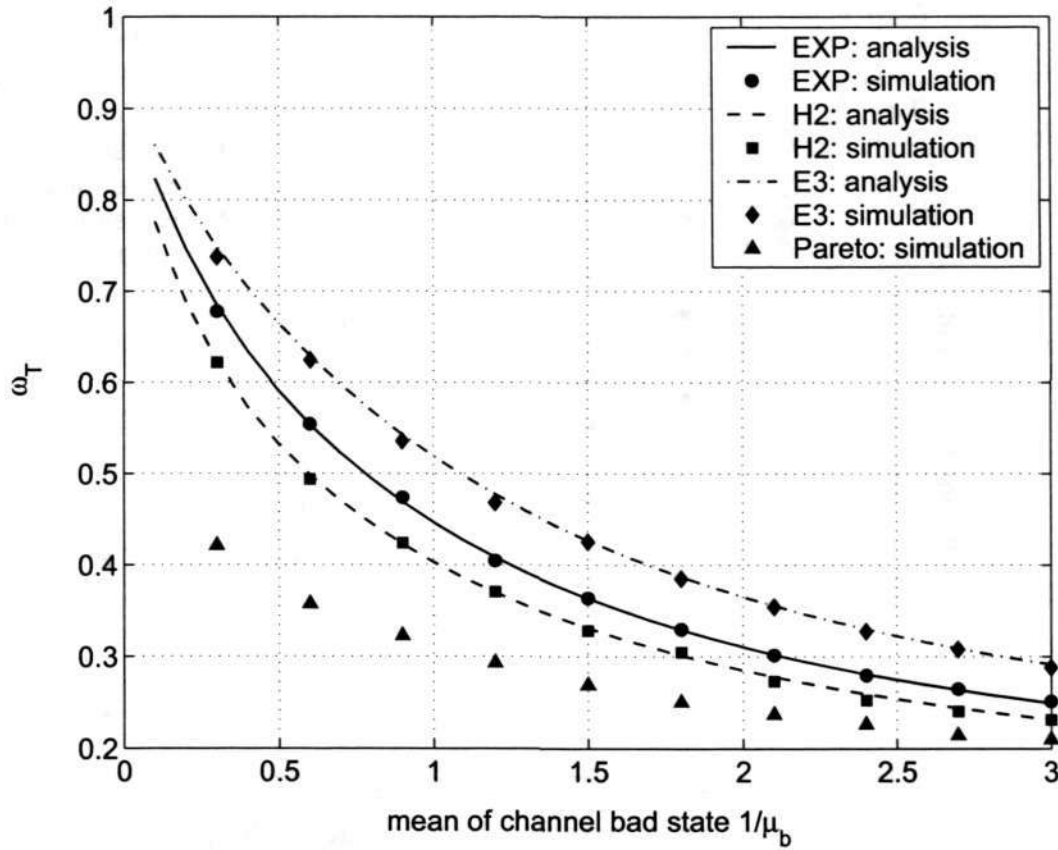


Figure 3.3: The normalized expected value of the CCHT ω_T in terms of the average channel bad state duration μ_b^{-1} with Gilbert-Elliott wireless channel model under different call holding time distribution

Fig. 3.4 illustrates the call complete probability in terms of the average channel bad state duration with the Fritchman wireless channel model under the different call holding time. Fig. 3.5 shows the result for ω_T . Similarly, the analytical result and the simulation match each other.

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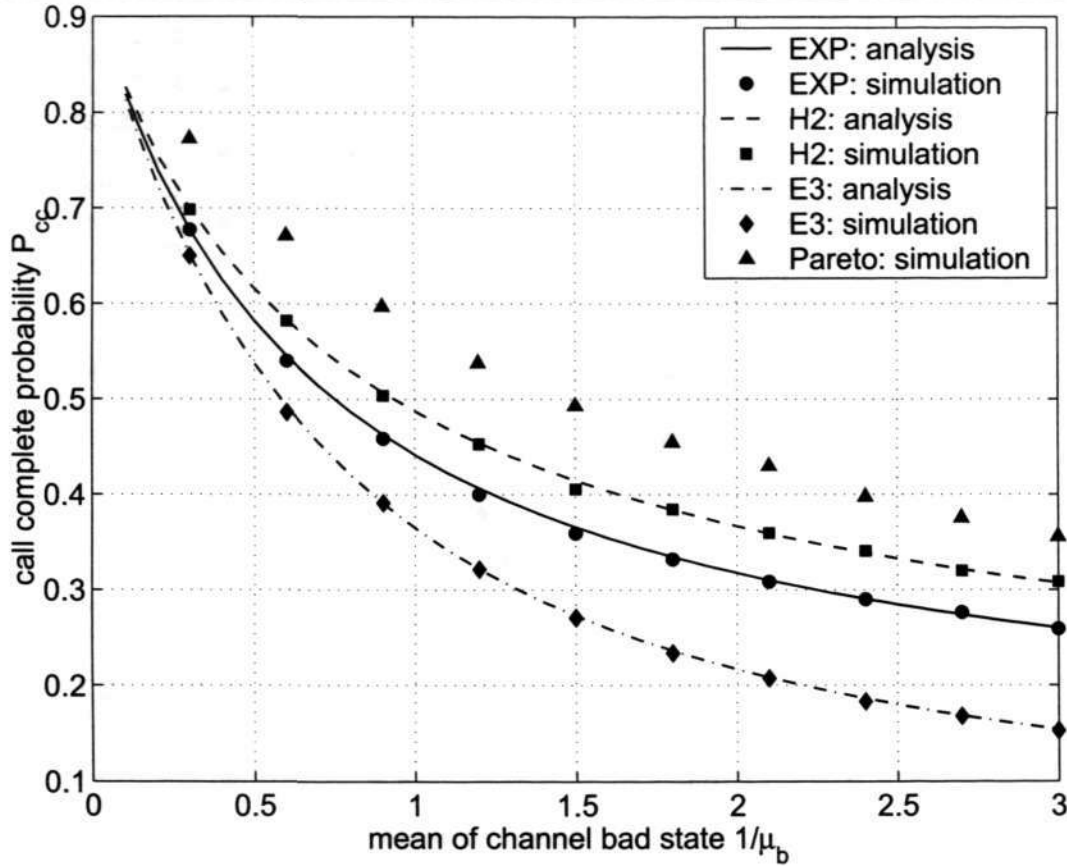


Figure 3.4: The call complete probability P_{cc} in terms of the average channel bad state duration μ_b^{-1} with the Fritchman wireless channel model under the different call holding time

3.5.3 Performance comparison with or without the presence of the wireless link unreliability effect

We will show the performance estimation discrepancy due to the ignorance of the wireless link unreliability on the call performance. In this example, the call holding time follows the 2-order balanced hyper-exponential (H2) distribution $0.2 \times 0.4\mu_c e^{-0.4\mu_c t} + 0.8 \times 1.6\mu_c e^{-1.6\mu_c t}$. The Fritchman wireless channel model with the good or bad state duration following the distribution given in (3.68).

Fig. 3.6 shows the call complete probability in terms of the ratio η_{crt}/μ_c in the

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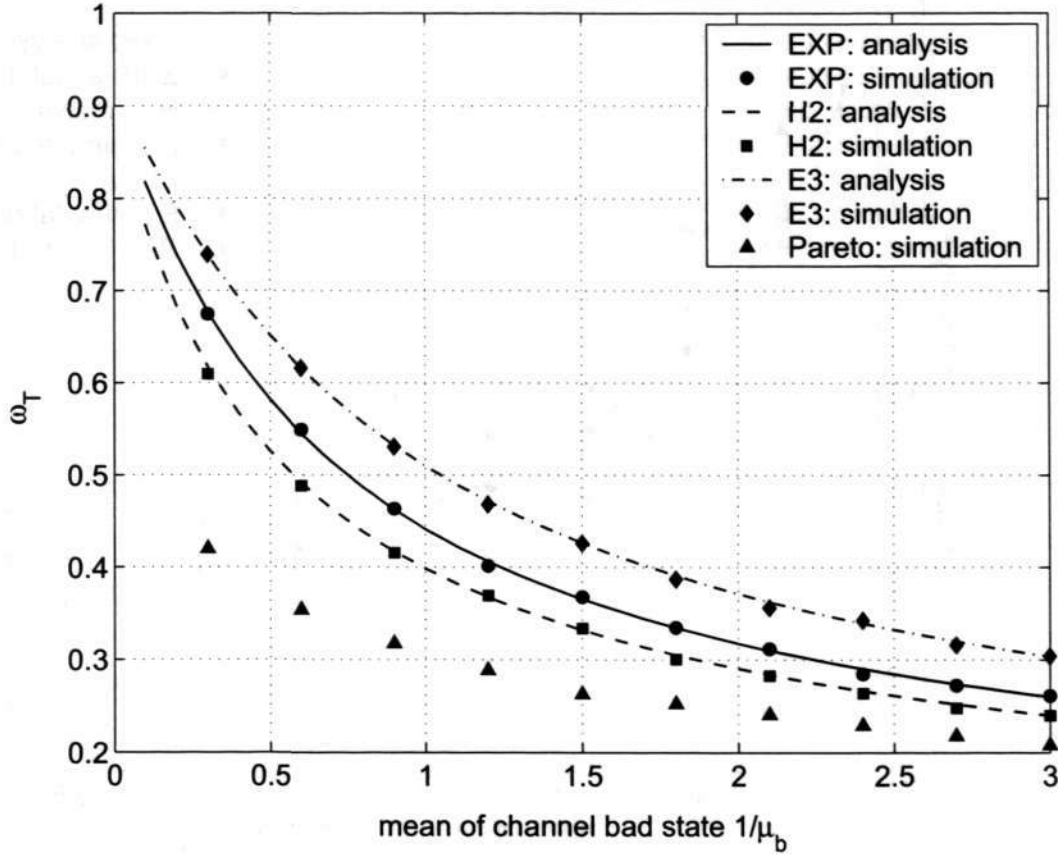


Figure 3.5: The normalized expected value of the CCHT ω_T in terms of the average channel bad state duration μ_b^{-1} with the Fritchman wireless channel model under the different call holding time

presence or absence of the wireless link unreliability impact. In the Figure, "w/o link" denotes the result without considering the unreliable wireless link while " $\mu_b = 1/0.5$ " and " $\mu_b = 1/2.0$ " represent the results in the presence of the possible physical link failure with the average bad state duration 0.5sec and 2.0sec, respectively. It is clear that P_{cc} is substantial overestimated without taking into account the wireless link effect on the call performance. The discrepancy in the performance estimation reduces with the larger η_{crt}/μ_c , which corresponds to the faster mobility. This is because, in such case, the resource insufficiency is dominating due to the strong intendency in handoff while the wireless link unreliability becomes insignificant in the consequence of the call

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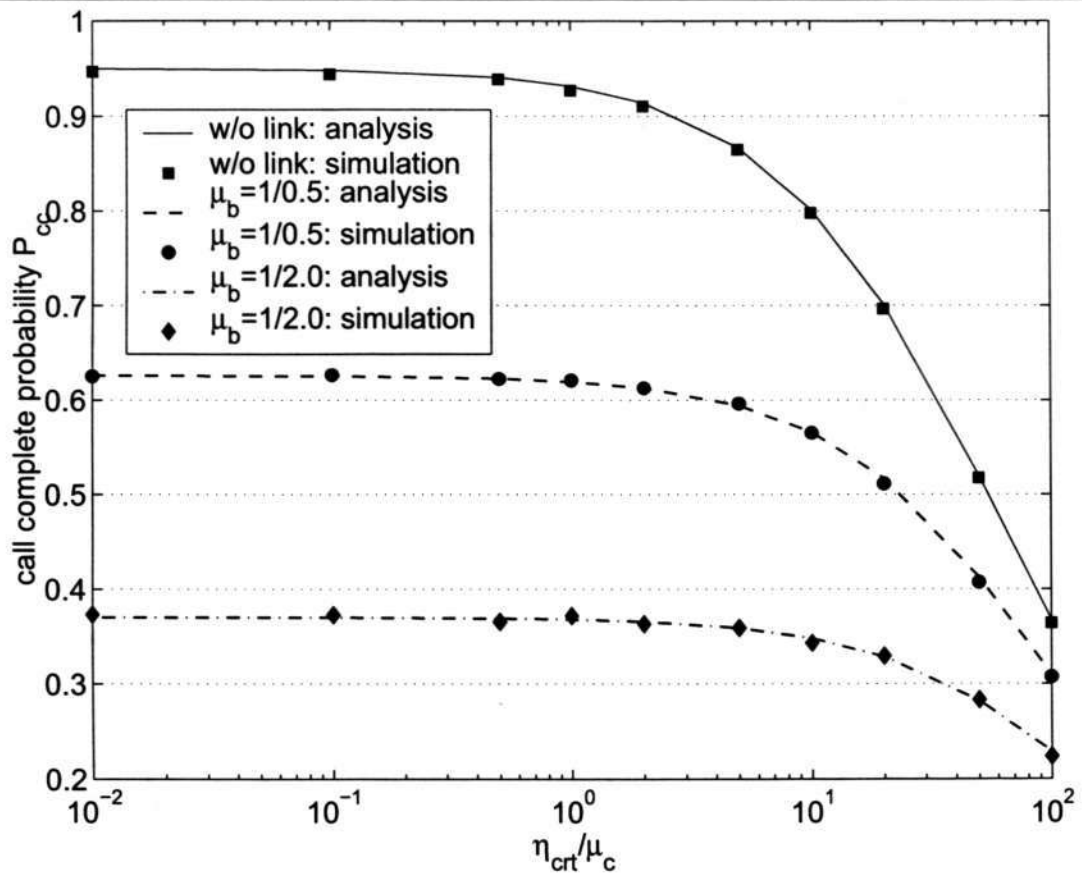


Figure 3.6: The call complete probability P_{cc} in terms of the ratio η_{crt}/μ_c with or without the presence of the wireless link unreliability effect

completion.

Fig. 3.7 shows the normalized average value of CCHT ω_T in terms of the ratio η_{crt}/μ_c in the presence or absence of the wireless link unreliability impact. Note that, ω_T is greatly overestimated without considering the wireless channel impairment, and similarly the faster mobility diminishes the estimation gap.

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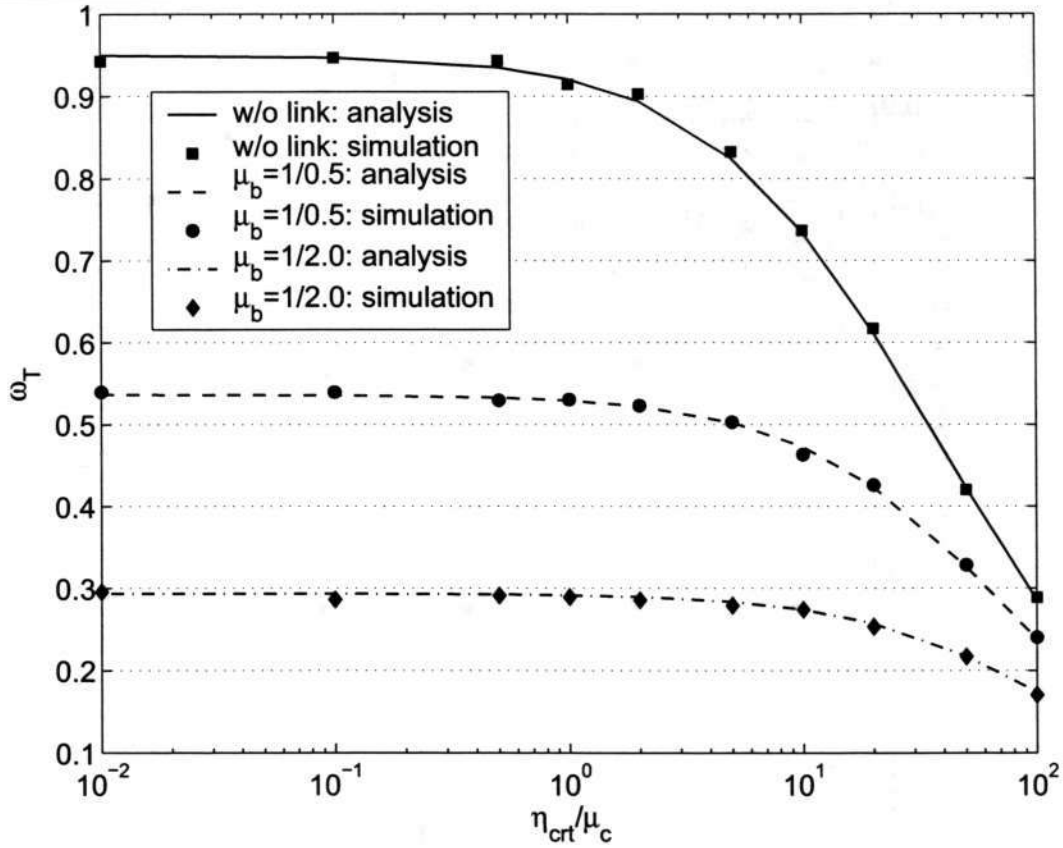


Figure 3.7: The normalized expected value of CCHT in terms of the ratio η_{crt}/μ_c with or without the presence of the wireless link unreliability effect

3.6 Conclusion

In this chapter, we studied the effects of the wireless link unreliability as well as the resource insufficiency on the wireless network performance. We derived the closed-form formula for the performance metrics call complete probability and the closed-form result for the probability density function of the completed call holding time under the general call holding time, general cell residence time and the generally distributed wireless channel good or bad state time duration. The analysis result is validated by the extensive simulation. Our comparison demonstrates that there is a considerable performance gap in applying different call holding time distribution. It is shown that

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the network performance will be substantially overestimated without integrating the unreliable wireless link impact.

Chapter 4

Handoff Dwell Time Distribution Effect on Mobile Network Performance

The previous two chapters have discussed the topic about the wireless link unreliability on the call performance in mobile network. We have at the same time examined the sensitivity with respect to the critical tele-traffic parameters such as the call holding time and the cell residence time. It is found that the call holding time as well as the cell residence time distribution function has a great impact upon the wireless network performance.

In this chapter, we will report the sensitivity problem in terms of the handoff dwell time upon the wireless network performance evaluation. For this, the handoff call queueing priority scheme, which relies heavily upon the handoff dwell time to provide the higher priority for the handoff call connection request, is adopted. In addition, for this Chapter, an efficient approximation approach is proposed to address the numerical

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intractability in computing the stationary state probability and the performance indices.

4.1 Introduction

Efficiently utilizing the limited bandwidth and controlling the call connection's request in a wireless mobile network are becoming increasingly important issues due to the user's seamless roaming requirement. In order to protect an ongoing conversation from being rejected, a number of handoff prioritization strategies based on channel allocation scheme, such as guard channel, have been proposed and studied. For the practical deployed wireless network, the overlapped area between neighboring cells will exist inevitably, and this benefits one of the handoff priority scheme, i.e., queuing priority scheme (QPS) which decreases the handoff blocking probability significantly with a slight expense on the new call blocking probability [17] [11]. We refer to the time interval that the user stays in the overlapped area as the handoff dwell time (HDT).

The HDT characteristics are critical for the mobile network planning and deployment. Several important and comprehensive studies on HDT modelling were presented in the following works [77]-[79]. After comparing the modelling and simulation results for a set of wide enough ranges of system parameters, e.g. cell radius, user speed and shadowing fading, the authors concluded that truncated Gaussian (t-Gaussian) function is suitable for fitting HDT distribution. Due to the analytical intractability with t-Gaussian HDT distribution, an exponential distribution of HDT is assumed to simplify the system performance derivation in [57]-[24]. However, to our knowledge, no studies have been presented to show whether there is a performance gap when HDT utilizes the exponential and t-Gaussian distributions.

To investigate the HDT effect on the wireless network performance, we study the

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performance evaluation from the perspective of Base Station (BS) and from the call behavior point of view. In the case of the former, the new call blocking probability and handoff call blocking probability are the most important performance metrics. For the latter, we need to examine the characteristics of call performance from the moment of the call's initial access to the time that the call ceases. In this case, call complete probability is one of the most significant performance metric [17] [35].

Furthermore, one essential characteristic of QPS that differs from the other handoff prioritization schemes, e.g. guard channel, is the buffer dedicated for handoff call. Hence, any handoff call may have to wait for a free channel for the case that all channels are occupied upon its arrival. The waiting time can be viewed as the queueing delay. Additionally, a call may exercise a number of handoff operations before call completion and, during each operation, the call may have to wait a period. Therefore, a successfully completed call may experience a number of queueing delay. The total waiting time is the summation of all the queueing delays for a successfully completed call.

In this chapter, the contributions in the numerical analysis are threefold: 1) we develop the balance equations for the new and handoff call traffic processes that is a function of the parameter γ_n (defined later), under the general HDT with handoff QPS scheme; 2) the closed-form expressions for the performance metrics with respect to new call/handoff call blocking probability, the call complete probability and total waiting time are developed; 3) The numerically intractable problem incurred by the infinite integral is addressed based on the universal approximation property of phase-type (PH) distribution [82]. Finally, t-Gaussian handoff dwell time distribution is fitted by PH distribution approximation via Expectation Maximization (EM) algorithm to obtain the closed form results. The application of PH distribution were pioneered earlier by [85] [25] for modelling the channel holding time or cell residence time in mobile network.

4.2 Handoff Queueing Priority Scheme with General Handoff Dwell Time Distribution

Considering a BS with C channels and a finite queue with length N in a homogeneous wireless network. Before all the channels in the cell are used up, the new call and the handoff call share the channel pool. When no channels are free, an arriving new call connection request is blocked, while a handoff call is saved into the queue provided that the queue is not full. We assume that both the new call arriving process and handoff call arriving process are Poisson processes with the arrival rates λ_n and λ_h , respectively. Denote $\lambda = \lambda_n + \lambda_h$ as the aggregate arrival rate to the BS. The call holding time t_c is exponential distribution with mean $1/\eta$. The cell residence time t_{ct} , which is the time duration that a user stays in the coverage of a cell, follows exponential distribution with mean $1/\nu$. Consequently, the channel holding time is exponential distribution with mean $1/\mu = 1/(\eta + \nu)$. It is noteworthy to point out that the assumption of the same channel holding time distributions of new call and handoff call may be not valid [38]. One solution is to approximate the mean of the common exponential channel holding time by the weighted summation of the new call average value and the handoff call mean [33]. The handoff dwell time θ is a random variable with general distribution function $F_\theta(t)$ and p.d.f. $f_\theta(t)$. Define (i, j) as the state of BS with i representing the number of calls in service and j the number of handoff calls waiting in the queue. Let $Pr[i][j]$ denote the steady-state probability in equilibrium.

Let \mathcal{R}^+ be the set of positive real number. For $t, \epsilon \in \mathcal{R}^+$, let us define,

$\Psi_j(t, \epsilon) \equiv$ the probability that a handoff call misses its deadline during $[t, t + \epsilon)$,

given that there are $j(> 0)$ handoff calls in the waiting queue at time t

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where j is greater than zero due to the fact that a handoff call may miss its deadline only when there are calls in the queue.

Define

$$\gamma_j = \lim_{t \rightarrow \infty} \left(\lim_{\epsilon \rightarrow 0} \frac{\Psi_j(t, \epsilon)}{\epsilon} \right) \quad (4.1)$$

Using the similar technique that employed by [75, page 232] and applying the PASTA (Poisson Arrivals See Time Average) property, [81] has shown that

$$\gamma_j = \frac{j\Phi(j-1)}{\Phi(j)} - C\mu; \quad 1 \leq j \leq N \quad (4.2)$$

where $\Phi(j)$ is defined as

$$\Phi(j) = \int_0^\infty \left[\int_0^\tau (1 - F_\theta(x)) dx \right]^j e^{-C\mu\tau} d\tau \quad (4.3)$$

with $\Phi(0) = \frac{1}{C\mu}$.

For the BS, there are two call traffic processes, i.e. new and handoff call traffic processes. Referring to the call admission control algorithm of new call and handoff call, we develop the balance equations

- For $1 \leq i \leq C, j = 0$,
 $\lambda \cdot Pr[i-1][0] = (i\mu) \cdot Pr[i][0]$
- For $i = C, 1 \leq j < N$,
 $\lambda_h \cdot Pr[C][j-1] + (C\mu + \gamma_{j+1}) \cdot Pr[C][j+1] = (\lambda_h + C\mu + \gamma_j) \cdot Pr[C][j]$
- For $i = C, j = N$,
 $\lambda_h \cdot Pr[C][N-1] = (C\mu + \gamma_N) \cdot Pr[C][N]$

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Solving the set of balance equations, together with (4.2), the steady state probability is shown below.

$$Pr[i][j] = \begin{cases} \frac{(\lambda/\mu)^i}{i!} \cdot Pr[0][0] & i = 0, 1 \dots C; j = 0 \\ \frac{\lambda^C}{\mu^{C-1}(C-1)!} \frac{\lambda_h^j \Phi(j)}{j!} \cdot Pr[0][0] & i = C; j = 1, 2 \dots N \end{cases} \quad (4.4)$$

Using the normalization condition $\sum_{i=0}^C Pr[i][0] + \sum_{j=1}^N Pr[C][j] = 1$, we have

$$Pr[0][0] = \left[\sum_{i=0}^C \frac{(\lambda/\mu)^i}{i!} + \frac{\lambda^C}{\mu^{C-1}(C-1)!} \sum_{j=1}^N \frac{\lambda_h^j \Phi(j)}{j!} \right]^{-1} \quad (4.5)$$

After selecting the HDT distribution function and substituting the function into (4.3), the steady state probability can be computed.

By equating the incoming call arrival rate to the outgoing call departure rate, we obtain

$$[\lambda_n(1 - P_n) + \lambda_h(1 - P_h)] \frac{\nu}{\nu + \eta} = \lambda_h \quad (4.6)$$

and,

$$\lambda_h = \frac{\nu(1 - P_n)}{\eta + \nu P_h} \lambda_n \quad (4.7)$$

where P_n and P_h are new call blocking probability and handoff call blocking probability, respectively. Note that the handoff call arrival rate is a function of the new call arrival rate and other system parameters.

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4.3 Performance Metrics: BS point of view

From the BS point of view, the most important indices for evaluating mobile network performance are the new call blocking probability and handoff call blocking probability.

4.3.1 New Call Blocking Probability

A new call connection request is rejected when all channels are busy upon the call arrival. Hence, the new call blocking probability P_n is given by

$$P_n = \sum_{j=0}^N Pr[C][j] = \frac{\frac{\lambda^C}{\mu^{C-1}(C-1)!} \sum_{j=0}^N \frac{\lambda_h^j \Phi(j)}{j!}}{\sum_{i=0}^C \frac{(\lambda/\mu)^i}{i!} + \frac{\lambda^C}{\mu^{C-1}(C-1)!} \sum_{j=1}^N \frac{\lambda_h^j \Phi(j)}{j!}} \quad (4.8)$$

4.3.2 Handoff Call Blocking Probability

Let

$W_j (j = 0, 1 \dots N - 1) \equiv$ the time an arriving handoff call with an infinite

(no) deadline must wait before its

service commences in the long run, given

that it finds $C + j$ calls in the system

Following the results given in [81], it can be shown that the p.d.f. of W_j is given by

$$f_{W_j}(t) = \frac{\left[\int_0^t (1 - F_\theta(x)) dx \right]^j e^{-C\mu t}}{\Phi(j)}$$

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From the above expression, we derive the following results. Handoff calls may be blocked in two conditions.

1. When all channels are busy and the finite buffer is full at the time of the call arrival. In this case, the blocking probability is

$$Pr[C][N]$$

2. At the time of the handoff call arrival, all channels are busy but there is empty space in the buffer. Then, the handoff call is saved in the queue. However, before the call captures a free channel, its actual waiting time is greater than the handoff dwell time and is forced to leave the queue. Here, the handoff dwell time can be alternatively viewed as an expiring timer. In this case, the blocking probability is expressed as

$$\sum_{j=0}^{N-1} Pr[C][j](1 - Pr(W_j \leq \theta))$$

Hence, the handoff blocking probability P_h is given by

$$\begin{aligned} P_h &= Pr[C][N] + \sum_{j=0}^{N-1} Pr[C][j](1 - Pr(W_j \leq \theta)) \\ &= Pr[C][N] + \sum_{j=0}^{N-1} Pr[C][j] \left(1 - \int_0^\infty (1 - F_\theta(w)) f_{W_j}(w) dw \right) \\ &= Pr[C][N] + \sum_{j=0}^{N-1} Pr[C][j] \left(1 - \frac{C\mu}{j+1} \frac{\Phi(j+1)}{\Phi(j)} \right) \\ &= \frac{\sum_{j=0}^N \frac{\lambda^C}{\mu^{C-1}(C-1)!} \frac{\lambda_h^j \Phi(j)}{j!} - \sum_{j=0}^{N-1} \frac{C\lambda^C}{\mu^{C-2}(C-1)!} \frac{\lambda_h^j \Phi(j+1)}{(j+1)!}}{\sum_{i=0}^C \frac{(\lambda/\mu)^i}{i!} + \sum_{j=1}^N \frac{\lambda^C}{\mu^{C-1}(C-1)!} \frac{\lambda_h^j \Phi(j)}{j!}} \end{aligned} \quad (4.9)$$

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4.4 Performance Metrics: Call behavior point of view

From the call behavior perspective, we are interested in the call performance from the call initial access to the end of the call due either to normal completion or to forced termination. We will describe the call complete probability (or call incomplete probability) and the total waiting time which are the principle metrics.

4.4.1 Call Complete Probability

The call complete probability, P_{cc} , is defined as the probability that a channel is available for initial access and all the handoff access is successful during the call holding time.

$$P_{cc} = (1 - P_n) \sum_{k=0}^{\infty} (1 - P_h)^k Pr(K = k) \quad (4.10)$$

where $Pr(K = k)$ is the probability that a call experiences K handoff upon call completion and given by

$$Pr(K = k) = \xi^k (1 - \xi) \quad (4.11)$$

with $\xi = \frac{\nu}{\nu + \eta}$ the handoff probability that a call leaves the coverage of the serving cell without call completion.

Substituting (4.11) into (4.10), we obtain the call complete probability

$$P_{cc} = (1 - P_n) \sum_{k=0}^{\infty} (1 - P_h)^k \xi^k (1 - \xi) = \frac{1 - P_n}{1 + \frac{\nu}{\eta} P_h} \quad (4.12)$$

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Thus, the call incomplete probability, P_{nc} , is given by

$$P_{nc} = 1 - P_{cc} \quad (4.13)$$

4.4.2 Total Waiting Time of a Successfully Completed Handoff Call

In contrast with the handoff prioritization scheme without queue, QPS shows a significantly different characteristics during a call trajectory. During each handoff operation, the handoff call may wait for an interval W due to all occupied channels upon its arrival time. The distribution of the waiting time W is represented as

$$\begin{aligned} f_W(t) &= \sum_{j=0}^{N-1} f_{W_j}(t) Pr[C][j] \\ &= \frac{\lambda^C}{\mu^{C-1}(C-1)!} Pr[0][0] e^{-C\mu t} \cdot \sum_{j=0}^{N-1} \left[\int_0^t (1 - F_\theta(x)) dx \right]^j \frac{\lambda_h^j}{j!} \end{aligned}$$

The expected waiting time of handoff call in each handoff operation is given by

$$\begin{aligned} \mathbb{E}(W) &= \int_0^\infty t f_W(t) dt \\ &= \frac{\lambda^C}{\mu^{C-1}(C-1)!} Pr[0][0] \cdot \sum_{j=0}^{N-1} \frac{\lambda_h^j}{j!} \int_0^\infty t e^{-C\mu t} \left[\int_0^t (1 - F_\theta(x)) dx \right]^j dt \quad (4.14) \end{aligned}$$

We define the call-mobility-ratio(CMR) as the ratio between the average call holding time against the average cell residence time.

$$CMR = \frac{\frac{1}{\eta}}{\frac{1}{\nu}} = \frac{\nu}{\eta} \quad (4.15)$$

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As the user speed is high, the user is likely to stay in a cell for a short period, resulting in shorter cell residence time (or equally larger ν), and hence larger CMR. In contrast, for a slow-mobility user, the likelihood that the user reside in a cell will be small, resulting in larger cell residence time (or equally smaller ν), and hence smaller CMR. As a consequence, CMR can directly reflect the user mobility. On the other hand, due to the memoryless property of exponential distribution, the mean number of handoff operation of a call is equal to $\frac{1/\eta}{1/\nu}$. Hence, the introduced parameter CMR can be equally interpreted as the average number of required handoff before call completion.

Denote T_w be the the mean total waiting time of a successful handoff call, i.e. the summation of the waiting time associated to each handoff operation.

$$T_w = CMR \cdot \mathbb{E}(W) \quad (4.16)$$

From the tele-traffic point of view, the system cost is induced by both the call blocking and handoff call waiting. It is proposed that the customer can understand and tolerate the call blocking and dropping in "hot-spot" area and peak hour, but the customer can not tolerate the payment associated with the total waiting time because the customer does not utilize this period. Basically, for any call admission control utilizing buffer, this condition will occur. Traditionally, the cost function is defined as the weighted summary of blocking probabilities [11], we suggest that it is more reasonable to include the effect of the total waiting time.

4.5 Handoff Dwell Time Distribution: Analysis and Approximation

From the expression of steady-state probability (4.4) and the two blocking probabilities (4.8) (4.9), it is found that the impact of general HDT is reflected by and encapsulated in $\Phi(j)$. To be convenient, the expression of $\Phi(j)$ is rewritten here.

$$\Phi(j) = \int_0^\infty \left[\int_0^\tau (1 - F_\theta(x)) dx \right]^j e^{-C\mu\tau} d\tau$$

However, the result is numerical intractable and not suitable for engineering computation due to the existence of infinite integral. After a number of experiments, we found that the computation is time consuming and prohibitive when using Runge-Kutta algorithm directly as HDT is t-Gaussian distribution. The computational time is even longer than the period for the simulation program to finish handling 800000 calls. Considering the universal approximation property of PH distribution, in the first subsection we focus on the calculation of $\Phi(j)$ when HDT is assumed as PH distribution. In the second subsection, the EM algorithm is presented to fit t-Gaussian distribution by PH distribution.

4.5.1 HDT is phase-type distribution

Assume that the HDT follows a phase-type distribution with representation (β, U) [82], i.e.,

$$F_\theta(t) = 1 - \beta e^{Ut} \mathbf{e}$$

$$f_\theta(t) = -\beta e^{Ut} U \mathbf{e}$$

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where $m \times m$ matrix \mathbf{U} is nonsingular with negative diagonal elements and nonnegative off-diagonal elements, $m \times 1$ vector \mathbf{e} denotes the column vector of ones with the appropriate dimension depending on the context. Let $\mathbf{I}_{\mathbf{X}}$ denote the identity matrix with the same dimension as matrix \mathbf{X} . For simplicity, let \mathbf{I} denote the identity matrix with obvious dimension, by neglecting the subscript.

To compute $\Phi(j)$, we need to first calculate the integral of $\bar{F}_{\theta}(t) = 1 - F_{\theta}(t)$, which is given by

$$\int_0^{\tau} (1 - F_{\theta}(x)) dx = \int_0^{\tau} \beta e^{Ux} \mathbf{e} dx = \beta \mathbf{U}^{-1} (e^{U\tau} - \mathbf{I}) \mathbf{e}$$

Furthermore, using the properties of Kronecker product \otimes and Kronecker sum \oplus ,

$$(\mathbf{X}_1 \mathbf{X}_2 \cdots \mathbf{X}_l) \otimes (\mathbf{Y}_1 \mathbf{Y}_2 \cdots \mathbf{Y}_l) = (\mathbf{X}_1 \otimes \mathbf{Y}_1)(\mathbf{X}_2 \otimes \mathbf{Y}_2) \cdots (\mathbf{X}_l \otimes \mathbf{Y}_l) \quad \forall l \geq 1$$

$$\exp(\mathbf{X}_1) \otimes \exp(\mathbf{X}_2) \otimes \cdots \otimes \exp(\mathbf{X}_l) = \exp(\mathbf{X}_1 \oplus \mathbf{X}_2 \oplus \cdots \oplus \mathbf{X}_l) \quad \forall l \geq 1$$

Let us introduce the symbols to represent the power of Kronecker product and the power of Kronecker sum

$$\mathbf{X}^{\otimes l} \equiv \underbrace{\mathbf{X} \otimes \cdots \otimes \mathbf{X}}_l ; \quad \mathbf{X}^{\oplus l} \equiv \underbrace{\mathbf{X} \oplus \cdots \oplus \mathbf{X}}_l \quad \forall l \geq 1$$

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Hence, we have

$$\begin{aligned}
 & \left(\int_0^\tau (1 - F_\theta(x)) dx \right)^j \\
 &= [\beta U^{-1} (e^{U\tau} - I) e]^j \\
 &= [\beta U^{-1} e^{U\tau} e - \beta U^{-1} I e]^j \\
 &= \sum_{k=0}^j \binom{j}{k} (\beta U^{-1} e^{U\tau} e)^k (-\beta U^{-1} I e)^{j-k} \tag{4.17}
 \end{aligned}$$

$$= \beta^{\otimes j} (U^{-1})^{\otimes j} \sum_{k=0}^j \binom{j}{k} (-1)^{j-k} [\exp(U^{\oplus k} \tau) \otimes I] e \tag{4.18}$$

while the dimension of all identity matrices before(including) equation (4.17) is $m \times m$, the dimension of identity matrix in equation (4.18) is $m^{j-k} \times m^{j-k}$, which result in the dimension of matrix $[\exp(U^{\oplus k} \tau) \otimes I]$ is $m^j \times m^j$ for any integer $k (= 0, 1 \dots j)$ with reference to the definition of Kronecker product. Hereafter, all the identity matrices without specified size have the dimension $m^{j-k} \times m^{j-k}$.

Substituting expression (4.18) into (4.3), $\Phi(j)$ is given by

$$\begin{aligned}
 \Phi(j) &= \int_0^\infty \left[\int_0^\tau (1 - F_\theta(x)) dx \right]^j e^{-C\mu\tau} d\tau \\
 &= \beta^{\otimes j} (U^{-1})^{\otimes j} \sum_{k=0}^j \binom{j}{k} (-1)^{j-k} D(k) e \tag{4.19}
 \end{aligned}$$

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where the $m^j \times m^j$ matrix $\mathbf{D}(k)$ is defined as

$$\begin{aligned}\mathbf{D}(k) &= \int_0^\infty [\exp(\mathbf{U}^{\oplus k} \tau) \otimes \mathbf{I}] e^{-C\mu\tau} d\tau \\ &= \int_0^\infty [\exp(\mathbf{U}^{\oplus k} \tau)] e^{-C\mu\tau} d\tau \otimes \mathbf{I} \\ &= (C\mu \mathbf{I}_{\mathbf{U}^{\oplus k}} - \mathbf{U}^{\oplus k})^{-1} \otimes \mathbf{I}\end{aligned}\tag{4.20}$$

Now, the new call blocking probability and handoff call blocking probability can be calculated when HDT is a PH distribution by substituting (4.19) into (4.8) and (4.9). Following the similar reasoning leading to (4.19), we obtain the average value of the waiting time during each handoff

$$\begin{aligned}\mathbb{E}(W) &= \frac{\lambda^C}{\mu^{C-1}(C-1)!} Pr[0][0] \cdot \sum_{j=0}^{N-1} \frac{\lambda_h^j}{j!} \beta^{\otimes j} (\mathbf{U}^{-1})^{\otimes j} \\ &\quad \cdot \sum_{k=0}^j \binom{j}{k} (-1)^{j-k} [(C\mu \mathbf{I}_{\mathbf{U}^{\oplus k}} - \mathbf{U}^{\oplus k})^{-2} \otimes \mathbf{I}] \mathbf{e}\end{aligned}\tag{4.21}$$

In the particular case of $m = 1$, matrices β, \mathbf{U} become real numbers β, U , respectively. An example of this case is the exponential distributed HDT.

$$\beta^{\otimes j} = \beta^j; \quad (\mathbf{U}^{-1})^{\otimes j} = \frac{1}{U^j}; \quad \mathbf{U}^{\oplus k} = kU$$

Then, equations (4.19) and (4.21) reduce to

$$\Phi(j) = \left(\frac{\beta}{U}\right)^j \sum_{k=0}^j \binom{j}{k} \frac{(-1)^{j-k}}{C\mu - kU}\tag{4.22}$$

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$$\mathbb{E}(W) = \frac{\lambda^C}{\mu^{C-1}(C-1)!} Pr[0][0] \cdot \sum_{j=0}^{N-1} \frac{\lambda_h^j}{j!} \left(\frac{\beta}{U}\right)^j \sum_{k=0}^j \binom{j}{k} \frac{(-1)^{j-k}}{(C\mu - kU)^2} \quad (4.23)$$

4.5.2 Fitting t-Gaussian Distribution

The p.d.f. of HDT is given by

$$g_{\theta}(t) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(t-\xi)^2}{2\sigma^2}}; \quad t \geq 0 \quad (4.24)$$

where ξ and σ^2 are mean and variance of HDT respectively.

To reuse the analytical result in the previous subsection, we need to approximate the t-Gaussian distribution by PH distribution. One possible method is to minimize the Kullback-Leibler distance(KLD) between the t-Gaussian distribution and phase-type distribution via the EM algorithm[83], which is essentially an iterative maximum likelihood method for estimation the elements of (β, U) .

The KLD of $f_{\theta}(t)$ with respect to $g_{\theta}(t)$ is given by

$$D(g_{\theta}(t)||f_{\theta}(t)) = \int_t g_{\theta}(t) \ln \frac{g_{\theta}(t)}{f_{\theta}(t)} dt$$

Thus, the criteria in EM algorithm is equivalent to maximizing

$$\max_{(\beta, U)} \int_t \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(t-\xi)^2}{2\sigma^2}} \ln(-\beta e^{U^t U} e) dt$$

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4.6 Numerical Results

In this section, we will investigate four aspects. First, the fitted t-Gaussian HDT by PH distribution is presented. Second, the analytical model and the approximation approach are verified by the simulation result. The effects of HDT distribution on the BS and call performance are illustrated. Then, the different mobility pattern reflected by CMR is incorporated to examine HDT. Finally, the exponential cell residence time assumption is relaxed. Instead, Gamma cell residence time is combined to explore HDT effect. In the following, the number of channel $C = 30$, the queue length $N = 4$ and the average call holding time is equal to 180.0sec.

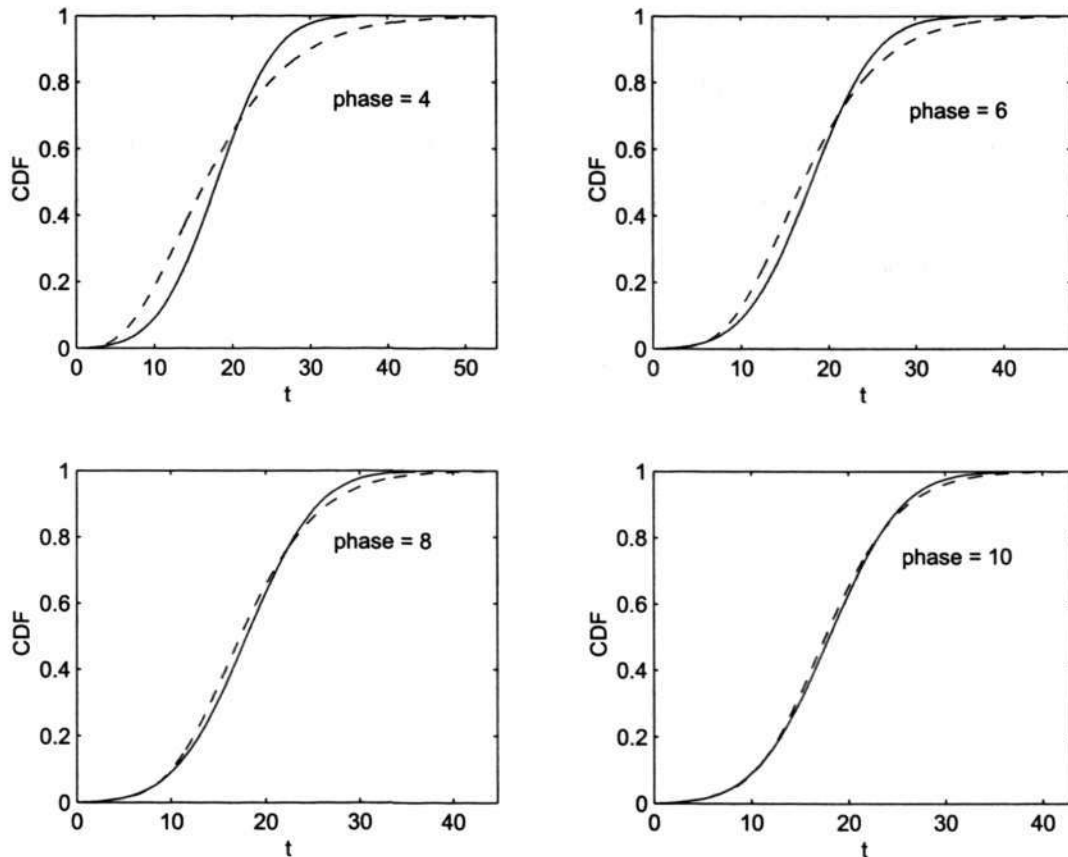


Figure 4.1: Comparison of the CDF truncated Gaussian (solid line) and the fitted phase-type distribution (dashed line) with different phases (phase=4, 6, 8, 10)

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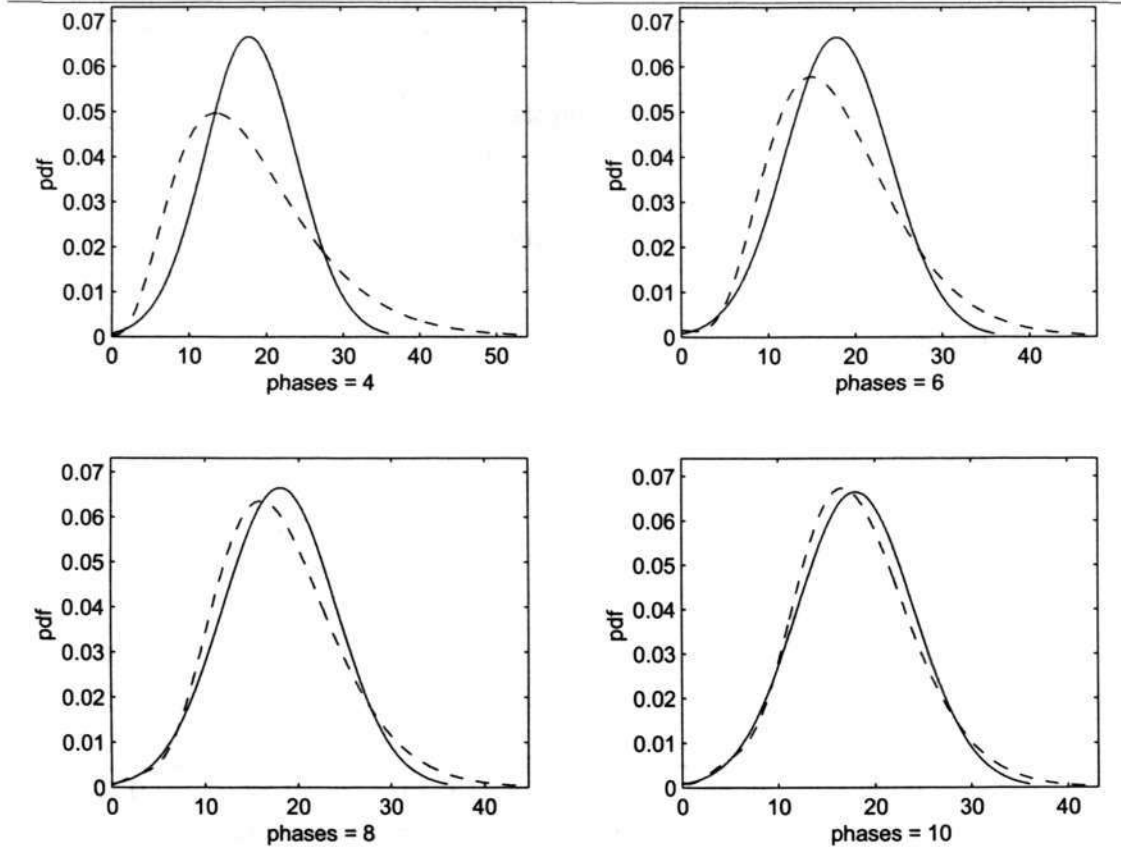


Figure 4.2: Comparison of the PDF truncated Gaussian (solid line) and the fitted phase-type distribution (dashed line) with different phases (phase=4, 6, 8, 10)

4.6.1 Fitting Distribution

Fig.4.1 shows the comparison between t-Gaussian c.d.f. (solid line) and the fitted c.d.f. by PH distribution with different phases (dashed line). Fig.4.2 shows the comparison between t-Gaussian p.d.f. (solid line) and the fitted p.d.f. by PH distribution with different phases (dashed line). The mean and standard deviation of the t-Gaussian distribution are $\xi = \frac{1/\eta}{10} = 18.0\text{sec}$, $\sigma = 6.0$, respectively. By increasing the number of phases, the error between the original t-Gaussian distribution and the fitted PH distribution will decrease dramatically. Comparing the results, it can be found that the discrepancy between the two distributions can be significantly small.

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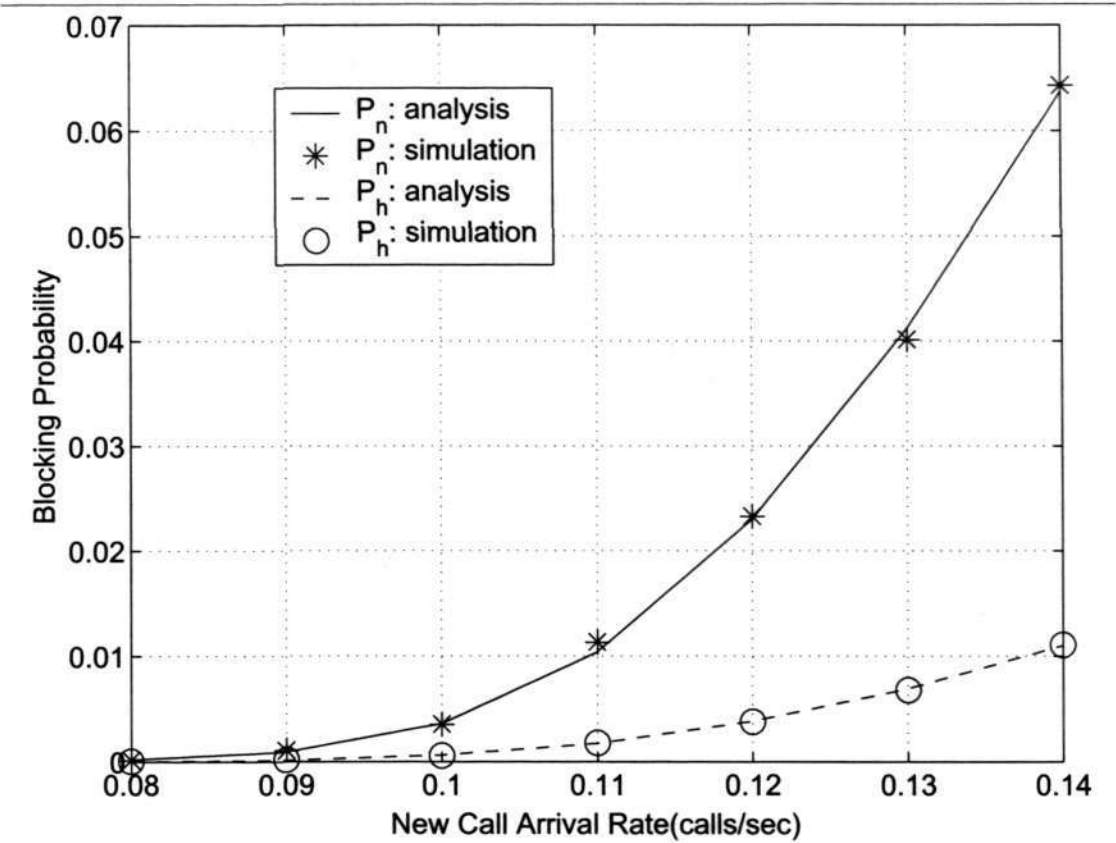


Figure 4.3: New call blocking probability P_n and handoff call blocking probability P_h in terms of new call arrival rate λ_n with exponential HDT (CMR=1.5)

4.6.2 Analysis and Approximation Result Validation

Fig. 4.3 shows the analysis result and the simulation result when HDT is exponential distribution with mean 18.0sec. It is clear that the analytical result matches the simulation quite well. In addition, the handoff call blocking probability is much smaller than the new call blocking probability, which is a critical requirement of wireless mobile network to protect the ongoing call connection from rejection.

Fig. 4.4 and Fig. 4.5 illustrate the approximation results with various phases and the simulation results when HDT is fitted t-Gaussian distribution with mean $\xi = 18.0$ sec and standard deviation $\sigma = 6.0$. It is observed that the analytical result is consistent

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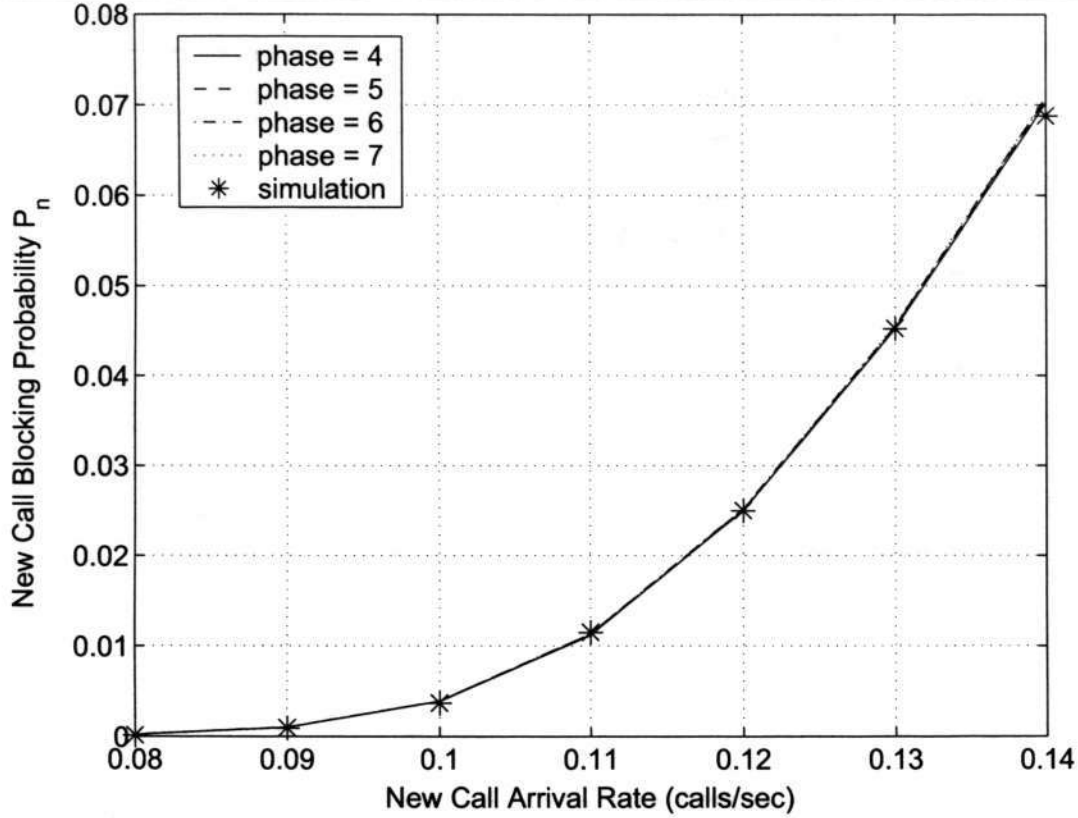


Figure 4.4: New call blocking probability P_n in terms of new call arrival rate λ_n with fitted t-Gaussian HDT (CMR=1.5)

with the simulation, which validates the correctness and efficiency of the approximation method.

Next, we make a comparison between the blocking probabilities when HDT follows exponential or t-Gaussian distribution. From Fig.4.3, Fig.4.4 and Fig.4.5, we find that the HDT distribution has a significant impact on the handoff call blocking probability, although the distribution has much less effect on the new call blocking probability. More specifically, handoff call blocking probability with t-Gaussian HDT is much smaller than the probability with exponential assumption. Under the t-Gaussian HDT, we identify the system operating point as the new call blocking probability $P_n^{t-Gaussian}$ equal to 2%, i.e. $P_n^{t-Gaussian} = 2\%$. In this case, the new call arrival rate $\tilde{\lambda}_n = 0.1168$ calls/sec and

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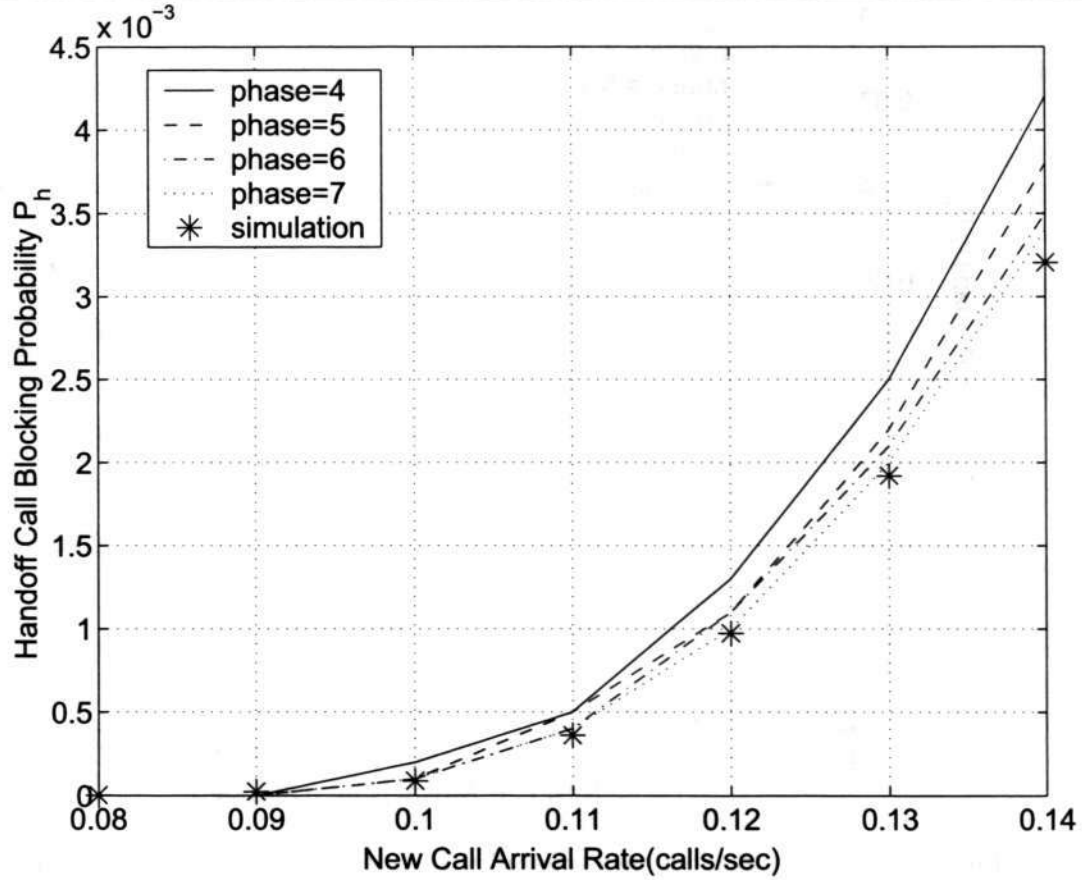


Figure 4.5: Handoff call blocking probability P_h in terms of new call arrival rate λ_n with fitted t-Gaussian HDT (CMR=1.5)

the handoff call blocking probability $P_h^{t-Gaussian} = 0.07743\%$. Comparatively, under the same new call arrival rate $\tilde{\lambda}_n = 0.1168$ calls/sec, for the exponential distribution HDT, the new call blocking probability $P_n^{EXP} = 1.83\%$ and the handoff call blocking probability $P_h^{EXP} = 0.3\%$. The relative error of new call blocking probability in the two cases is $\frac{|P_n^{EXP} - P_n^{t-Gaussian}|}{P_n^{t-Gaussian}} = 8.5\%$. On the other hand, the relative error of handoff call blocking probability in the two cases is $\frac{|P_h^{EXP} - P_h^{t-Gaussian}|}{P_h^{t-Gaussian}} = 287.45\%$. Hence, we can see that, under the identified operating point, the HDT distribution has negligible effect on the new call blocking probability but considerable impact on the handoff call blocking probability. The reason is due to the different nature of exponential and t-Gaussian distribution functions, where the exponential distribution is consistently decreasing

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while t-Gaussian function firstly increases and then decreases.

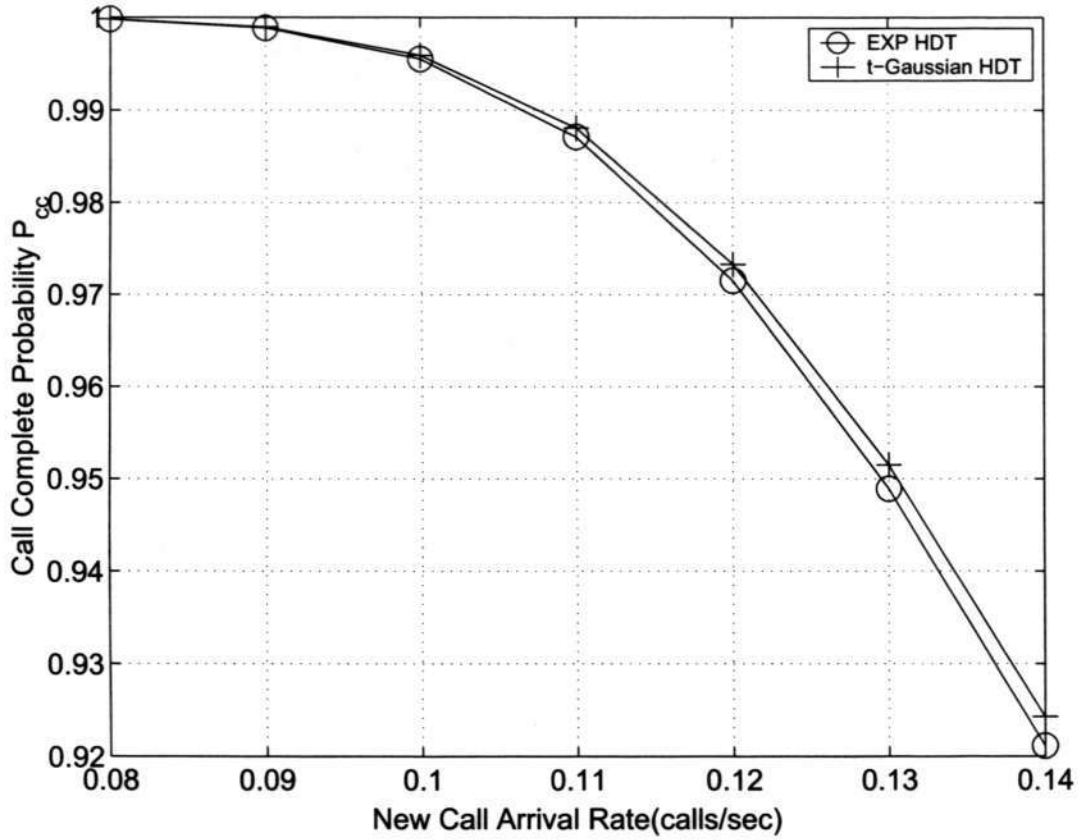


Figure 4.6: Call complete probability P_{cc} in terms of new call arrival rate λ_n with different HDT distribution (CMR=1.5)

Since the call complete probability is derived from the perspective of the call behavior and a call may exercise a few handoff operations before the call completion, it is intuitively expected that the call complete probability under exponential HDT shows a significant discrepancy against the probability under t-Gaussian HDT distribution. We plot the call complete probability in terms of the new call arrival rate shown in Fig.4.6. It is seen that the call complete probabilities in the two cases, however, exhibit little discrepancy. We take the operating point $\tilde{\lambda}_n = 0.1168$ calls/sec as the example to explain. Under such new call arrival rate, the call complete probabilities with exponential and t-Gaussian HDT are respectively given as $P_{cc}^{EXP} = 0.9773$ and $P_{cc}^{t-Gaussian} = 0.9789$.

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From the equation (4.12), we have

$$\lim_{P_h \rightarrow 0} P_{cc} = \lim_{P_h \rightarrow 0} \frac{1 - P_n}{1 + \frac{\rho}{\eta} P_h} = 1 - P_n \quad (4.25)$$

i.e. the call complete probability approaches $1 - P_n$ as the handoff call blocking probability approaches zero. In addition, from the previous observation and explanation, P_n is insensitive to HDT distribution. Hence, it is not surprising that under the dissimilar HDT functions, there is almost no variation in the call complete probabilities when P_h approaches zero.

4.6.3 Effect of CMR on metrics from BS point of view

Fig.4.7 depicts the new call blocking probability and handoff call blocking probability in terms of CMR. We can observe that P_n is almost insensitive to HDT regardless of the different user mobility pattern, but P_h indicates a significant difference with respect to the quantity as well as the variation trend.

When CMR is extremely small, the call is almost impossible to handoff to adjacent cell before call completion. As CMR becomes medium, the queue for handoff call will efficiently handle the handoff request and most of the handoff calls can access a channel before HDT expiration. Hence, P_h will decrease in this case. With constantly increasing CMR, the finite queue can not accommodate the floods of handoff request and hence P_h will increase. We can observe that the curve with t-Gaussian HDT corresponds to the described P_h property but the line with exponential HDT does not match.

In addition, under the cases of the exponential and t-Gaussian HDT, P_h exhibits decreasing discrepancy with faster mobility. This is due to the less likelihood of fast user in staying within the coverage of a cell and hence less impact by different HDT

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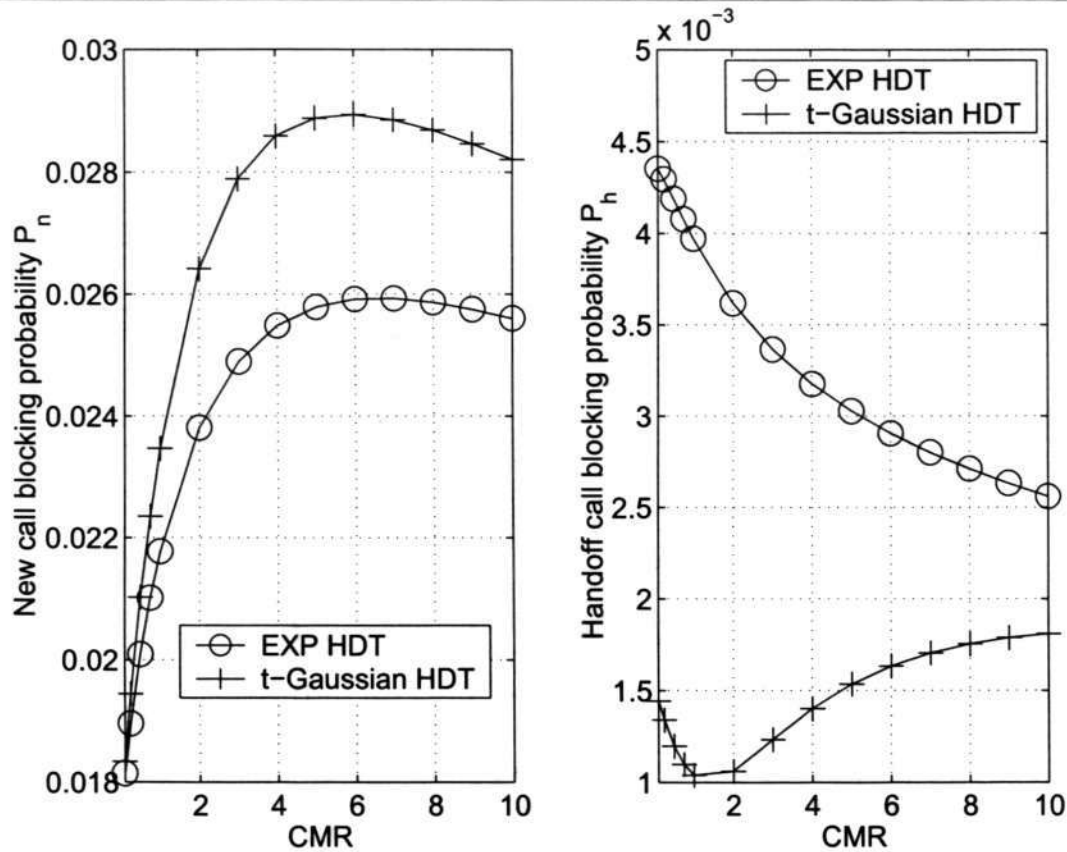


Figure 4.7: New call blocking probability P_n and handoff call blocking probability P_h in terms of CMR ($\lambda_n = 0.12$ calls/sec)

model.

4.6.4 Effect of CMR on metrics from call behavior perspective

Fig.4.8 plots the call complete probability and the total waiting time as the function of CMR. The curves indicate that

- when CMR is very small or medium and as P_h is close to zero, from the equation (4.12), P_{cc} approaches $1 - P_n$. Since P_n exhibits negligible discrepancy under different HDT or diverse mobility pattern, P_{cc} will correspondingly show little

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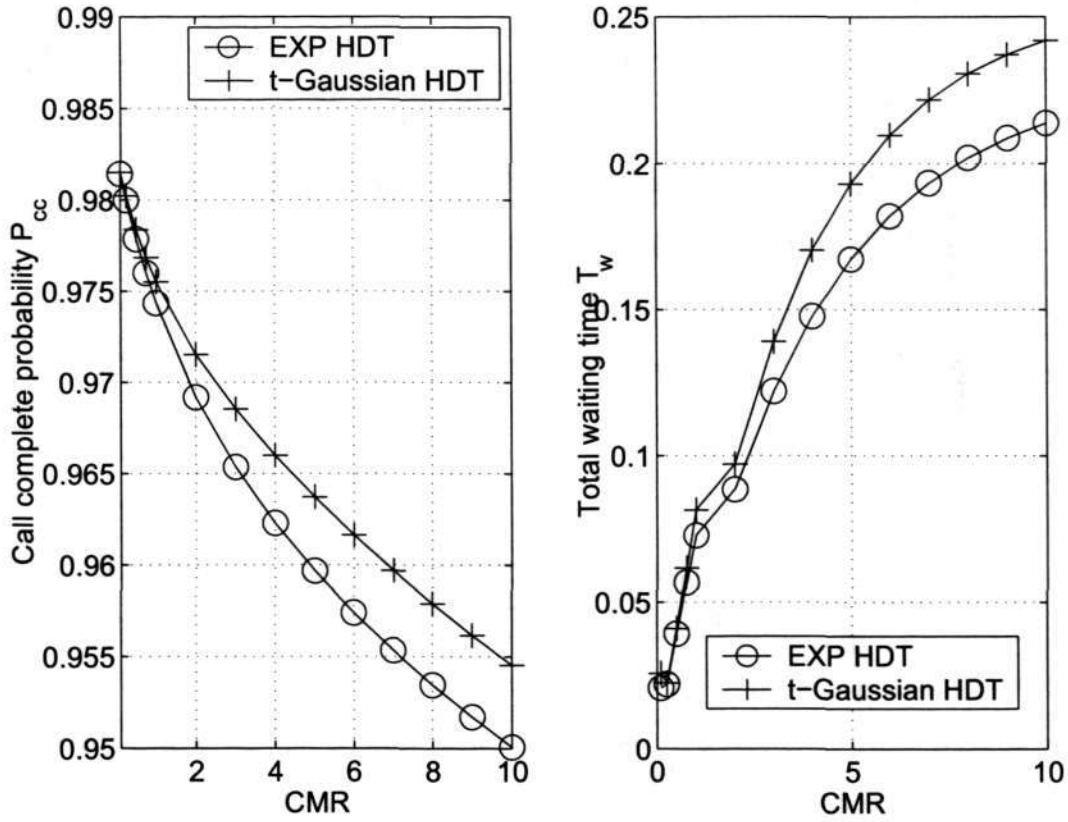


Figure 4.8: Call complete probability P_{cc} and total waiting time T_w in terms of CMR ($\lambda_n = 0.12$ calls/sec)

variation in this case.

- when CMR becomes greater, the second item of the denominator in the equation (4.12) can not be ignored. However, as we have stated in section 4.6.3, faster mobility pattern incurs less variation in P_h , which results in the approximately identical P_{cc} in combination with the insensitive property of P_n . As a consequence, HDT has insignificant impact on the call complete probability.
- the gap between T_w with exponential or t-Gaussian HDT is also negligible.

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4.6.5 Effect of cell residence time

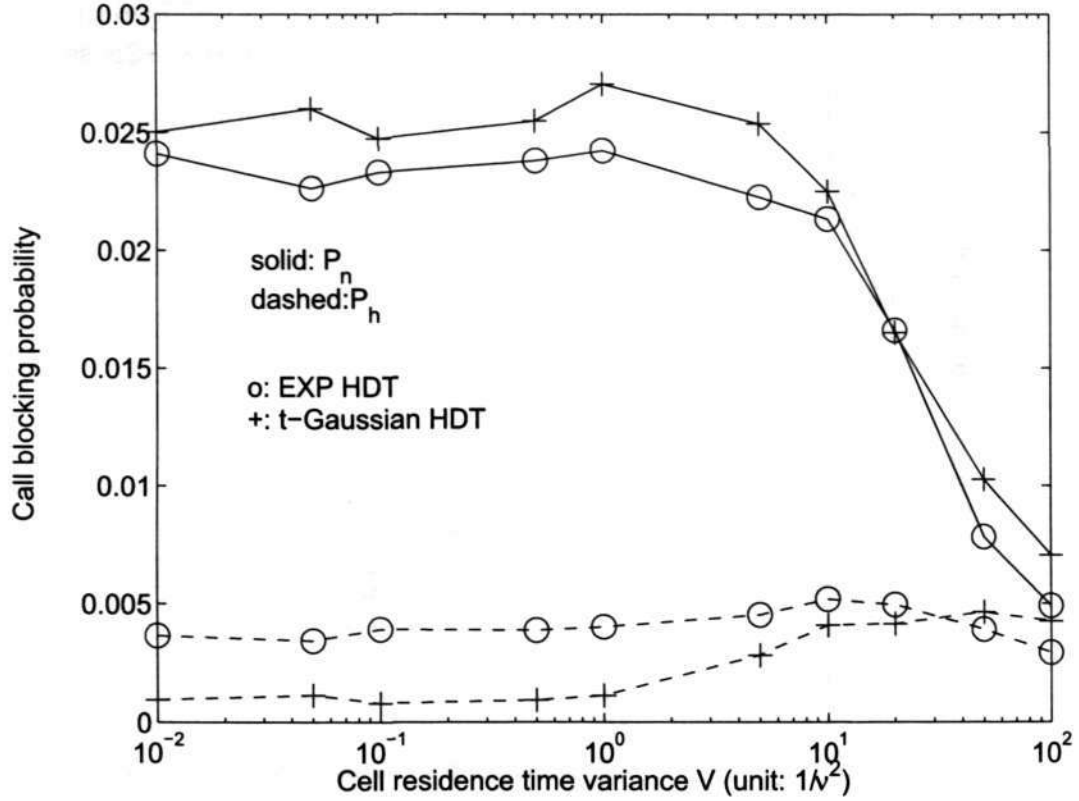


Figure 4.9: New call and handoff call blocking probability in terms of Gamma cell residence time variance V ($\lambda_n = 0.12$ calls/sec)

To present the effect of cell residence time, we assume that the cell residence time follows the Gamma distribution with mean $1/\nu$ and variance V [38] [68] [58]. Note that when $V = 1/\nu^2$, the Gamma distribution becomes an exponential distribution. Fig.4.9 shows the new call blocking probability (solid line) and the handoff call blocking probability (dashed line) in terms of the cell residence time variance. Fig.4.10 illustrates the call complete probability in terms of the cell residence time variance. It is found that for a fixed V , HDT distribution has an insignificant impact on P_n and P_{cc} . As $V \leq 1/\nu^2$, P_h shows a substantial gap while using different HDT and the gap decreases with larger V . It is known that higher variance implies more variation in traffic pattern. Hence, more bursty call traffic benefits the elimination of the performance discrepancy

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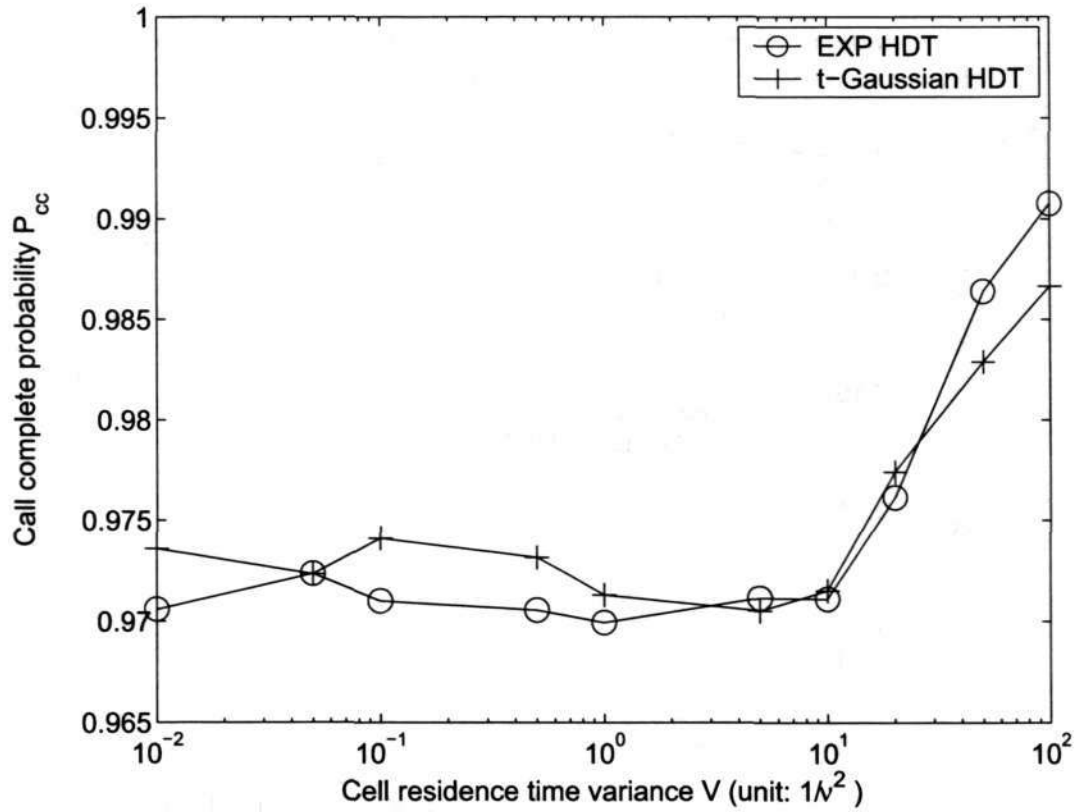


Figure 4.10: Call complete probability P_{cc} in terms of Gamma cell residence variance V ($\lambda_n = 0.12$ calls/sec)

caused by different HDT model.

4.7 Conclusions

In this chapter, we investigated the sensitivity problem with respect to the HDT model in wireless network. The numerical intractability problem due to the t-Gaussian HDT is addressed based on the PH distribution with the universal approximation property. The performance of the wireless network are analyzed from the BS perspective and from the call performance point of view. The consistent analytical and simulation

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results indicate that HDT model has a substantial impact on P_h but a negligible effect on P_n . In particular, P_h with the exponential HDT greatly overestimates the probability with t-Gaussian HDT. In addition, HDT distribution shows an insignificant effect on the call performance with respect to the P_{cc} and T_w . Moreover, larger CMR decreases P_h sensitivity caused by different HDT model.

Chapter 5

Handoff Counting in Hierarchical Cellular System with Overflow Scheme

In the previous Chapters 2, 3, 4, we have discussed the sensitivity problem with respect to the call holding time, cell residence and handoff dwell time upon the network performance as well as the call performance in the stand-alone network architecture. In the next generation wireless network, the hierarchical cellular system will play a crucial role due to the co-existence of numerous mature or appearing wireless system standards applicable to diverse environments such as Wireless LAN, Bluetooth, GSM/GPRS and UMTS.

In this chapter and the next one, we will contribute to the characteristics of the handoff counting and the channel holding time with the general call holding time and cell residence time in the hierarchical cellular system.

5.1 Introduction

With the rapidly increasing rate of mobile users and diverse mobile computing scenario, one of the major concerns in the wireless mobile network design is to efficiently utilize the precious limited bandwidth. The other issue is to maintain connectivity while the user is roaming from one cell to another cell. For this situation, the hierarchical cellular network, i.e. one upper layer macrocell overlaying several lower layer microcells, has been proposed to share the resource between the two levels [57] [64] [86] [87] [88] [89]. Recently, a specific flexible speed-sensitive cell selection mechanism is studied by directing Mobile Stations (MS) to an appropriate cell layer according to their speed, e.g. slow call to microcell and fast call to macrocell [64] [86] [87] [88]. The studies present the system performance analysis involving the overflow scheme, wherein the overflow means that if there is not sufficient resource in the appropriate service layer, the call may overflow to the other layer to avoid the connection request from being rejected. The overflow schemes has become one of the main schemes in hierarchical cellular system (HCS) to handle the problem of insufficient resource and to share the bandwidth effectively between lower microlayer and upper macrolayer. As stated, there is no universal function for the call holding time duration. In this Chapter, the call holding time distribution is not dedicated to a specific function, but a general one to derive the important performance indicator in HCS.

Handoff counting, defined as the number of handoff a call connection experiences, is becoming increasingly important in mobile network design and implementation since the parameter has a direct impact on the system signaling traffic, the handoff arrival traffic, the call admission control (CAC) policy design and Quality of Service (QoS) the user perceives. The complex quantity is related to a multitude of system configurations and parameters setting. Handoff counting is: 1) network-related in the sense

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that it depends on the network architecture. For example, the cell residence times in single layer Personal Communication System (PCS) and HCS are apparently different at least in the aspect of the average value in microcell and macrocell due to their different geographic range; 2) user-related, which means that the user moving speed and direction has the considerable effect on the number of handoff; 3) service-related because of the service traffic characteristics diversity. For example, exponential, Erlang, hyper-Exponential or hyper-Erlang have been used to model the call holding time in conventional voice mandatory wireless system while a widely accepted property of Web traffic and WLAN traffic is heavy-tailed; 4) related to call admission control/resource allocation algorithm. Different priority schemes, e.g. guard channel, queueing scheme and overflow scheme, have a direct impact on the call blocking probability, and thus affect the handoff counting. The average handoff counting, *handoff rate*, during a non-blocked call in previous literatures is restricted to the single layer cellular network [37] [17] [90] [91] [68]. In addition, the strict constraint of the call holding time is the existence of its Laplace-Stieltjes Transform(LST), which may not be necessarily reasonable since heavy-tailed call holding time may not have closed-form LST as shown later. As a consequence, it is necessary to further analyze the handoff counting characteristics in HCS with different topology and diverse service types associated different call holding time. One recent paper [86] discussing the HCS system supporting bi-directional overflow schemes proposes the expression of handoff rate for slow call in hierarchical system, but residual cell residence time is not considered. Only the probability for at most one handoff operation is described and general handoff rate expression is not given.

In this Chapter, we present the analytical expression for handoff counting probability distribution with general cell residence time and call holding time in velocity-based hierarchical cellular system applying the overflow scheme. Our main contribution is to: 1) develop the handoff counting probability distribution and statistical moments

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with very general scenario, i.e. general call holding time and general cell residence time distribution in the hierarchical cellular system with overflow scheme; 2) present the analytical result and numerical algorithm for the cases whether the call holding time has closed-form LST representation or not; 3) perform numerical examples to show our algorithm superiority and investigate the different system parameters such as user mobility, microcell and macrocell diversity impact on the handoff counting behavior. In the following, we use the subscript m, M representing the *microcell* and *macrocell*. n, h, o representing *new call*, *handoff call* and *overflow call*, respectively.

5.2 Handoff counting in HCS applying overflow

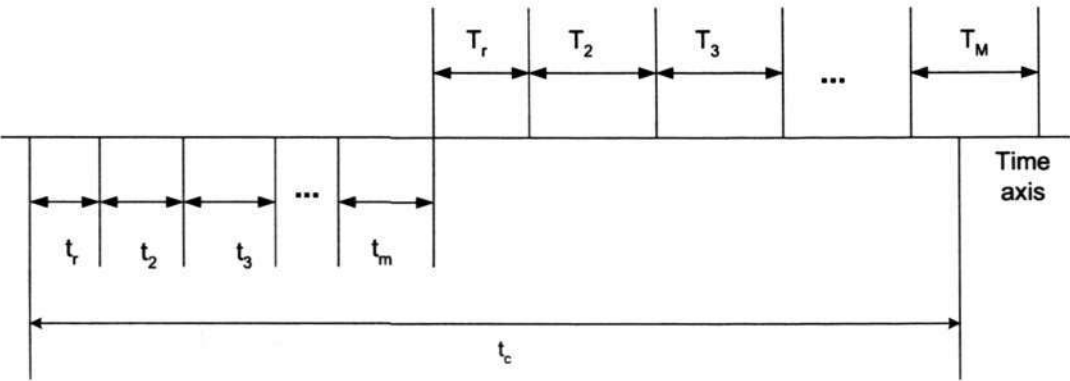


Figure 5.1: The time diagram for a typical slow call in HCS system with overflow scheme

For the hierarchical cellular system applying overflow scheme, since the slow call may overflow from microcell-level to upper macrocell-level on encountering insufficient resources in the microcell layer, the characteristics of handoff counting is different from the single layer PCS network. In detail, as a slow roaming mobile user originates a connection request, the call request may be denied to access with new call blocking probability P_n in the microcell, or the call is accepted when there is enough channels in the microcell. After the connection request acceptance, if the call is not able to complete

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in the first microcell the call initialized, the call connection is required to transfer to the adjacent microcell without link break, which is defined as handoff procedure. In this operation, the call may be rejected by the adjacent microcell with handoff call blocking probability P_{hm} . If the neighboring cell does not have free channel allocated to the handoff call request, the call overflows into the macrocell layer with overflow blocking probability P_o . It is noteworthy to point out that during the overflow procedure, there are essentially two sequent handoff operations: one is the failed handoff in the microcell; and the other is the inter-system handoff from the lower layer to the upper macrocell layer. If not rejected by the macrocell, the call can continue its call connection in the macrocell with the handoff blocking probability P_{hM} in the macrocell layer until the forced termination or normal completion. Note that if the network supports the fast moving user overflowing from macrocell to underlying microcell level, then due to symmetry the method to find the handoff counting of fast call is same as that of slow call. Therefore, without loss generality, we concentrate on the handoff counting analysis of slow call in this Chapter.

Fig.5.1 shows the typical slow call trajectory in hierarchical cellular system with overflow. t_c is the call holding time with mean $1/\mu_c$. Let $f_{t_c}(t)$ and $f_{t_c}^*(s)$ denoting the pdf and the Laplace-Stieltjes Transform(LST) of the pdf of t_c (for the cases without analytical LST will be described and solved in section III). The notations $t_k(k = 2, 3 \dots)$ are the independent identically distributed (i.i.d.) cell residence time in the consecutive microcells the mobile user traversed before the call overflows into the macrocell layer. t_r is the residual cell residence time, defined as the time duration elapsed from the call initialization to the time the call leaves the first microcell. For the upper layer, T_r is the residual cell residence time in the first macrocell the call overflowed. $T_k(k = 2, 3 \dots)$ are the i.i.d cell residence time in the consecutive macrocells the user travels. Let $1/\eta_m, 1/\eta_M$ denoting the mean of cell residence time of the slow moving user in microcell

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and macrocell, respectively. Using the fluid flow model [97], we obtain the cell residence time parameters

$$\eta_m = \frac{VL_m}{\pi S_m}; \quad \eta_M = \frac{VL_M}{\pi S_M} \quad (5.1)$$

where V represents the average speed of slow moving user. L_m, L_M the length of the perimeter of the microcell and macrocell, respectively. S_m, S_M the area of microcell and macrocell, respectively.

Define the mobility ratio as

$$\delta_m = \frac{1/\mu_c}{1/\eta_m}; \quad \delta_M = \frac{1/\mu_c}{1/\eta_M} \quad (5.2)$$

One can define the proportion between the mobility ratio in microcell and macrocell by introducing the parameters

$$\delta = \frac{\delta_m}{\delta_M} = \frac{\eta_m}{\eta_M} = \frac{L_m/S_m}{L_M/S_M} \quad (5.3)$$

With circle cell shape assumption, then $\delta = R_M/R_m$, where R_m, R_M represent the radius of the microcell and macrocell. When the cells are assumed to be regular hexagon, then $\delta = a_M/a_m$, with a_m, a_M representing the side length of the microcell and macrocell. Hence, δ can be understood as the user's mobility difference in microcell and macrocell, and can be simultaneously viewed as the size or shape or other characteristics diversity between microcell and macrocell as well.

Denote the pdf, cdf and LST of pdf of the cell residence time $t_k (k = 2, 3 \dots)$ as $f(t), F(t), f^*(s)$, respectively. Referring to the result in [75], the pdf of the residual cell residence time t_r in the microcell is given as

$$f_r(t) = \eta_m(1 - F(t)) \quad (5.4)$$

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Correspondingly, the LST of pdf of t_r is given by

$$f_r^*(s) = \eta_m \frac{1 - f^*(s)}{s} \quad (5.5)$$

Likewise, denote the pdf, cdf and LST of pdf of the cell residence time $T_k (k = 2, 3 \dots)$ as $g(t), G(t), g^*(s)$, respectively. The pdf of the residual cell residence time T_r in the macrocell is given as

$$g_r(t) = \eta_M (1 - G(t)) \quad (5.6)$$

Correspondingly, the LST of pdf of T_r is given by

$$g_r^*(s) = \eta_M \frac{1 - g^*(s)}{s} \quad (5.7)$$

Denote

$$\xi_m(k) = (t_2 + t_3 + \dots t_k) \mathbf{1}_{k \geq 2}; \quad (5.8)$$

$$\xi_M(k) = (T_2 + T_3 + \dots T_k) \mathbf{1}_{k \geq 2}; \quad (5.9)$$

Let Θ represent the handoff counting the slow call experiences. For $\theta = 0$, we have

$$Pr(\Theta = \theta) = (1 - P_n) Pr(t_c < t_r) \quad (5.10)$$

which means that the slow call is not blocked when the call is initialized in the microcell and the call connection is successfully completed in the first microcell, thus no handoff request is needed.

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For $\theta = 1$, we have

$$Pr(\Theta = \theta) = (1 - P_n) Pr(t_r < t_c \leq t_r + t_2)(1 - P_{hm}) \quad (5.11)$$

which means that the slow call is not blocked when the call is initialized in the microcell and the call connection is successfully handoff from the first microcell to the adjacent one. It is noted that if the handoff request is rejected in the handoff target microcell, then the call will require inter-system handoff from microlayer to macrolayer, which results in totally at least two handoffs. Thereafter, the case with handoff request rejection is excluded.

For $\theta \geq 2$, the possible conditions include

1. The call is completed in the microcell layer without overflow attempt, which means that the call does not encounter blocking during all handoff procedures in the traversed microcells.
2. The call completes $k(k = 1, 2 \dots \theta - 1)$ handoff in the microcell level and finishes the remaining $\theta - k$ times of handoff in the macrocell level. Notice that the overflow procedure actually includes two handoffs, one is the failed handoff in microcell and the other one is the inter-system handoff, regardless failed or successful, from lower layer to upper layer.

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As a result, the probability distribution of handoff counting is represented as

$$\begin{aligned}
 & Pr(\Theta = \theta) \\
 &= Pr(\text{complete } \theta \text{ handoffs in microcell level without overflow attempt}) \quad (5.12) \\
 &\quad + \sum_{k=1}^{\theta-1} Pr(\text{complete } k \text{ handoffs in microcell, and } \theta - k \text{ in macrocell level}) \\
 &= (1 - P_n) Pr(t_r + \xi_m(\theta) < t_c \leq t_r + \xi_m(\theta + 1)) (1 - P_{hm})^\theta \\
 &\quad + (1 - P_n) \\
 &\quad \cdot \sum_{k=1}^{\theta-2} [Pr(t_r + \xi_m(k) + T_r + \xi_M(\theta - k - 1) < t_c \leq t_r + \xi_m(k) + T_r + \xi_M(\theta - k)) \\
 &\quad \cdot (1 - P_{hm})^{k-1} P_{hm} (1 - P_o) (1 - P_{hM})^{\theta-k-1} \\
 &\quad + Pr(t_c > t_r + \xi_m(k) + T_r + \xi_M(\theta - k - 1)) \\
 &\quad \cdot (1 - P_{hm})^{k-1} P_{hm} (1 - P_o) (1 - P_{hM})^{\theta-k-2} P_{hM}] \\
 &\quad + (1 - P_n) \\
 &\quad \cdot [Pr(t_r + \xi_m(\theta - 1) < t_c \leq t_r + \xi_m(\theta - 1) + T_r) \cdot (1 - P_{hm})^{\theta-2} P_{hm} (1 - P_o) \\
 &\quad + Pr(t_c > t_r + \xi_m(\theta - 1)) (1 - P_{hm})^{\theta-2} P_{hm} P_o] \quad (5.13)
 \end{aligned}$$

In order to simplify the long and complex expression, we define two probabilities

$$\begin{aligned}
 a(k) &= Pr(t_r + \xi_m(k) < t_c); \quad k \geq 1 \\
 b(k, l) &= Pr(t_r + \xi_m(k) + T_r + \xi_M(l) < t_c); \quad k \geq 1, l \geq 1
 \end{aligned}$$

Hence, the probability distribution of handoff counting can be written as a simple

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expression represented by $a(k)$ and $b(k, l)$

$$Pr(\Theta = 0) = (1 - P_n)[1 - a(1)] \quad (5.14)$$

$$Pr(\Theta = 1) = (1 - P_n)a(1)[1 - a(2)](1 - P_{hm}) \quad (5.15)$$

$$\begin{aligned} Pr(\Theta = \theta \geq 2) &= (1 - P_n) \left\{ a(\theta) [1 - a(\theta + 1)] (1 - P_{hm})^\theta \right. \\ &+ \sum_{k=1}^{\theta-2} [Q_1 \cdot b(k, \theta - k - 1) (1 - b(k, \theta - k) (1 - P_{hm}))] \\ &\left. + Q_2 \cdot a(\theta - 1) [b(\theta - 1, 1) (1 - P_o) + P_o] \right\} \end{aligned} \quad (5.16)$$

where

$$Q_1 = (1 - P_{hm})^{k-1} P_{hm} (1 - P_o) (1 - P_{hm})^{\theta-k-2}; \quad Q_2 = (1 - P_{hm})^{\theta-2} P_{hm}$$

From the equation, it is clear that the expression for handoff counting probability distribution in hierarchical cellular system is much more complicated than that in single layer PCS network and no similar closed form analytical result in this condition. Here, we have derived the distribution of the handoff counting for slow call. It is thus trivial to obtain the statistical moments of the handoff counting

$$E(\Theta) = \sum_{\theta=0}^{\infty} \theta \cdot Pr(\Theta = \theta) \quad (5.17)$$

$$Var(\Theta) = \sum_{\theta=0}^{\infty} \theta^2 \cdot Pr(\Theta = \theta) - [E(\Theta)]^2 \quad (5.18)$$

where $E(X), Var(X)$ represents the mean and variance of random variable X , respectively. As stated before, $E(\Theta)$ is also named as handoff rate.

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5.3 Analysis and Algorithms in Computing $a(k), b(k, l)$

It is clear that the critical items to be solved from the handoff counting probability distribution are the quantities $a(k)$ and $b(k, l)$. They have the same algorithm owing to their analogous definition. In this section, we take $a(k)$ as the example to describe the analysis procedure when call holding time has closed-form LST and to present the algorithm when no call holding time analytical closed-form LST exists. For the sake of clarity, we rewrite the expression for $a(k), b(k, l)$

$$a(k) = Pr(t_r + \xi_m(k) < t_c); \quad k \geq 1 \quad (5.19)$$

$$b(k, l) = Pr(t_r + \xi_m(k) + T_r + \xi_M(l) < t_c); \quad k \geq 1, l \geq 1 \quad (5.20)$$

5.3.1 Analysis procedure when call holding time has analytical LST representation

Denote $\omega = t_r + \xi_m(k)$, then the LST of pdf of ω is given by

$$f_\omega^*(s) = \eta_m \frac{[1 - f^*(s)][f^*(s)]^{k-1}}{s} \quad (5.21)$$

Applying Residue Theorem [98], we have

$$\begin{aligned} a(k) &= Pr(\omega < t_c) = \int_0^\infty F_\omega(t) f_{t_c}(t) dt \\ &= \int_0^\infty \mathcal{L}^{-1} \left(\frac{f_\omega^*(s)}{s} \right) f_{t_c}(t) dt \\ &= \frac{\eta_m}{2\pi j} \int_{\sigma-j\infty}^{\sigma+j\infty} \frac{[1 - f^*(s)][f^*(s)]^{k-1} f_{t_c}^*(-s)}{s^2} ds \\ &= -\eta_m \sum_{p \in \Omega} Res_{s=p} \frac{[1 - f^*(s)][f^*(s)]^{k-1} f_{t_c}^*(-s)}{s^2} \end{aligned} \quad (5.22)$$

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where j is the imaginary unit and $j^2 = -1$, \mathcal{L}^{-1} represents the inverse Laplace transform. Ω denotes the set of poles of $f_c^*(-s)$ in the right complex plane and $Res_{s=p}$ represents the residue at poles $s = p$. Following the similar analysis, the probability $b(k, l)$ can be obtained as

$$b(k, l) = \frac{\eta_m \eta_M}{2\pi j} \int_{\sigma-j\infty}^{\sigma+j\infty} \frac{[1 - f^*(s)][f^*(s)]^{k-1}[1 - g^*(s)][g^*(s)]^{l-1}f_c^*(-s)}{s^3} ds \quad (5.23)$$

$$= -\eta_m \eta_M \sum_{p \in \Omega} Res_{s=p} \frac{[1 - f^*(s)][f^*(s)]^{k-1}[1 - g^*(s)][g^*(s)]^{l-1}f_c^*(-s)}{s^3} \quad (5.24)$$

For specific important call holding time distribution, we have

- Exponential $f_c(t) = \mu_c e^{-\mu_c t}$

$$a(k) = \frac{\eta_m}{\mu_c} [1 - f^*(\mu_c)][f^*(\mu_c)]^{k-1}$$

$$b(k, l) = \frac{\eta_m \eta_M}{\mu_c^2} [1 - f^*(\mu_c)][f^*(\mu_c)]^{k-1}[1 - g^*(\mu_c)][g^*(\mu_c)]^{l-1}$$

- n-order Hyperexponential $f_c(t) = \sum_{i=1}^n \alpha_i \eta_i e^{-\eta_i t}$, $\sum_{i=1}^n \alpha_i = 1$, ($n \in \mathcal{N}, 0 \leq \alpha_i \leq 1, \eta_i > 0$), where \mathcal{N} stands for the set of positive integer.

$$a(k) = \eta_m \sum_{i=1}^n \frac{\alpha_i}{\eta_i} [1 - f^*(\eta_i)][f^*(\eta_i)]^{k-1}$$

$$b(k, l) = \eta_m \eta_M \sum_{i=1}^n \frac{\alpha_i}{\eta_i^2} [1 - f^*(\eta_i)][f^*(\eta_i)]^{k-1}[1 - g^*(\eta_i)][g^*(\eta_i)]^{l-1}$$

- n-stage Erlang $f_c(t) = \frac{\nu^n}{(n-1)!} t^{n-1} e^{-\nu t}$, ($n \in \mathcal{N}, \nu > 0$)

$$a(k) = \frac{(-1)^{n-1} \nu^n \eta_m}{(n-1)!} \cdot \left(\frac{d^{n-1} [1 - f^*(s)][f^*(s)]^{k-1}}{ds^{n-1}} \right) \Big|_{s=\nu}$$

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$$b(k, l) = \frac{(-1)^{n-1} \nu^n \eta_m \eta_M}{(n-1)!} \cdot \left(\frac{d^{n-1} \frac{[1-f^*(s)][f^*(s)]^{k-1} [1-g^*(s)][g^*(s)]^{l-1}}{s^3}}{ds^{n-1}} \right) \Big|_{s=\nu}$$

It is important to note that the expressions are derived under the assumption that the analytical Laplace transform of call holding time exists. For instance, when call holding time is exponential, hyperexponential, Erlang or hypererlang. As a result, the result in this subsection can not apply to the environment when the call holding time has no closed-form LST. In the next subsection, we will present the algorithm to tackle the condition with no closed-form LST of the call holding time.

5.3.2 Algorithms with heavy-tailed call holding time

It has been shown that the Pareto distribution can approximate the packet data traffic very well [93] [94]. Let us consider the Pareto distribution with shape parameter α and scale parameter β for the call holding time

$$f_{t_c}(t) = \frac{\alpha \beta^\alpha}{t^{\alpha+1}}; \quad F_{t_c}(t) = 1 - \left(\frac{\beta}{t} \right)^\alpha, \quad 1 < \alpha < 2, t \geq \beta > 0 \quad (5.25)$$

Taking the Laplace transform on the pdf function, we have

$$f_{t_c}^*(s) = \int_0^\infty f_{t_c}(t) e^{-st} dt = \alpha \beta^\alpha (D + E_{\alpha+1}(s)), \quad \text{Re}(s) > 0 \quad (5.26)$$

where the constant $D = \alpha \beta^\alpha \int_0^1 e^{-st} t^{\alpha+1} dt$, the expression $E_{\alpha+1}(s) = \int_1^\infty e^{-st} t^{\alpha+1} dt$ is the generalized exponential integral [73] and can be written in terms of incomplete gamma or confluent hypergeometric functions [74]. From here, it is clear that no closed form or analytical Laplace transform exists for the Pareto call holding time distribution. Hence, for the heavy-tailed call holding time, the previous formula for handoff counting maybe not applicable.

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There are basically two methods around this difficulty: (1) fitting the probability density function (pdf) with the universal approximating distribution; or (2) approximating the Laplace transform of pdf directly. The study in [69] [70] corresponds to the first method. In these literatures, hyperexponential is chosen to fit the power-tail distributions. [83] proposed phase-type distribution to fit any positive random variable distribution via EM algorithm, which is also a candidate to approximate the Pareto distribution. The main disadvantage of the pdf fitting method is that too many components may be required to approximate the original distribution and thus the computing time is prohibitive. The second method by directly approximating the Laplace transform of pdf is the Transform Approximation Method (TAM) [95] [96]. In this Chapter, we improve the TAM to approximate the Pareto distribution in the aspect of the convergence speed in finding critical parameters. The main idea in TAM is that for a given cumulative distribution function $F_{t_c}(t)$ with Laplace transform:

$$f_{t_c}^*(s) = \int_0^\infty e^{-sx} dF_{t_c}(x)$$

The TAM approximation is expressed as:

$$\hat{f}_{t_c}^*(s) \doteq \sum_{i=1}^N \gamma_i e^{-sx_i} \quad (5.27)$$

where the points x_i satisfy $F_{t_c}(x_i) = y_i (\equiv 1 - v^i)$ with the geometric parameter $0 < v < 1$, the coefficient γ_i is given by

$$\begin{aligned} \gamma_i &= \frac{y_{i+1} - y_{i-1}}{2}, i = 2, 3, \dots, N-1 \\ \gamma_1 &= \frac{y_1 + y_2}{2}, \gamma_N = 1 - \frac{y_{N-1} + y_N}{2}, \end{aligned} \quad (5.28)$$

In the algorithm TAM, the geometric parameter v is the most important one since

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other parameters x_i, y_i, γ_i are essentially derived from this quantity. Hence, the stable and fast algorithm to find v is the pre-requisite of TAM, in which binary search algorithm is used by searching the interval $(0, 1)$. We propose that the parameter v can be determined such that the sample mean matches the true mean, which is described with the equation

$$-\frac{df_{t_c}^*(s)}{ds}\Big|_{s=0} = \int_{\beta}^{\infty} t f_{t_c}(t) dt \quad (5.29)$$

This is equivalent to

$$\begin{aligned} & \frac{(1-v) + (1-v^2)}{2} \cdot \beta v^{-\frac{1}{\alpha}} + \sum_{i=2}^{N-1} \frac{(1-v^{i+1}) - (1-v^{i-1})}{2} \cdot \beta v^{-\frac{i}{\alpha}} \\ & + \left(1 - \frac{(1-v^{N-1}) + (1-v^N)}{2}\right) \cdot \beta v^{-\frac{N}{\alpha}} = \frac{\alpha\beta}{\alpha-1} \end{aligned} \quad (5.30)$$

After mathematical manipulation, we have

$$\left(1 - \frac{v+v^2}{2}\right) \cdot v^{-\frac{1}{\alpha}} + \sum_{i=2}^{N-1} \frac{v^{-1}-v}{2} \left(v^{1-\frac{1}{\alpha}}\right)^i + \frac{v^N + v^{N-1}}{2} \cdot v^{-\frac{N}{\alpha}} = \frac{\alpha}{\alpha-1} \quad (5.31)$$

Further, this equation becomes

$$\left(1 - \frac{v+v^2}{2}\right) \cdot v^{-\frac{1}{\alpha}} + \frac{v^{-1}-v}{2} \cdot \frac{q^2 - q^N}{1-q} + \frac{1+v}{2} \cdot v^{N-1-\frac{N}{\alpha}} = \frac{\alpha}{\alpha-1} \quad (5.32)$$

where $q = v^{1-\frac{1}{\alpha}}$.

This explicit equation for unknown variable v is only relevant to the shape parameter α and N , not related to the scale parameter β . This important point can not be observed from the TAM, which thus needs at least one more input parameter compared with our presented equation. The significance of this equation is to provide deeper understanding and to design more efficient algorithm.

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Denote

$$\phi(v, N) = \left[\left(1 - \frac{v + v^2}{2} \right) \cdot v^{-\frac{1}{\alpha}} + \frac{v^{-1} - v}{2} \cdot \frac{q^2 - q^N}{1 - q} + \frac{1 + v}{2} \cdot v^{N-1-\frac{N}{\alpha}} \right] \cdot \frac{\alpha - 1}{\alpha} v \quad (5.33)$$

We develop the following iterative algorithm IA-v to find the suitable v with a satisfactory accuracy.

Iterative algorithm IA-v:

- Input α, N , set initial condition v_0 (e.g. $v_0 = 0.5$)
- Repeat and calculate

$$v_{j+1} = \phi(v_j, N) \quad (5.34)$$

Until $|v_{j+1} - v_j| < \epsilon$

where ϵ is the stopping criteria.

For the approximated expression of $f_{tc}^*(s)$ given by $\hat{f}_{tc}^*(s) = \sum_{i=1}^N \gamma_i e^{-sx_i}$, we obtain $a(k), b(k, l)$ in the case of Pareto call holding time as

$$a(k) = \frac{\eta_m}{2\pi j} \int_{\sigma-j\infty}^{\sigma+j\infty} \frac{[1 - f^*(s)][f^*(s)]^{k-1} \sum_{i=1}^N \gamma_i e^{sx_i}}{s^2} ds \quad (5.35)$$

$$= \eta_m \sum_{i=1}^N \gamma_i \cdot \mathcal{L}^{-1} \left(\frac{[1 - f^*(s)][f^*(s)]^{k-1}}{s^2} \right) \Big|_{t=x_i} \quad (5.36)$$

$$= \eta_m \sum_{i=1}^N \gamma_i \cdot \left(\sum_{p \in \Omega_a} \text{Res}_{s=p} \frac{[1 - f^*(s)][f^*(s)]^{k-1} e^{st}}{s^2} \right) \Big|_{t=x_i} \quad (5.37)$$

where the summation in the commas is taken over all residues of the complex function $\frac{[1 - f^*(s)][f^*(s)]^{k-1} e^{st}}{s^2}$, and Ω_a denotes the set of all poles of function $\frac{[1 - f^*(s)][f^*(s)]^{k-1}}{s^2}$.

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$$b(k, l) = \frac{\eta_m \eta_M}{2\pi j} \int_{\sigma-j\infty}^{\sigma+j\infty} \frac{[1-f^*(s)][f^*(s)]^{k-1}[1-g^*(s)][g^*(s)]^{l-1} \sum_{i=1}^N \gamma_i e^{sx_i}}{s^3} ds \quad (5.38)$$

$$= \eta_m \eta_M \sum_{i=1}^N \gamma_i \cdot \mathcal{L}^{-1} \left(\frac{[1-f^*(s)][f^*(s)]^{k-1}[1-g^*(s)][g^*(s)]^{l-1}}{s^3} \right) \Big|_{t=x_i} \quad (5.39)$$

$$= \eta_m \eta_M \sum_{i=1}^N \gamma_i \cdot \left(\sum_{p \in \Omega_b} \text{Res}_{s=p} \frac{[1-f^*(s)][f^*(s)]^{k-1}[1-g^*(s)][g^*(s)]^{l-1} e^{st}}{s^3} \right) \Big|_{t=x_i} \quad (5.40)$$

where the summation in the commas is taken over all residues of the complex function $\frac{[1-f^*(s)][f^*(s)]^{k-1}[1-g^*(s)][g^*(s)]^{l-1} e^{st}}{s^3}$, and Ω_b denotes the set of all poles of function $\frac{[1-f^*(s)][f^*(s)]^{k-1}[1-g^*(s)][g^*(s)]^{l-1}}{s^3}$.

In summary, our proposed algorithm to calculate the probability distribution of handoff counting with Pareto call holding time is described as the following steps.

1. Input θ, α, β ; choose the expression for $Pr(\Theta = \theta)$ from Eq. (5.14) or (5.15) or (5.16)
2. Calculate $a(k)$ in $Pr(\Theta = \theta)$:
 - (a1) Set the initial N and the step δ_N
 - (a2) Save $a^0(k) = a(k)$
 - (a3) Apply the algorithm IA-v to find parameter v
 - (a4) Assign $x_i = \beta \cdot v^{-i/\alpha}$, $y_i = 1 - v^i$, $i = 1, 2 \dots N$ and γ_i through Eq. (5.28)
 - (a5) Calculate $a(k)$ through Eq. (5.37)
 - (a6) If $|a^0(k) - a(k)| < \epsilon$, then exit the loop; otherwise $N = N + \delta_N$ and repeat the steps (a2)(a3)(a4)(a5)(a6)
3. Calculate $b(k, l)$ in $Pr(\Theta = \theta)$:

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-
- (b1) Set the initial N and the step δ_N
 - (b2) Save $b^0(k, l) = b(k, l)$
 - (b3) Apply the algorithm IA-v to find parameter v
 - (b4) Assign $x_i = \beta \cdot v^{-i/\alpha}$, $y_i = 1 - v^i$, $i = 1, 2 \dots N$ and γ_i through Eq. (5.28)
 - (b5) Calculate $b(k, l)$ through Eq. (5.40)
 - (b6) If $|b^0(k, l) - b(k, l)| < \epsilon$, then exit the loop; otherwise $N = N + \delta_N$ and repeat the steps (b2)(b3)(b4)(b5)(b6)
4. Substitute $a(k)$, $b(k, l)$ into $Pr(\Theta = \theta)$ to obtain the probability of handoff counting.

5.4 Numerical Results

In this section, we present numerical examples to compare our improved algorithm and TAM and show the handoff counting characteristics. The mean of call holding time is $1/\mu_c = 180.0\text{sec}$. The blocking probabilities: $P_n = 0.2$, $P_{hm} = 0.15$, $P_{hM} = P_o = 0.05$. The non-heavy-tailed call holding time distributions are chosen via the coefficient of variation criteria. For the heavy-tailed call holding time distribution, different shape parameter α is selected. Note that all the chosen distributions have the same average value.

- exponential distribution $1/180.0e^{-1/180.0t}$
- 2-order hyperexponential (H_2) distribution: $0.8101 \times 0.009e^{-0.009t} + 0.1899 \times 0.0021e^{-0.0021t}$. In this case, the coefficient of variation $C_v = 1.5$.
- 4-stage Erlang(E_4) distribution distribution: $\frac{1/45.0(1/45.0t)^{4-1}}{(4-1)!}e^{-1/45.0t}$, which results in the coefficient of variation $C_v = 1/\sqrt{4} = 0.5$.

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- Pareto distribution: $\alpha = 1.1, 1.3, 1.5, 1.7, 1.9$, which result in the parameter $\beta = \frac{\alpha-1}{\alpha} \frac{1}{\mu_c} = 16.36, 41.54, 60, 74.12, 85.26$, respectively.

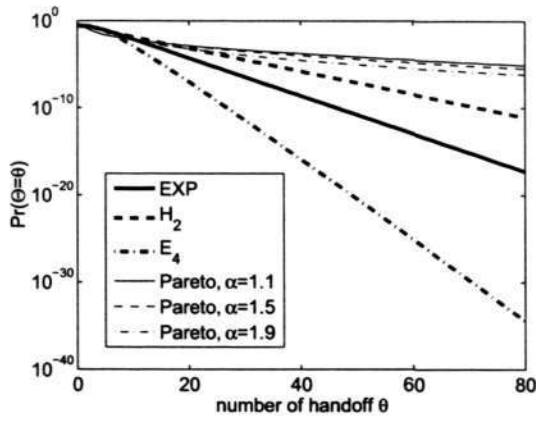
Table 5.1 compares the relative computation complexity in finding the parameter v between TAM and our algorithm with the accuracy 10^{-6} on a 1.7GHz PC. It can be seen that our algorithm is significantly faster to converge than the TAM.

Fig. 5.2 shows the handoff counting distribution with different mobility pattern in the microcell layer and distinct call holding time distribution. The cell residence time is assumed to be exponential distribution. The most impressive pattern of the handoff counting is the heavy-tailed property when the call holding time is heavy-tailed. The heavier call holding time is, namely, when the parameter α approaches 1, the handoff counting decays more slowly. Comparing the rapid decaying lines associated with exponential, hyperexponential and Erlang call holding time, we can see that smaller coefficient of variation leads to faster decaying. As far as the effect of the mobility pattern is concerned, the curves imply that greater mobility ratio δ_m in microcell will result in more handoff operations, and this is expected intuitively.

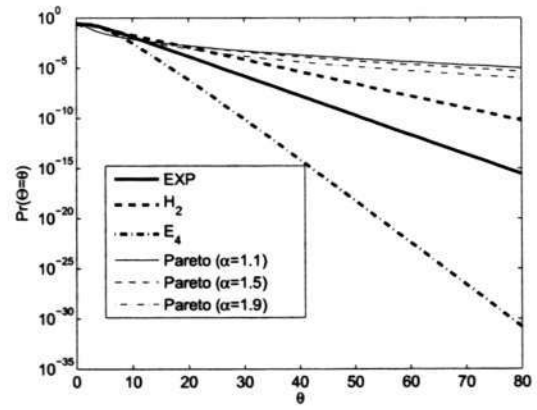
Fig. 5.3 illustrates the handoff counting probability distribution with different mobility pattern and distinct call holding time distribution. This example is the truncated version of Fig.5.2(b) to show the more reasonable and practical range. It is clearly seen that the call holding time diversity leads to significantly different handoff counting distribution.

Fig. 5.4 plots the handoff rate as the function of the mobility ratio with different call holding time distributions. It is evident that the handoff rate is increasing with the mobility ratio regardless of the call holding time distribution function. However, the increasing gradient is significantly different with respect to the call holding time distribution. In particular, in case of the non-heavy-tailed call holding time, the

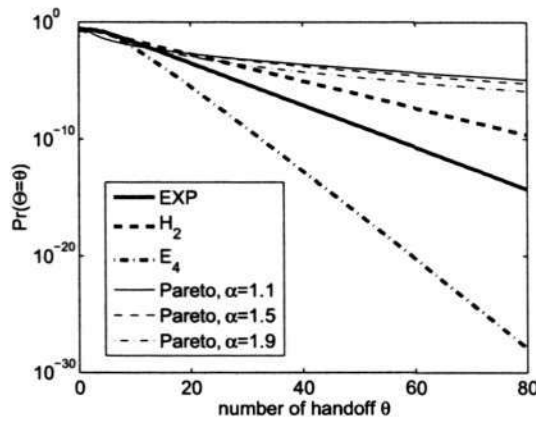
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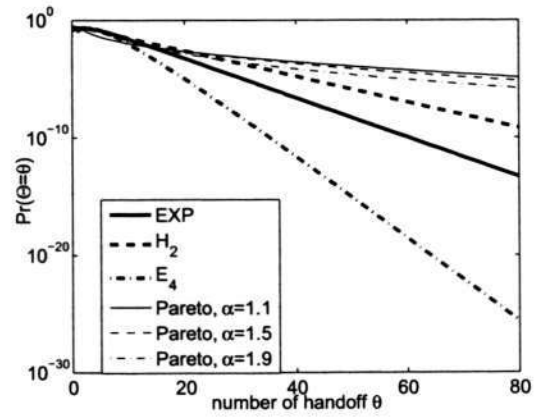
(a) $\delta_m = 2.5, \delta = 4.0$



(b) $\delta_m = 3.0, \delta = 4.0$



(c) $\delta_m = 3.5, \delta = 4.0$



(d) $\delta_m = 4.0, \delta = 4.0$

Figure 5.2: The handoff counting probability distribution with different mobility property and different call holding time distributions

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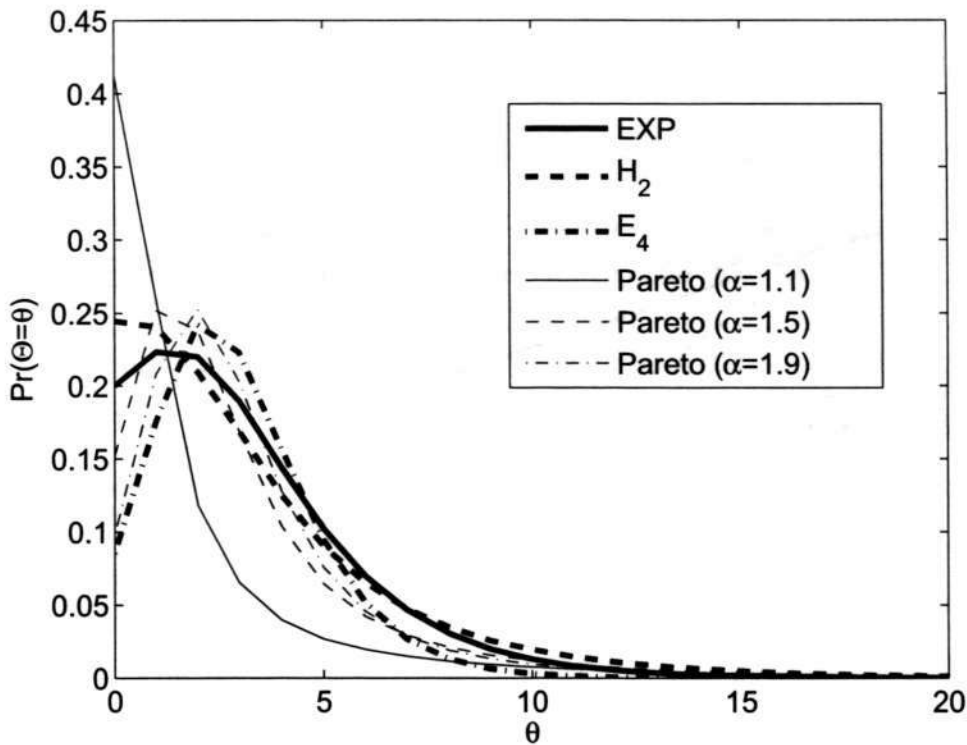


Figure 5.3: The handoff counting probability distribution with different call holding time distributions ($\delta_m = 3.0, \delta = 4.0$)

handoff rate with greater coefficient of variation rises faster than the handoff rate with smaller coefficient of variation. For the heavy-tailed call holding time, the handoff rate is consistently less than that in case of exponential call holding time. Moreover, no monotone increasing tendency can be observed in accordance with the shape parameter α reflecting the tail effect of the Pareto distribution.

From theory perspective of view, it is difficult to analyze and describe the specific effect under specific distribution. We can only provide the comparison via numerical results. This is exactly the reason we propose approximation and numerical algorithms to study the handoff counting characteristics.

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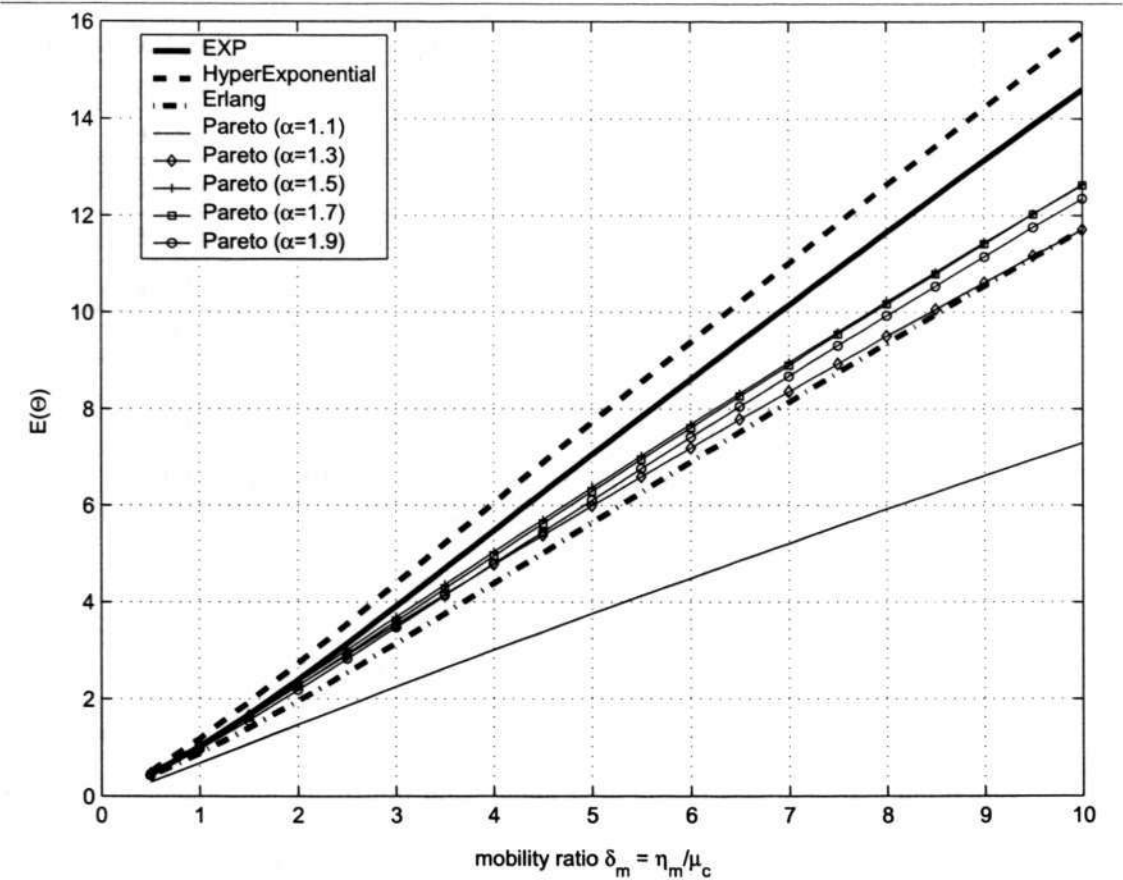


Figure 5.4: The handoff rate with respect to the mobility ratio with different call holding time distributions

5.5 Conclusion

Handoff counting in hierarchical cellular system applying overflow scheme is studied under general call holding time and general cell residence time. The analytical expression and numerical algorithm are respectively presented for the cases where the LST of call holding time distribution function exists or not. It is found that 1) heavy-tailed property of handoff counting will appear when the call holding time shows heavy-tailed pattern; 2) smaller coefficient of variation of the call holding time will result in less handoff rate; 3) for the heavy-tailed call holding time, the handoff rate is consistently less than that in case of exponential call holding time; 4) heavier tail of the call holding

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Table 5.1: Computation Complexity Comparison in Finding the Parameter v

α	N	TAM		Our Algorithm	
		v	Time(sec)	v	Time(sec)
1.1	100	0.6797	0.0773	0.6797	0.0020
1.5	100	0.8608	0.0675	0.8608	0.0025
1.9	100	0.8926	0.0678	0.8926	0.0035
1.1	1000	0.9281	0.6989	0.9281	0.0048
1.5	1000	0.9748	0.6064	0.9747	0.0111
1.9	1000	0.9813	0.6659	0.9813	0.0153
1.1	10000	0.9885	5.4203	0.9885	0.0234
1.5	10000	0.9963	5.7078	0.9962	0.0562
1.9	10000	0.9973	5.6983	0.9971	0.0797

time will not be necessarily lead to less handoff rate. We believe that the typical call behavior analysis and the handoff counting result is important for the system traffic signalling load analysis in the next generation multi-tier heterogeneous network.

Chapter 6

Channel Holding Time in Hierarchical Cellular System

6.1 Introduction

The characteristics of the channel holding time (CHT) plays a pivotal role in the performance evaluation of the stand-alone wireless network, e.g. GSM, as well as the next generation multi-tier wireless multimedia network such as the currently standardizing UMTS and WLAN interworking network [99]. Due to the critical significance, the CHT derivation in stand-alone wireless network has attracted extensive studies (e.g.[37]). However, in multi-tier wireless network, CHT still remains a significant research issue since it is not only dependent on the relationship between call holding time and cell residence time but reliant on the resource allocation strategy and the network architecture. In addition, the general call holding time and cell residence time further complicate CHT investigation. For the sake of analytical tractability, CHT is traditionally provided under the exponential call holding time and the exponential cell

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residence time [87] [100] [88] in hierarchical cellular system(HCS). One recent work [64] calculated CHT with the hyper-erlang call holding time and general cell residence time.

In this chapter, we present a new approach for the CHT derivation in a two-layer HCS supporting slow and fast call overflow and underflow schemes. Both the call holding time and cell residence time follow general distribution functions. The lower micro-layer is designed to provide service for the slow-mobility Mobile Station(MS) while the upper macro-layer for the fast-mobility MS. Overflow mechanism indicates that if there is insufficient resource in the appropriate service layer upon a call arrival, the call may overflow to another layer to avoid the connection from being dropped. With the underflow scheme, an overflowed call can return to its own service level upon crossing the microcell boundary. In the following, let $f_x(t), F_x(t), f_x^*(s), F_x^*(s)$ denote the probability density function (p.d.f.) of random variable x , the cumulative distribution function (c.d.f.) of x , Laplace-Stieltjes transform (LST) of the p.d.f., and the LST of the c.d.f..

6.2 System Model and Analysis

Fig. 6.1 shows the typical call trajectory for different call traffics in microcell and macrocell. It is evident that the derivation of the slow call and fast call CHT in microcell, or fast call in macrocell, is exactly similar as the technique in stand-alone network, which has been already discussed extensively (e.g.[37]). Hence, we will neglect these types of call traffic and dedicate to the slow call CHT in macrocell.

Let t_c denote the call holding time with the average $1/\mu_c$. Denote by X_M (X_{Mr}) as the slow call cell residence time (residual cell residence time) in macrocell with expected value $1/\eta_M$. Using the residual life theorem, the p.d.f. of X_{Mr} is given by

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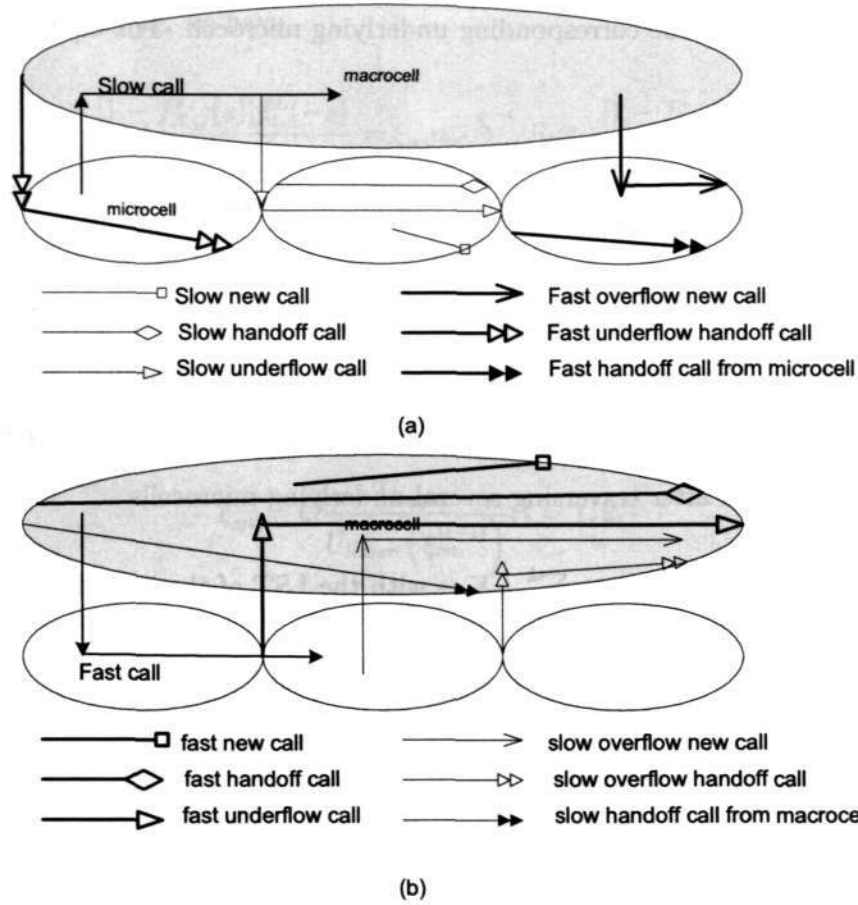


Figure 6.1: The different call traffic and the corresponding typical behavior in (a) microcell; and (b) macrocell

$$f_{X_{Mr}}(t) = \eta_M [1 - F_{X_M}(t)].$$

We will focus on the overflowed slow new call CHT T_{on} . Let $X_{m,k}$ ($k = 1, 2, 3 \dots$) represent the i.i.d. cell residence time in the k^{th} underlying microcell an overflowed slow new call traversed with the generic form X_m and the average $1/\eta_m$. Accordingly, the residual cell residence time in the k^{th} microcell is denoted as $X_{mr,k}$ with the generic form X_{mr} .

Denote by ξ_{sn} as the probability that an overflowed slow new call is moving out the coverage of the current serving macrocell under the condition that it is leaving

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the coverage of the corresponding underlying microcell. The equation to calculate this quantity is,

$$\Phi_{sn} = \sum_{k=1}^{\infty} Pr(X_{mr,1} + X_{m,2} + \cdots + X_{m,k} < t_c)(1 - \xi_{sn})^{k-1}\xi_{sn} \quad (6.1)$$

where $\Phi_{sn} = \mathcal{P}(X_{Mr} < t_c)$ represents the probability that an overflowed slow new call moves out the serving macrocell when virtually no underflow mechanism is utilized. The right side is the summation of probabilities that the MS will eventually move out the macrocell after traversing several underlying microcells.

Denote $\chi_k = X_{mr,1} + \sum_{i=2}^k X_{m,i}$ with the LST of the its p.d.f. given by

$$f_{\chi_k}^*(s) = \frac{\eta_m[1 - f_{X_m}^*(s)][f_{X_m}^*(s)]^{k-1}}{s}; \quad k = 1, 2, \dots \quad (6.2)$$

Employing the similar technique in [37], the probability in equation (6.1) right-side becomes

$$\begin{aligned} Pr(\chi_k < t_c) &= \int_{t=0}^{\infty} \mathcal{P}(\chi_k < t) f_{t_c}(t) dt \\ &= \int_{t=0}^{\infty} \frac{1}{2\pi j} \int_{\sigma-j\infty}^{\sigma+j\infty} \frac{f_{\chi_k}^*(s)}{s} e^{st} ds f_{t_c}(t) dt \\ &= \frac{\eta_m}{2\pi j} \int_{\sigma-j\infty}^{\sigma+j\infty} \frac{[f_{X_m}^*(s)]^{k-1} [1 - f_{X_m}^*(s)] f_{t_c}^*(-s)}{s^2} ds \end{aligned} \quad (6.3)$$

where j is the imaginary unit. Analogously, the probability

$$\Phi_{sn} = \frac{\eta_M}{2\pi j} \int_{\sigma-j\infty}^{\sigma+j\infty} \frac{[(1 - f_{X_M}^*(s)) f_{t_c}^*(-s)]}{s^2} ds \quad (6.4)$$

Hence, by substituting Φ_{sn} and (6.3) into the equation (6.1), and applying the

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Residue Theorem [72], we have

$$\eta_M \sum_{s_0 \in \Omega} \text{Res}_{s=s_0} \frac{[1 - f_{X_M}^*(s)]f_{t_c}^*(-s)}{s^2} = \xi_{sn} \eta_m \sum_{s_0 \in \Omega} \text{Res}_{s=s_0} \frac{[1 - f_{X_m}^*(s)]f_{t_c}^*(-s)}{s^2 [1 - f_{X_m}^*(s)(1 - \xi_{sn})]} \quad (6.5)$$

where Ω denotes the set of poles of $f_{t_c}^*(-s)$ in the right complex plane and $\text{Res}_{s=s_0}$ represents the residue at poles $s = s_0$.

Based on (6.5), a recursive approach is developed to compute ξ_{sn} .

$$\xi_{sn}^{(l)} = C \frac{U_{upper}}{U_{lower}(\xi_{sn}^{(l-1)})}; l = 1, 2, \dots \quad (6.6)$$

with

$$C = \frac{\eta_M}{\eta_m} \quad (6.7)$$

$$U_{upper} = \sum_{s_0 \in \Omega} \text{Res}_{s=s_0} \frac{[1 - f_{X_M}^*(s)]f_{t_c}^*(-s)}{s^2} \quad (6.8)$$

$$U_{lower}(\xi_{sn}^{(l-1)}) = \sum_{s_0 \in \Omega} \text{Res}_{s=s_0} \frac{[1 - f_{X_m}^*(s)]f_{t_c}^*(-s)}{s^2 [1 - f_{X_m}^*(s)(1 - \xi_{sn}^{(l-1)})]} \quad (6.9)$$

Next, we will compute the channel holding time of the overflowed slow new call T_{on} . For an accepted slow overflow new call in macrocell, its behavior can be broadly classified into two categories. On the one hand, the call connection can be: 1) normally completed in the coverage of the first microcell when $t_c < X_{mr,1}$; or 2) normally completed in the coverage of the second microcell after a failed underflow attempt when $X_{mr,1} < t_c \leq X_{mr,1} + X_{m,2}$; or 3) normally completed in the coverage of the third microcell after two times failed underflow attempts in the case of $X_{mr,1} + X_{m,2} < t_c \leq X_{mr,1} + X_{m,2} + X_{m,3}$, and so on. In this case, T_{on} is equal to t_c due to the call normal completion in the upper layer.

On the other hand, the CHT can be: 1) $X_{mr,1}$ due to the successful underflow upon

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crossing the first microcell boundary or leaving the macrocell coverage; 2) $X_{mr,1} + X_{m,2}$ due to the successful underflow upon crossing the second microcell boundary or leaving both the second microcell and the macrocell coverage provided that the first underflow is failed; 3) $X_{mr,1} + X_{m,2} + X_{m,3}$ due to the successful underflow upon crossing the third microcell boundary or leaving the third microcell coverage provided that the first and second underflows are failed, and so on. Therefore, the c.d.f. of the overflowed slow new call CHT is expressed as

$$\begin{aligned}
 Pr(T_{on} < t) &= \sum_{k=1}^{\infty} Pr(t_c < t, \chi_{k-1} < t_c \leq \chi_k) \cdot [(1 - \xi_{sn})P_{bu}]^{k-1} \\
 &\quad + \sum_{k=1}^{\infty} Pr(\chi_k < t, \chi_k < t_c) \cdot [(1 - \xi_{sn})P_{bu}]^{k-1} [\xi_{sn} + (1 - \xi_{sn})(1 - P_{bu})]
 \end{aligned} \tag{6.10}$$

where P_{bu} is the underflow blocking probability. The item $[(1 - \xi_{sn})P_{bu}]^{k-1}$ accounts for the probability that the overflowed slow call remains in the macrocell after $k - 1$ times of failed underflow attempts. The term $[(1 - \xi_{sn})P_{bu}]^{k-1} [\xi_{sn} + (1 - \xi_{sn})(1 - P_{bu})]$ represents the probability that the overflowed slow call remains in the macrocell after $k - 1$ times of failed underflow attempts, but in the k^{th} underflow, the call either moves out the coverage of the serving macrocell with probability ξ_{sn} or successfully underflow to the lower layer with probability $(1 - \xi_{sn})(1 - P_{bu})$.

After the mathematical manipulation, we obtain the p.d.f. as

$$\begin{aligned}
 f_{T_{on}}(t) &= f_{t_c}(t)[1 - F_{\chi_1}(t)] + (1 - a)f_{\chi_1}(t)[1 - F_{t_c}(t)] \\
 &\quad + \sum_{k=2}^{\infty} a^{k-1} \{f_{t_c}(t)h_k(t) + (1 - a)f_{\chi_k}(t)[1 - F_{t_c}(t)]\}
 \end{aligned} \tag{6.11}$$

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where $a = (1 - \xi_{sn})P_{bu}$ and $h_k(t) = \int_0^t f_{\chi_{k-1}}(\tau)[1 - F_{\chi_m}(t - \tau)]d\tau$ with its LST

$$h_k^*(s) = \frac{\eta_m[1 - f_{\chi_m}^*(s)]^2 f_{\chi_m}^*(s)^{k-2}}{s^2} \quad (6.12)$$

Consequently, the statistical moments of the CHT can be obtained on the basis of the p.d.f. of T_{on} . In particular, the expected value is given by $\mathbb{E}(T_{on}) = \int_0^\infty t f_{T_{on}}(t)dt$.

Suppose that the call holding time has an n-stage Erlang distribution with mean $1/\mu_c = n/\mu$, variance $V_c = n/\mu^2$, and the probability density function

$$f_{t_c}(t) = \frac{\mu^n t^{n-1}}{(n-1)!} e^{-\mu t}, \quad t > 0; n = 1, 2, \dots \quad (6.13)$$

In this case, the mean of T_{on} is given by

$$\begin{aligned} \mathbb{E}(T_{on}) = & \frac{n}{\mu} - \frac{(-1)^n \mu^n}{(n-1)!} \frac{d^n F_{\chi_1}^*(s)}{ds^n} \Big|_{s=\mu} + \sum_{k=2}^{\infty} a^{k-1} \frac{(-1)^n \mu^n}{(n-1)!} \frac{d^n h_k^*(s)}{ds^n} \Big|_{s=\mu} \\ & + (1-a) \sum_{k=1}^{\infty} a^{k-1} \sum_{j=0}^{n-1} \frac{(-1)^{j+1} \mu^j}{j!} \frac{d^{j+1} f_{\chi_k}^*(s)}{ds^{j+1}} \Big|_{s=\mu} \end{aligned} \quad (6.14)$$

6.3 Numerical Results

The set of parameters are chosen as: $1/\mu_c = 180.0\text{sec}$, $\eta_m/\eta_M = 3.0$, and $P_{bu} = 0.1$. With the exponential call holding time and the exponential cell residence time, all the slow call CHT in macrocell follows the same exponential distribution. Let T denote the CHT in this case. Then, we have

$$1/\mathbb{E}(T) = \mu_c + \eta_m(1 - P_{bu}) + \eta_M P_{bu} \quad (6.15)$$

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In contrast, the earlier results in [87] (denoted as JF) and [100] [64] (denoted as BCF&YJ) are given by

$$1/\mathbb{E}(T)_{JF} = \mu_c + \eta_M \quad (6.16)$$

$$1/\mathbb{E}(T)_{BCF\&YJ} = \mu_c + \eta_m(1 - P_{bu}) + \eta_M \quad (6.17)$$

We argue that JF result has ignored the reason for channel release due to successful underflow and that the studies BCF&YJ have disregarded the pre-requisite for the validity of overflow slow call CHT equal to the cell residence time in macrocell. Fig. 6.2 plots the mean CHT of slow call in macrocell in terms of η_m/μ_c . It is evident that our result matches the simulation result perfectly well while JF result exhibits a significant discrepancy from the simulation, and BCF&YJ is smaller than and only approximative to the actual value.

Fig.6.3 shows $E(T_{on})$ in terms of η_m/μ_c with different stage of the Erlang call holding time. X_m and X_M follow the exponential distribution. Note that the mean of the call holding time keeps fixed as different stages are used. In the figure, symbol represents the corresponding simulation result. Again, the analytical and the simulation model are in perfect agreement. Smaller η_m/μ_c , implying lower velocity, leads to larger T_{on} . This is because slower MS is more likely to stay in the coverage of a microcell and to experience less underflow attempts, and intends to complete the entire call connection in macro-layer. Fig.6.3 also indicates that CHT increases with smaller $V_c(= 1/(n\mu_c^2))$.

Note that we have discussed the η_m/μ_c varying in an extensive range despite that slow-mobility MS may not have η_m/μ_c as large as 10. We propose two reasons for this point. One is that in a particular speed-sensitive HCS, the speed threshold may vary in a large range; the other reason is that the methodology as well as the result presented in this Chapter is also applicable to the fast call CHT in the HCS where fast call is

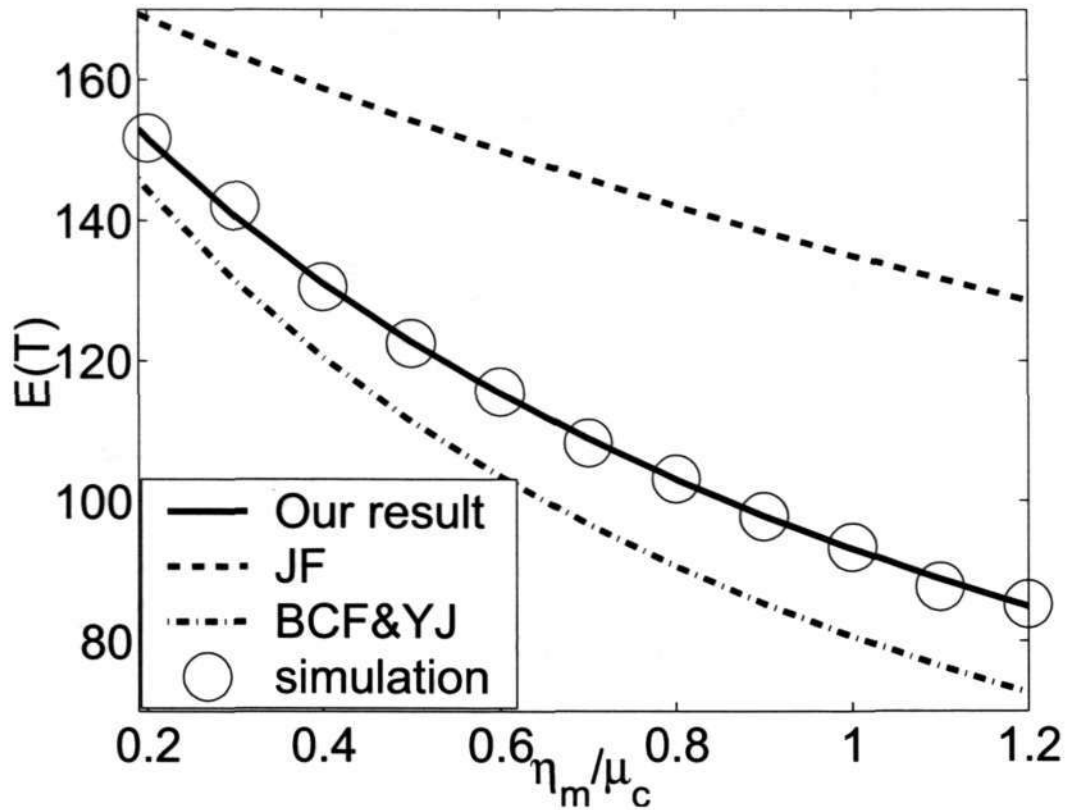
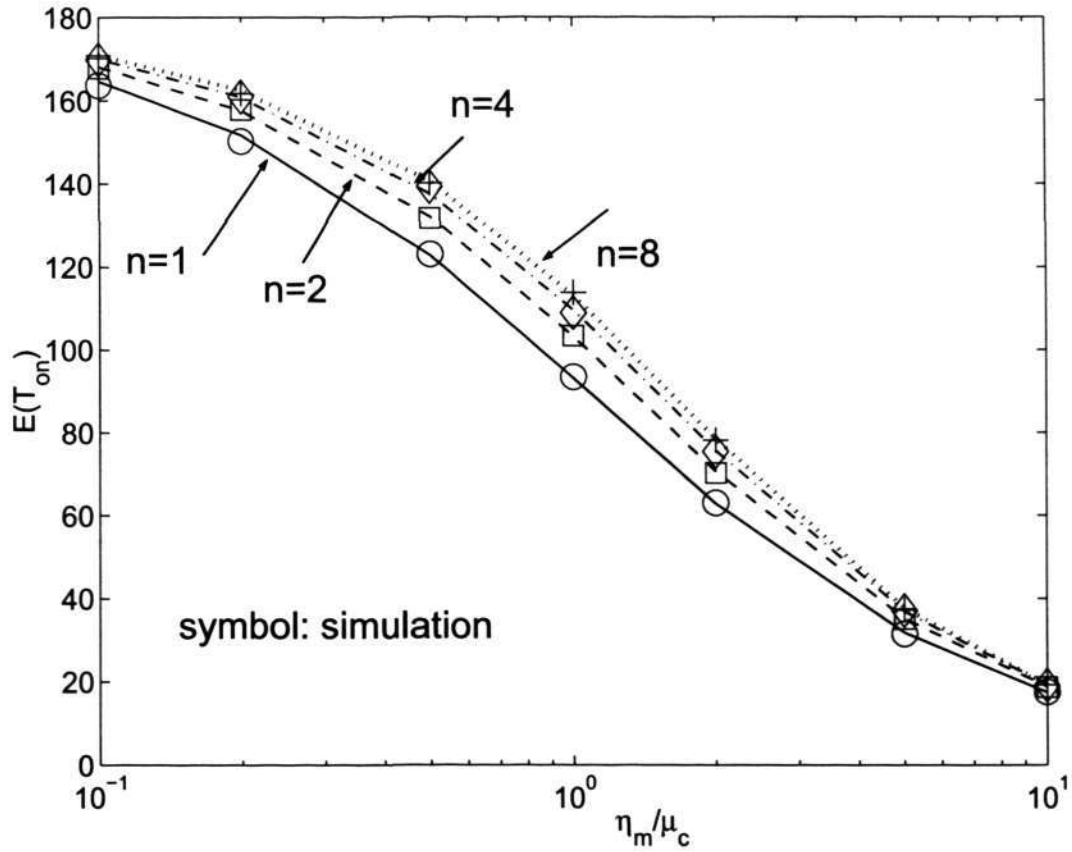


Figure 6.2: $E(T)$ in terms of η_m/μ_c with exponential call holding time and exponential cell residence time

initially serviced by the microcell and the macrocell only provides service for overflow call (e.g. [88]).

Suppose that the cell residence time of the slow call in microcell or macrocell follows Gamma distribution [68]. Denote by V_m, V_M as the slow call cell residence time variance in microcell and macrocell, respectively. Fig.6.4 depicts the effect of the cell residence time variance on T_{on} . In figure 6.4, the call holding time is 4-stage Erlang distribution. The result indicates that: 1) T_{on} is almost insensitive to V_M ; 2) for very slow-mobility MS, when $V_m\eta_m^2 < 1$, T_{on} is insensitive to V_m . When $V_m\eta_m^2 > 1$, T_{on} increases slowly with the larger V_m ; 3) as the movement is not extremely slow, in case of $V_m\eta_m^2 < 1$, T_{on} increases slowly with the greater V_m . When $V_m\eta_m^2 \geq 1$, T_{on} increases very quickly with V_m . Hence, more random call traffic incurs longer slow call CHT.

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Figure 6.3: $E(T_{on})$ in terms of η_m/μ_c

In summary, we believe that, comparing with the previous results, our result is superior in the following aspects: 1) more general in the sense of the absence of any specific distribution assumption for the call holding time and cell residence time, and the support of the overflow and underflow mechanisms in HCS; 2) more accurate validated by the simulation result; 3) easier to compute due to the closed-form formula.

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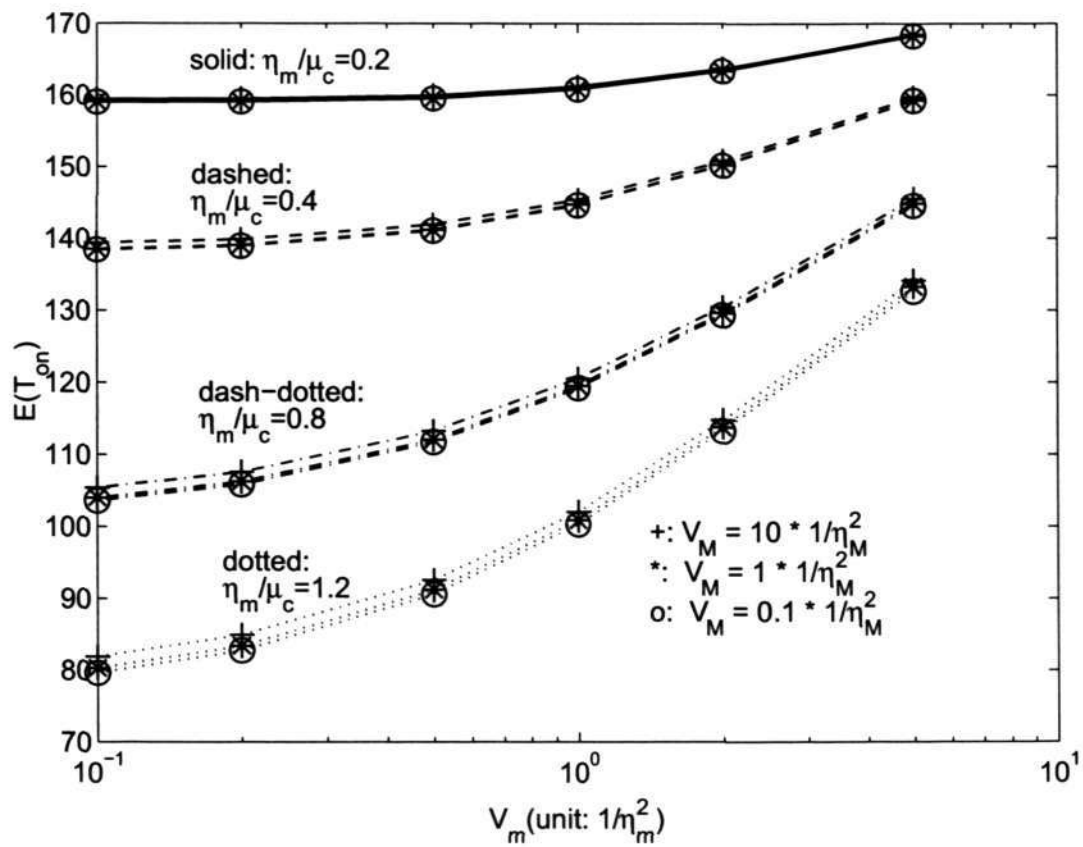


Figure 6.4: $E(T_{on})$ in terms of cell residence time variance

Chapter 7

Performance Evaluation of GSM/GPRS Networks with Channel Re-allocation Scheme

The previous chapters 2, 3, 4, 5, 6 have studied the wireless channel unreliability effect as well as the sensitivity with respect to the call holding time, the cell residence time and the handoff dwell time upon the network performance and the call performance in the stand-alone and the hierarchical cellular system.

In this chapter, we will present the contribution in the aspect of the resource management in the voice/data integrated GSM/GPRS network with the attempt to fully utilize the available bandwidth. A novel approach is proposed in formulating the generic transit rate, which can greatly facilitate the steady state probability as well as the performance metrics calculation.

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7.1 Introduction

The integration of General Packet Radio Service (GPRS) [101] with the popular GSM network represents a major development toward the next generation wireless multimedia network. Due to the diverse Quality of Service (QoS) requirements of voice and data and the motivation for efficient bandwidth utilization, the channel allocation scheme in the voice/data integrated GSM/GPRS network is one of the most crucial issues to achieve the best system performance.

The adaptive characteristics implied by the multi-slot capability, one of the key features of GPRS network providing a flexible mechanism for voice/data sharing the precious radio resources, has been investigated by a few works. Lin *et al.*[103] [104] employed the multi-slot service to assign channels to a GPRS data under the condition of insufficient resources. Chen *et al.*[102] recently proposed de-allocation scheme (DAS) specifically employing the multi-slot property upon voice call arrival to prevent the voice call from rejection. For the sake of analytical simplicity and tractability, the aforementioned studies assume that only 1 or 2 or 3 maximum channels are required by GPRS data request. In this chapter, we relax this assumption, i.e. generalize the channel requirement by GPRS data as M channels.

Referring to prior studies, upon channel release, the freed channels are left idle. We argue that these idle channels can be re-allocated to the *degraded GPRS call*, terming the GPRS data using less than M channels, with the potential to reduce the GPRS packet transmission duration and to fully utilize the available resources, which is called as channel re-allocation scheme (RAS). On the other hand, the general channel requirement of GPRS data considerably complicates DAS as well as RAS. However, when $M = 2$, only the GPRS calls using two channels should be de-allocated upon voice call arrival, while only those GPRS calls using one channel should be re-allocated upon

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channel release. For general case, since the possible utilizing channels by a GPRS call vary from 1 to M , two natural problems arise: which GPRS call should be selected to de-allocate a channel for a voice call connection request and which one should be chosen to re-allocate in RAS. The channel allocation policies corresponding to these two questions will be described in the next section.

7.2 Traffic model and channel allocation scheme

Consider a Base Station(BS) with C channels for the voice call and GPRS packet sharing in a homogeneous GSM/GPRS network. We term the GPRS packet using $m(m = 1, 2, \dots, M)$ channels as *type- m GPRS call*. We assume that the voice new call, voice handoff call and GPRS packet follow the Poisson Process with the arrival rate λ_{vn} , λ_{vh} and λ_g , respectively. Let $\lambda_v = \lambda_{vn} + \lambda_{vh}$ be the total voice call arrival rate. The call holding time and the cell residence time of voice call are exponentially distributed with service rate μ_c and μ_{crt} , respectively. Hence, the channel holding time of voice call is exponential distribution with the parameter $\mu_v = \mu_c + \mu_{crt}$. The service time of each GPRS packet with one channel is exponentially distributed with mean $1/\mu_g$.

The state transition can be triggered by the following events: voice call arrival, voice call normal completion, voice call handoff, GPRS data arrival and GPRS data completion. Upon a GPRS data arrival (denoted as ARR_g), if the number of idle channels $C_{idle} \geq M$, M channels are allocated to ARR_g . If $0 < C_{idle} < M$, C_{idle} channels are allocated to ARR_g . Otherwise, whenever $C_{idle} = 0$, ARR_g is blocked.

For a voice call arrival (denoted as ARR_v), if $C_{idle} > 0$, one channel is assigned to ARR_v . If $C_{idle} = 0$, DAS is extended for general case. We adopt the following method:

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type- m GPRS call can be degraded if and only if type- q ($q = M, M - 1, \dots, m + 1$) have been already degraded to type-1. Let $j_m(t)$ be the number of type- m GPRS call at time t . Denote $j_{\alpha(t)}(t)$ as the first non-zero value in the ordered sequence $(j_M(t), j_{M-1}(t) \dots j_2(t))$. The non-existence of $\alpha(t)$ implies that no GPRS call exists or all GPRS calls are type-1. Hence, if $C_{idle} = 0$ and $\alpha(t)$ exists, we de-allocate a channel from a type- $\alpha(t)$ GPRS call and then assign this channel to ARR_w , and the type- $\alpha(t)$ GPRS call becomes type- $(\alpha(t) - 1)$. If $C_{idle} = 0$ and $\alpha(t)$ does not exist, ARR_v is blocked.

Next, we describe the RAS. Upon the channel release, if there are degraded GPRS calls, the released channel will be re-allocated to upgrade such calls. We adopt the worst degraded first upgrading policy, i.e. type- m GPRS call can be upgraded if and only if type- q ($q = 1, 2, \dots, m - 1$) have been already upgraded. In upgrading a specific type- m GPRS call, it will attempt to upgrade to type- M if sufficient channels are available. Otherwise, the type- m GPRS call will expand to the possible type by using up the idle channels. If there are remaining channels after all type- m GPRS calls have been successfully upgraded to type- M , the type- $(m + 1)$ will attempt to upgrade to type- M , this process will be repeated till the released channels are used up for re-allocation or all degraded GPRS calls are fully upgraded to type- M .

7.3 Performance Analysis

Let the BS state denote as $\mathbf{x} = (i, j_1, j_2 \dots j_M)$ with i representing the number of voice call in service, j_m ($m \in \mathcal{M} \equiv \{1, 2 \dots M\}$) the number of type- m ongoing GPRS call. The state space of BS, \mathcal{X} , is defined as

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$$\mathcal{X} \equiv \left\{ \mathbf{x} = (i, j_1, j_2 \cdots j_M) \mid 0 \leq i + \sum_{m=1}^M m \cdot j_m \leq C; \right. \\ \left. 0 \leq j_m \leq \left\lfloor \frac{C}{m} \right\rfloor, m = 1, 2 \cdots M \right\} \quad (7.1)$$

with $\lfloor z \rfloor$ standing for the maximum integer less than or equal to z . Let $r_{\mathbf{x} \rightarrow \mathbf{x}'}$ ($\mathbf{x} \in \mathcal{X}, \mathbf{x}' \in \mathcal{X}$) be the transition rate from the current legal state $\mathbf{x} = (i, j_1, j_2 \cdots j_M)$ to the destination legal state $\mathbf{x}' = (i', j'_1, j'_2 \cdots j'_M)$. If $\mathbf{x} \notin \mathcal{X}$ or $\mathbf{x}' \notin \mathcal{X}$, then $r_{\mathbf{x} \rightarrow \mathbf{x}'} = 0$. In state \mathbf{x} , denote $\xi = C - i - \sum_{m=1}^M m \cdot j_m$ as the number of free channels in the BS. Similarly, we define the indicator function $\mathbf{1}_E$ equal to 1 when the event E is true, or equal to zero otherwise. Let j_α denote the first non-zero value in the ordered sequence $(j_M, j_{M-1}, \cdots, j_2)$. Let j_β denote the first non-zero value in the sequence $(j_1, j_2, \cdots, j_{M-1})$. If α does not exist, then all GPRS calls (if available) are type-1. If β does not exist, then all GPRS calls (if available) are type- M .

Upon a type- m GPRS call completion, the number of type- q ($q \in \mathcal{M}$) GPRS data becomes $(j_1, j_2, \cdots, j_m - 1, \cdots j_M)$ and m free channels are available to upgrade the degraded GPRS call. Denote the index q^* ($1 \leq q^* \leq M - 1$) satisfying

$$\sum_{q=1}^{q^*-1} j_q(M - q) \leq m < \sum_{q=1}^{q^*} j_q(M - q) \quad (7.2)$$

The inequality shows that the type-1 to type- $(q^* - 1)$ can be fully upgraded to type- M , and the type- q^* can be partially upgraded to type- M under the condition of m channel availability. In the special case $\sum_{q=1}^{M-1} j_q(M - q) \leq m$, showing that all the degraded GPRS calls in service can be fully upgraded to type- M GPRS call, we designate $q^* = M$. The non-existence of q^* in the set \mathcal{M} suggests that there is no GPRS call or all GPRS calls are type- M after the type- m GPRS call completion.

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The transition rate will be given by (7.3) below, where the component in the destination state $\mathbf{x}'_{MU,GPRS \text{ complete}} = (i', j'_1, j'_2 \dots j'_M)$ due to a type- m GPRS call completion is expressed as follows.

i) In case of $1 \leq q^* \leq M - 1$

$$\begin{aligned} i' &= i, j'_q = 0 (q = 1, 2 \dots q^* - 1), j'_{q^*} = j_{q^*} - \Delta - 1, \\ j'_{q^* + \Delta_r} &= j_{q^* + \Delta_r} + 1, j'_M = \sum_{q=1}^{q^*-1} j_q + \Delta + j_M, \\ j'_q &= j_q \text{ (other index } q \text{ in the set } \mathcal{M}) \end{aligned}$$

where $\Delta = \left\lfloor \frac{m - \sum_{q=1}^{q^*-1} j_q (M - q)}{M - q^*} \right\rfloor$ is the maximum number of type- q^* GPRS data that can be upgraded. $\Delta_r = m - \sum_{q=1}^{q^*-1} j_q (M - q) - \Delta (M - q^*)$ represents the number of channels to upgrade one type- q^* GPRS call to type- $(q^* + \Delta_r)$.

ii) In case of end value $q^* = M$

$$i' = i, j'_q = 0 (q = 1, 2 \dots M - 1), j'_M = j_1 + j_2 + \dots + j_M$$

$$r_{\mathbf{x} \rightarrow \mathbf{x}'} = \begin{cases} \lambda_v \cdot \mathbf{1}_{\xi > 0} & i' = i + 1, j'_q = j_q (q \in \mathcal{M}) \\ \lambda_v \cdot \mathbf{1}_{\xi = 0} \mathbf{1}_{(\text{exist } \alpha)} & i' = i + 1, j'_{\alpha-1} = j_{\alpha-1} + 1, j'_\alpha = j_\alpha - 1, \\ & j'_q = j_q (q \in \mathcal{M} - \{\alpha - 1, \alpha\}) \\ \lambda_g \cdot \mathbf{1}_{\xi \geq M} & i' = i, j'_M = j_M + 1, j'_q = j_q (q \in \mathcal{M} - \{M\}) \\ \lambda_g \cdot \mathbf{1}_{1 \leq \xi < M} & i' = i, j'_\xi = j_\xi + 1, j'_q = j_q (q \in \mathcal{M} - \{\xi\}) \\ i\mu_v \cdot \mathbf{1}_{(\text{exist } \beta)} & i' = i - 1, j'_\beta = j_\beta - 1, j'_{\beta+1} = j_{\beta+1} + 1, \\ & j'_q = j_q (q \in \mathcal{M} - \{\beta, \beta + 1\}) \\ i\mu_v \cdot \mathbf{1}_{(\text{not exist } \beta)} & i' = i - 1, j'_M = j_M, j'_q = 0 (q \in \mathcal{M} - \{M\}) \\ j_m(m\mu_g) \cdot \mathbf{1}_{(\text{exist } q^*)} & \mathbf{x}'_{MU,GPRS \text{ complete}}; \quad m \in \mathcal{M} \\ j_m(m\mu_g) \cdot \mathbf{1}_{(\text{not exist } q^*)} & i' = i, j'_M = j_M, j'_q = 0 (q \in \mathcal{M} - \{M\}); \quad m \in \mathcal{M} \end{cases} \quad (7.3)$$

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From this, the generator matrix, \mathbf{R} , governing the evolution of the multi-dimensional Markov chain, can be easily obtained. The steady-state probability of the state \mathbf{x} is denoted as $\pi(\mathbf{x})$. Let $\mathbf{\Pi}$ be the stationary state probability vector of the system and be ordered in the lexicographic order based on the state \mathbf{x} . Then, $\mathbf{\Pi}$ is the solution of linear equation $\mathbf{\Pi R} = 0$ and $\mathbf{\Pi e} = 1$ with \mathbf{e} representing the column entity vector with all ones.

The voice handoff call arrival rate is described as

$$\lambda_{vh} = \left(\sum_{\mathbf{x} \in \mathcal{X}} i \cdot \pi(\mathbf{x}) \right) \cdot \mu_{crt} \quad (7.4)$$

Denote $P_{bv}, P_{bg}, T_g, \gamma$ as the voice call blocking probability, GPRS packet blocking probability, average GPRS packet transmission time and channel utilization, respectively. These performance metrics are expressed as

Voice call blocking probability:

$$P_{bv} = \sum_{i+j_1=C, j_2=0, j_3=0, \dots, j_M=0} \pi(\mathbf{x}) \quad (7.5)$$

GPRS packet blocking probability:

$$P_{bg} = \sum_{i+\sum_{q=1}^M q \times j_q=C} \pi(\mathbf{x}) \quad (7.6)$$

Average GPRS packet transmission time:

$$T_g = \frac{\sum_{\mathbf{x} \in \mathcal{X}} (\sum_{m=1}^M j_m) \cdot \pi(\mathbf{x})}{\lambda_g (1 - P_{bg})} \quad (7.7)$$

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Channel utilization:

$$\gamma = \frac{\sum_{\mathbf{x} \in \mathcal{X}} \left(i + \sum_{m=1}^M m \cdot j_m \right) \cdot \pi(\mathbf{x})}{C} \quad (7.8)$$

Since the voice handoff call arrival rate and steady state probability is mutually dependent, a fixed point algorithm FPA shown below should be used. Note that we may call a $(M+1)$ -dimension state in \mathcal{X} simply as state $k \in [1, S_{max}]$ without confusion in the algorithm.

Fixed point algorithm FPA:

1. Input $C, M, \lambda_{vn}, \mu_c, \mu_{crt}, \lambda_g, \mu_g$;
2. Construct the matrix \mathbf{R} ;
3. Set initial $\lambda_{vh}^{(0)} (= 0.1)$. Set the convergence criteria ϵ_1 and ϵ_2 , set the relaxation factor $\omega (1 \leq \omega < 2)$;
4. Repeat
 - (a) • Set initial state probability $\mathbf{\Pi}^{(0)}$ with each element equal to $\frac{1}{S_{max}}$;
 - Repeat and calculate

$$\mathbf{\Pi}^{(n)} = \omega \mathbf{\Pi}^{(n-1)} \mathbf{R} + (1 - \omega) \mathbf{\Pi}^{(n-1)}$$

$$\text{until } \sum_{k=1}^{S_{max}} \frac{|\pi_k^{(n)} - \pi_k^{(n-1)}|}{|\pi_k^{(n)} + \pi_k^{(n-1)}|} < \epsilon_1.$$

- (b) Calculate the handoff call arrival rate l^{th} iteration

$$\lambda_{vh}^{(l)} = \left(\sum_{k=1}^{S_{max}} (\text{number of voice call in state } k) \cdot \pi_k \right) \cdot \mu_{crt}$$

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until $\left| \lambda_{vh}^{(l)} - \lambda_{vh}^{(l-1)} \right| < \epsilon_2$.

5. Output the steady state probability Π .
6. Calculate the performance metrics P_{bv} , P_{bg} , T_g and γ .

7.4 Numerical Results

We choose the following set of parameters: $C = 12$, $\mu_c = 1/180.0$, $\mu_{crt} = 1/120.0$, $\mu_g = 1/2.0$, $\lambda_{vn} = 0.04$ calls/sec. Fig.7.1 shows the performance metrics in terms of GPRS packet arrival rate. It is evident that RAS can substantially decrease P_{bv} and T_g . This is because, when one is using RAS, more channels are accessible for GPRS packet, leading to the great reduction in the GPRS packet transmission time. As a consequence, in a fixed interval, more GPRS packet can complete the service and more channels are available for voice call connection, which results in smaller P_{bv} and T_g . In addition, there is a slight increase in the channel utilization when using RAS due to the tendency of RAS to fully utilize all idle channels. We can observe that the penalty on P_{bg} is negligible. From the perspective of GPRS data request, RAS reduces its available channels. Hence, P_{bg} becomes larger with the involvement of RAS. However, the substantially reduced GPRS packet transmission time, leading to more available channels for GPRS packet access, compensates such deterioration and makes this issue insignificant. Furthermore, better performance can be achieved with larger M and such benefit becomes more apparent with burstier GPRS packet. Hence, the commonly used assumption, i.e. two channels requirement by a GPRS data, underestimates the actual achievement of DAS as well as RAS.

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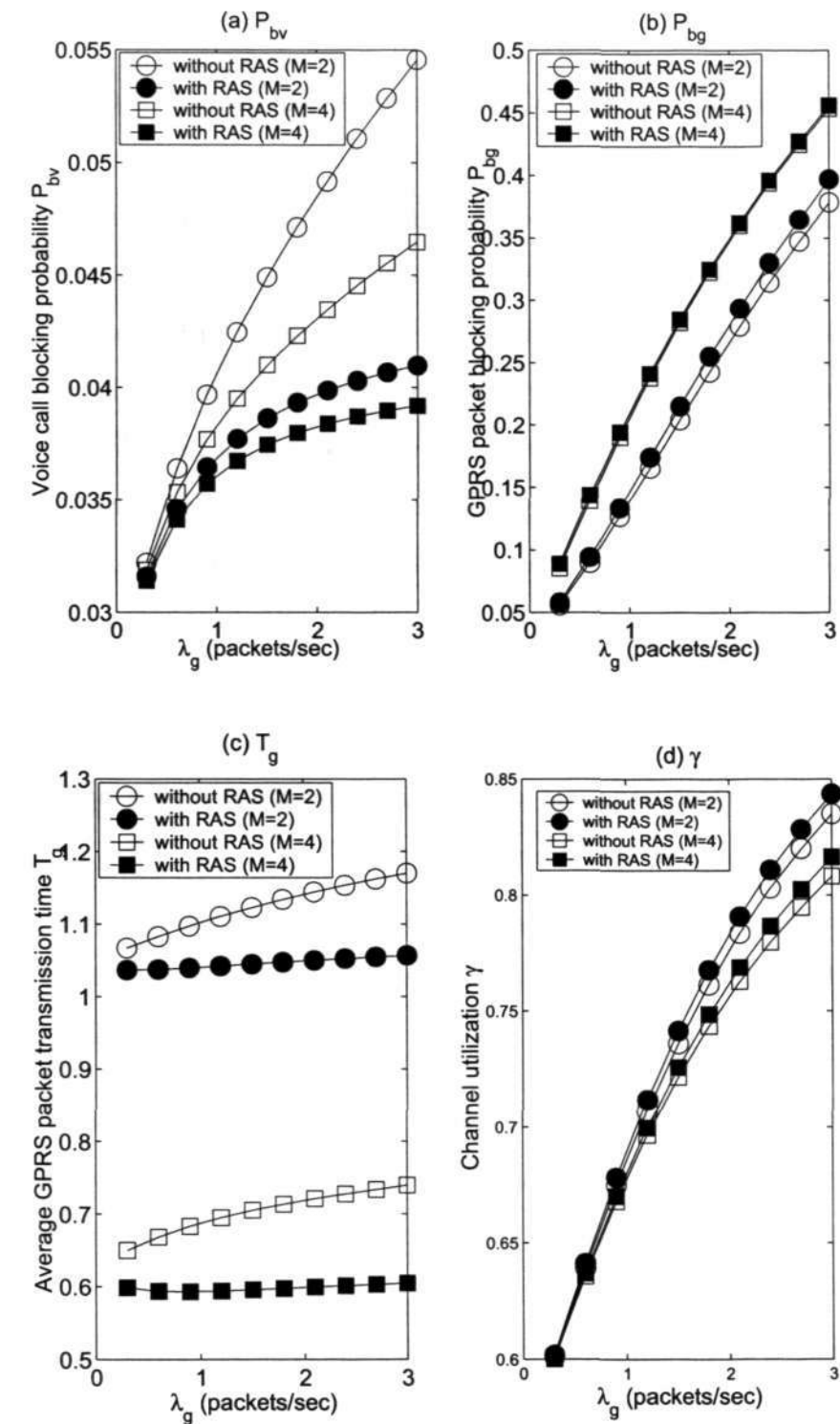


Figure 7.1: Performance metrics in terms of the GPRS packet arrival rate

7.5 Conclusion

In this chapter, we generalize the channel requirement of GPRS data and propose the channel re-allocation scheme (RAS) in GSM/GPRS network with the emphasis on employing the adaptive characteristics implied by multi-slot capability. The result shows that RAS can considerably reduce the voice call blocking probability and GPRS packet transmission time with negligible expense on GPRS packet blocking probability. Moreover, the assumption for two channels requirement of GPRS data underestimates the performance of DAS as well as RAS. Note that the flexibility property of the scheme RAS facilitate its easy integration into the call admission control or channel allocation policy algorithms. For instance, the buffer mechanism can be employed to protect the voice handoff call or the GPRS data packet from rejection upon the moment of arrival. This will be examined in a future research topic. Recently, based on stochastic Petri net formalism, Y. Cao [109] analyzed the queueing mechanism in GPRS/EGPRS systems. This is an interesting topic for future investigation in employing Petri net technique to resolve the specific problem in our scenario.

Chapter 8

Conclusions and Future Work

This dissertation has centered an issue relating to two problems: wireless link unreliability and sensitivity. A novel analytical model is proposed to investigate the wireless channel impairment. The results have shown that by neglecting the wireless link effect will greatly overestimate the wireless network performance. The handoff dwell time sensitivity is examined in the handoff queueing priority scheme, wherein the handoff dwell time is the most crucial component in introducing the buffer mechanism for the hand-off call. The other sensitivity problems are investigated in the future highly promising hierarchical cellular network.

The wireless link unreliability, as an inherent nature of any wireless system, will still play a significant role in determining the current as well as the next generation wireless network performance. By studying the effect of unreliable wireless link in the wireless network with different characteristics, this should be a potential research direction. In addition, in different wireless system, the tele-traffic parameters may function different accordingly. As a result, sensitivity in diverse scenarios needs further examination.

In the thesis, EM algorithm, TAM algorithm, TPT algorithm have been employed to

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resolve either the numerical intractability problem or to simplify the implementation. Different approximation may have its own applicable scenario. There is no standard criterion to choose an algorithm. For example, either of EM, TAM or TPT algorithm can be used to approximate Pareto distribution. TAM has fewer requirements for computation capability when comparing with TPT since TPT may need too many components to approximate the heavy-tailed distribution. EM is more general algorithm while TAM is a specific algorithm handling heavy-tailed Pareto distribution. Developing more efficient and generally applicable algorithms is also one of the future directions. In the following, we will list a few future research directions.

8.1 Ad hoc Network

The dominant mode for the communication between end users in the current wireless network is through the infrastructure. MS has to build up a radio link with BS before communicating with the other users. Comparatively, in ad hoc mode, MS can connect directly peer-to-peer without the participation of BS. It is clear that the ad hoc network has the lower cost in deployment. However, the ad hoc mode suffers a few challenges such as dynamic topology, vulnerable routing and complicated location management. All these problems require a further investigation.

8.2 Handoff mechanism in heterogenous network

As stated in the chapter 1, heterogeneous network integration will be a highly promising wireless mobile network architecture in the future. In Chapters 5 and 6, we solved a few issues relevant to the performance analysis of hierarchical cellular network. The

provision of the seamless handoff mechanism between these networks holding the diverse characteristics is still a critical requirement as well as a significant challenge.

8.3 Resource management in wireless multimedia network

In the Chapter 7, we proposed and studied the channel re-allocation scheme in voice / data GSM / GPRS network with the attempt to fully utilize available precious bandwidth. The next generation wireless mobile network will support a wide range of service types, and hence a large amount of traffic with diverse characteristics. The intelligent and efficient resource management in such networks is still an open research issue. We can conjecture that the information of the mobile station mobility pattern should be carefully investigated and hence utilized in the resource management policies. We are also considering automatically generating and solving the underlying Markov Chain (Chapter 7) starting from a more concise representation based on a variation of stochastic Petri Nets and a well-known software package such as GreatSPN, SPNP and UltraSAN.

8.4 Performance Analysis in wireless multimedia network

The wireless multimedia network is characterized as the wide range of traffic streams, each of which has its own particular property in terms of traffic pattern, arrival rate, resource request priority and bandwidth allocation fairness etc. It has been widely ac-

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cepted that the packet traffic exhibits the self-similarity property while currently the packet traffic is popularly assumed to follow Poisson distribution for the sake of analytical tractability. In modeling the wireless multimedia network, more natural characteristics such as self-similarity, wireless link unreliability, adaptivity and sensitivity should be combined together.

Author's Publications

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