國立交通大學

資訊工程系

碩士論文

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Caching in I-CSCF of UMTS IP Multimedia Subsystem

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摘　要

UMTS(Universal Mobile Telecommunications System)的IP多媒體子系統(IP Multimedia Subsystem; IMS)提供多媒體的服務。在IMS中，所有的來話都會先到達I-CSCF(Interrogating Call Session Control Function)。I-CSCF向HSS (Home Subscriber Server) 詢問到用户的S-CSCF(Serving CSCF) 之後，由S-CSCF負責爲用户建立通話。本論文針對IMS通話建立的效能進行分析，並提出快取及容錯的機制以加速通話建立的程序。我們的研究指出，I-CSCF上的快取機制能顯著地減少通話建立的延遲時間，容錯機制能有效地增加I-CSCF的可用性。

Caching in I-CSCF of UMTS IP Multimedia Subsystem

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Abstract

The *IP Multimedia Core Network Subsystem* (IMS) provides multimedia services for Universal Mobile Telecommunications System (UMTS). In IMS, any incoming call will first arrive at the Interrogating Call Session Control Function (I-CSCF). The I-CSCF queries the Home Subscriber Server to identify the serving CSCF (S-CSCF) of the called mobile user. The S-CSCF then sets up the call to the called mobile user. This thesis investigates the performance of the IMS incoming call setup. We also propose cache schemes with fault tolerance to speed up the incoming call setup process. Our study indicates that the I-CSCF cache can significantly reduce the incoming call setup delay, and checkpointing can effectively enhance the availability of I-CSCF.

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Notation

The notations used in this thesis are listed below.

- μ: the checkpoint frequency
- λ: the registration arrival rate
- V: the variance of the inter-registration intervals
- γ: the incoming call arrival rate
- $1/\delta$: the mean transmission delay between two IMS nodes
- $V1$: the variance of the transmission delay between two IMS nodes
- t_m: the inter-registration interval
- t_c: the inter-checkpointing interval
- τ_m: the period between a checkpoint and the next registration
- p_u: the probability that the S-CSCF record for a UE is saved at a checkpoint
- $f(\cdot)$: the density function of inter-registration interval t_m
- $f^*(s)$: Laplace transform of $f(\cdot)$
- $R(\cdot)$: distribution function of excess life τ_m
- $r(\cdot)$: density function of excess life τ_m
- $r^*(s)$: Laplace transform of $r(\cdot)$

- K: the number of records that are modified between two checkpoints
- t_H: round-trip transmission delay between I-CSCF and the HSS
- t_S: round-trip transmission delay between I-CSCF and the S-CSCF
- t_M: round-trip transmission delay between S-CSCF and the UE
- T_x: the incoming call setup delay from the I-CSCF to the UE (without QoS negotiation) for the "x" scheme (where $x \in \{$B,C,C1,C2$\}$)
- θ_x: the timeout threshold for the "x" scheme (where $x \in \{$B,C,C1,C2$\}$)
- $p_{\theta,x}$: the probability that a call setup is misleadingly aborted because its transmission delay is longer than the timeout period
- α: the probability that the first event after I-CSCF failure is a registration
- β: the probability that the S-CSCF record restored from the backup is invalid
- T_x^*: round-trip transmission delay of the first incoming call setup after an I-CSCF failure (where $x \in \{$B,C,C1,C2$\}$)

Chapter 1

Introduction

Universal Mobile Telecommunications System (UMTS) is one of the major standards for the third generation (3G) mobile telecommunications. In UMTS, the *IP Multimedia Core Network Subsystem* (IMS) provides multimedia services by utilizing the *Session Initiation Protocol* (SIP) [15]. Figure 1.1 illustrates a simplified UMTS network architecture. (The reader is referred to [8, 1, 17, 16] for the detailed descriptions.) This architecture consists of a radio access network, the *General Packet Radio Service* (GPRS) core network and the IMS network. The GPRS core network connects to the IMS network through *Gateway GPRS Support Nodes* (GGSNs). The *Home Subscriber Server* (HSS) is the master database containing all user-related subscription information. Both the GPRS and the IMS networks access the HSS for mobility management and session management. A mobile user utilizes a *Mobile Station* (MS) or *User Equipment* (UE) to access IMS services. To provide a data session for the UE, a connection between the UE and the GGSN is established. This connection is specified by a *Packet Data Protocol (PDP) Context*. The PDP context must be activated before a UE can access the IMS network. The IMS user data traffic is transported through the *Media Gateways* (MGWs), which are controlled by

Media Gateway Control Function (MGCF). The IMS signaling is carried out by *Proxy-Call Session Control Function* (P-CSCF), *Interrogating CSCF* (I-CSCF), and *Serving CSCF* (S-CSCF). The I-CSCF determines how to route incoming calls to the S-CSCF and then to the destination UEs. That is, the I-CSCF is the contact point for the IMS network of the destination UE, which may be used to hide the configuration, capacity, and topology of the IMS network from the outside world. When a UE attaches to the GPRS/IMS network and performs PDP context activation, a P-CSCF is assigned to the UE. The P-CSCF contains limited address translation functions to forward the requests to the I-CSCF. Authorization for bearer resources in the network (where the UE visits) is performed by the P-CSCF. By exercising the IMS registration , an S-CSCF is assigned to serve the UE. This S-CSCF supports the signaling interactions with the UE for call setup and supplementary services control (e.g., service request and authentication). This thesis investigates the performance of the IMS incoming call setup. Specifically, we propose cache schemes with fault tolerance to speed up the incoming call setup process.

This thesis is organized as follows. In Chapter 2, we describe UMTS all-IP architecture and the components in IMS. In Chapter 3, a cache scheme and two checkpoint schemes are proposed to speed up the incoming call setup process. In Chapter 4, we use an analytic model to investigate the overhead of checkpointing. In Chapter 5, the incoming call setup costs are analyzed. Finally, we conclude our research.

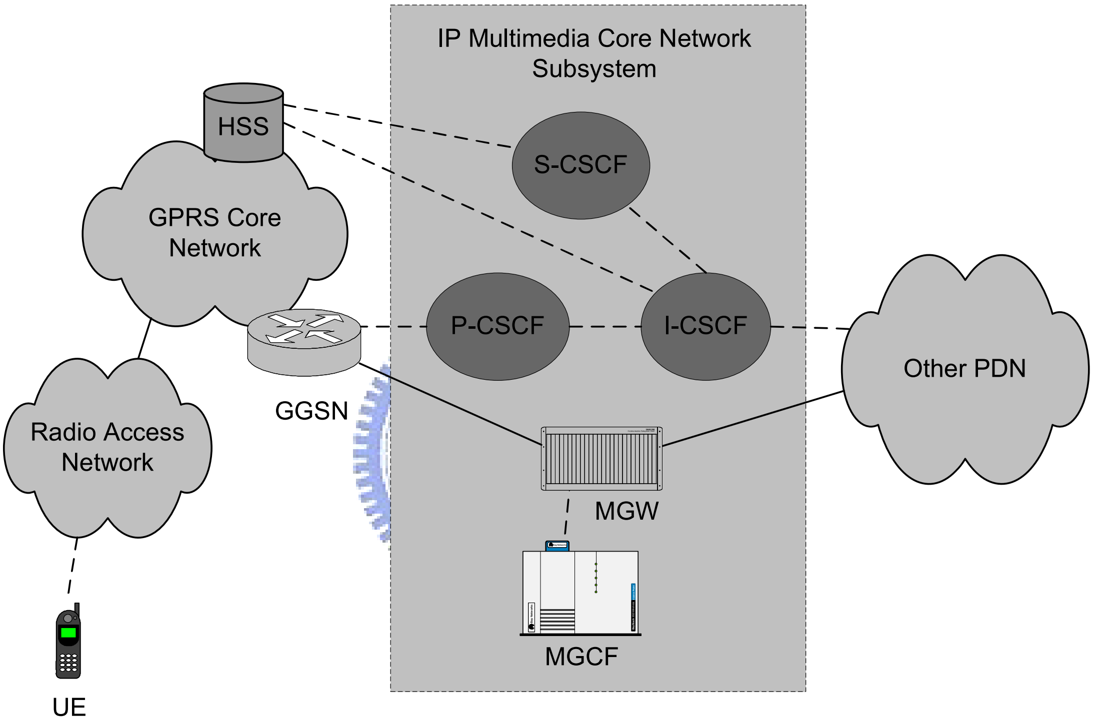


Figure 1.1: The UMTS Network Architecture

Chapter 2

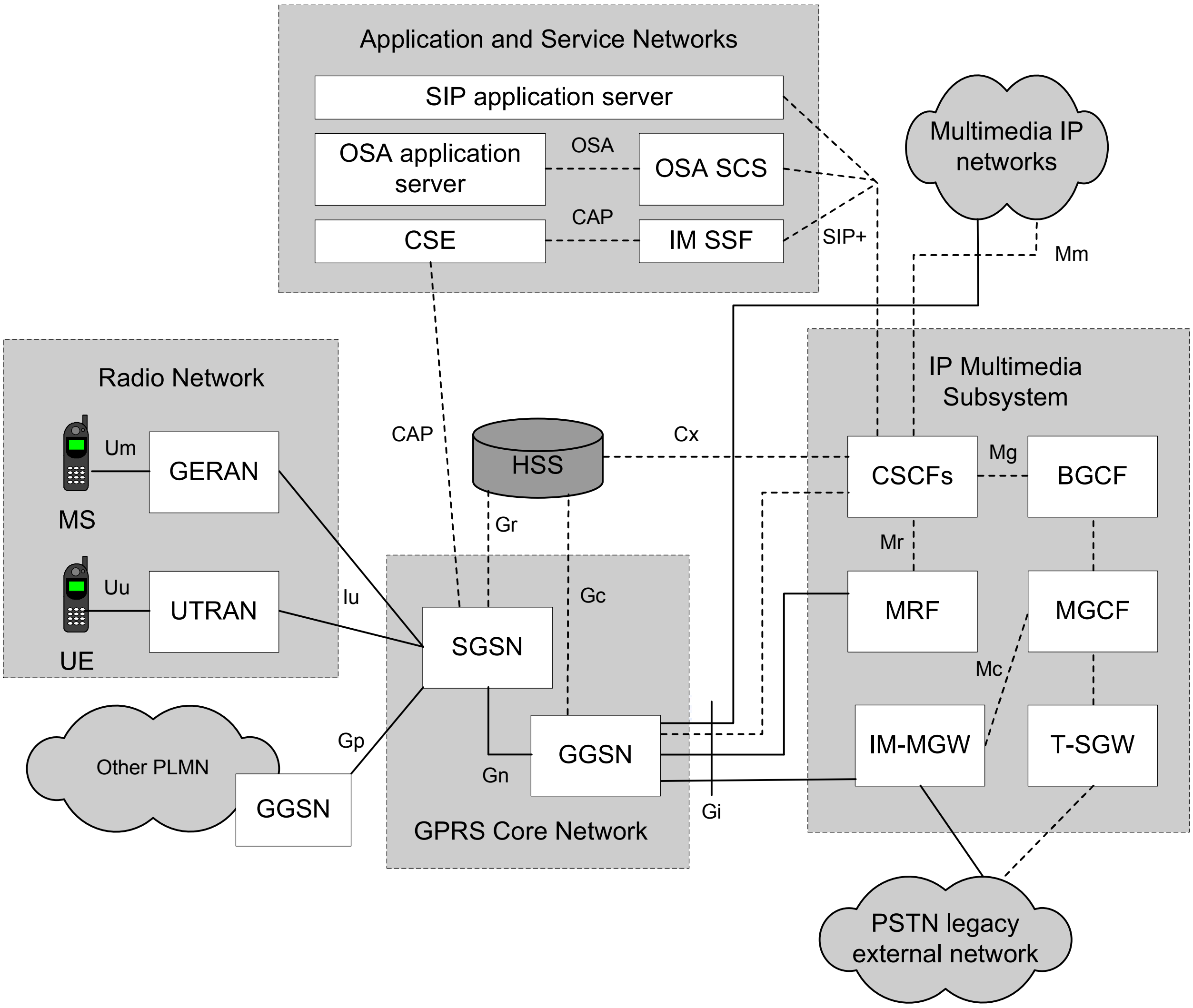
UMTS All-IP Architecture

The 3GPP proposed the UMTS all-IP architecture to integrate IP and wireless technologies. This architecture evolved from the GSM (Global System for Mobile Communications), GPRS, UMTS Release 1999 (UMTS R99) [6], UMTS Release 4 [9], UMTS Release 5 [10], and UMTS Release 6 [11]. This chapter introduces two options for the UMTS all-IP network. Option 1 architecture supports PS domain multimedia and data services. Option 2 architecture extends the option 1 network by accommodating CS domain voice services over a packet-switched core network.

2.1 Option 1 for All IP Architecture

The UMTS all-IP network architecture option 1 consists of the following segments (see Figure 2.1).

Radio Access Network (RAN) can be *UMTS Terrestrial Radio Access Network* (UTRAN) or *GSM Enhanced Data Rates for Global Evolution (EDGE) Radio Access Network* (GERAN). More information about RAN can be found in [14, 4, 16].



MS: Mobile Station
UE: User Equipment
GERAN: GSM EDGE Radio Access Network
UTRAN: UMTS Terrestrial Radio Access Network

SIP: Session Initiation Protocol
OSA: Open Service Architecture
SCS: Service Capability Server
CSE: CAMEL Service Environment
CAP: CAMEL Application Part
IM-SSF: IM Service Switching Function
HSS: Home Subscriber Server
SGSN: Serving GPRS Support Node
GGSN: Gateway GPRS Support Node

CSCF: Call Session Control Function
BGCF: Breakout Gateway Control Function
MRF: Media Resource Function
MGCF: Media Gateway Control Function
IM-MGW: IM Media Gateway
T-SGW: Transport Signaling Gateway

Figure 2.1: UMTS All-IP Network Architecture (option 1)

Home Subscriber Server (HSS) is the master database containing all 3G user-related subscription information. The HSS consists of

1. the IM functionality (i.e., IM user database),
2. the subset of the *Home Location Register* (HLR) functionality required by the PS domain (i.e., 3G GPRS HLR), and
3. the subset of the HLR functionality (i.e., 3G CS HLR) [16, 2] to support CS-domain call handling entities.

GPRS Network consists of SGSNs and GGSNs that provide the mobility management and the PDP context activation services to mobile users [16]. An SGSN connects to the radio access network, and a GGSN connects to the external *Packet Data Network* (PDN). The GPRS network interfaces with a variety of RANs such as UTRAN and GERAN. Both SGSN and GGSN communicate with 3G GPRS HLR through *Gr* and *Gc* interfaces, respectively. These two interfaces are based on *Mobile Application Part* (MAP) [16, 12]. SGSN communicates with GGSN through the *Gn* interface in the same network, and through the *Gp* interface in the different networks. GGSN interacts with external PDN through the *Gi* interface. Gn, Gp and Gi are standard GPRS interfaces and are described in [16, 1].

IP Multimedia Core Network Subsystem is located behind the GGSN. In this subsystem, the CSCFs (including P-CSCF, I-CSCF and S-CSCF) are SIP servers, which are responsible for call control. The *Breakout Gateway Control Function* (BGCF) is responsible for selecting an appropriate PSTN breakout point based on the received SIP request from the S-CSCF. The MGCF is the same as the MGC in a VoIP network, which controls the connection for media channels in an MGW. The *Transport*

Signaling Gateway Function (T-SGW) serves as the PSTN signaling termination point and provides the PSTN/legacy mobile network to IP transport level address mapping. The *Media Resource Function* (MRF) performs functions such as multiparty call, multimedia conferencing, and tone and announcement. These nodes are typically used in a VoIP network [18, 13]. Most interfaces among these nodes (i.e., Mc, Mg, Mh, Mm, Mr and Ms) are IP-based gateway control protocols.

Application and Service Network supports flexible services through a service platform. The all-IP network architecture will provide a separation of service control from call/connection control, and the applications are implemented in dedicated application servers that host service-related databases or libraries. 3GPP defines three possible ways to provide flexible and global services.

(1) Direct SIP+[1] link between CSCF and SIP Application Server: This method will be used by mobile operators to provide new multimedia SIP applications. The SIP application services are either developed by the mobile operators or purchased from trusted third parties.

(2) SIP+ link between CSCF and *IM-Service Switching Function* (IM-SSF) followed by *Customized Application Mobile Enhanced Logic* (CAMEL) *Application Part* (CAP) link between IM-SSF and *CAMEL Service Environment* (CSE) [5]: This method will be used by the mobile operators to provide popular CAMEL services (e.g., prepaid service) to the IM domain users. Note that similar services for the CS domain have already been provided via the CAMEL platform.

(3) SIP+ link between CSCF and *Open Service Architecture* (OSA) *Service Capability Server* (SCS) followed by OSA link between OSA SCS and OSA Appli-

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[1] SIP+ is SIP with extensions for service control.

cation Server: This method will be used to give third parties controlled access to the operator's network and let third parties run their own applications (in the third party application servers) using the IM capabilities of the operator's network.

In the UMTS all-IP network architecture, the GGSN is considered as the border of the network toward the public IP network. The GGSN and MGW together are the network border toward the *Public Switched Telephone Network* (PSTN) and legacy mobile networks.

2.2 Option 2 for All IP Architecture

All-IP network option 2, which supports R99 CS UEs, allows the R99 CS and PS domains to evolve independently. The UMTS all-IP network architecture option 2 is shown in Figure 2.2. Two control elements, the MSC server and GMSC server, are introduced in option 2. The MSC servers and the HLR functionality in the HSS provide an evolution of R99 telephony services. MAP is the signaling interface between the HSS and the MSC server (GMSC server).

The R99 Iu interface separates transport of user data from control signals. Evolving from this interface, option 2 UTRAN accesses the core network via a CS-MGW (user plane) separated from the MSC server (control plane). UTRAN communicates with MSC server using the *RAN Application Part* (RANAP) over the *Iu* interface. The *Iu* interface between UTRAN and CS-MGW is based on *Iu User Plane* (UP) protocol [3]. Notice that there are one or more CS-MGWs in the option 2 network. If more than one CS-MGWs exist, then they communicate through the Nb interface. In our example, there are two CS-MGWs in the all-IP option 2 architecture (see Figure 2.2), one of which is connected to the PSTN and the other is connected to UTRAN via Iu-CS interface. These two CS-MGWs are responsible for voice format conversion between PS and CS networks.

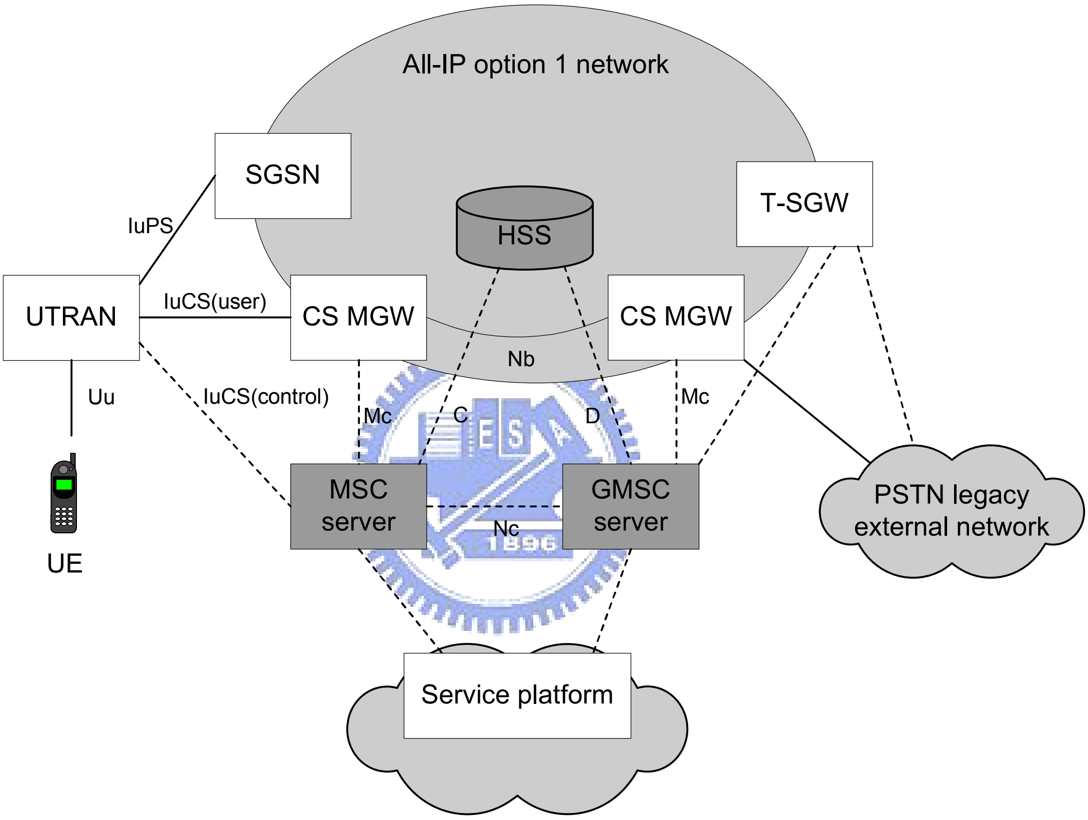

Figure 2.2: UMTS All-IP Network Architecture (option 2)

Chapter 3

IMS Registration and Call Setup

This chapter describes the registration and the incoming call setup procedures for UMTS IMS. We first elaborate on the basic scheme proposed in 3GPP 23.228 [8]. Then we propose a cache scheme and two checkpoint schemes that speed up the incoming call setup process.

3.1 The Basic Scheme

Suppose that a UE already obtained the IP connectivity through the PDP context activation, and has performed at least one IMS registration. The UE may issue re-registration due to, for example, movement among different service areas. Figure 3.1 illustrates the registration message flow for the basic scheme (called B-RP) defined in 3GPP [8, 7], which includes the following steps:

Step 1. The UE issues the Register message to the I-CSCF through the P-CSCF (not shown in Figure 3.1).

Step 2. The I-CSCF exchanges the User-Authorization-Request (UAR) and User-Authorization-

Answer message pair with the HSS to obtain the S-CSCF name for the UE.

Step 3. By using a name-address resolution mechanism, I-CSCF identifies the S-CSCF address and sends the Register message to the S-CSCF.

Step 4. Through the Server-Assignment-Request (SAR) and Server-Assignment-Answer (SAA) message pair exchange between the S-CSCF and the HSS, the S-CSCF obtains the user profile of the UE from the HSS. The user profile will be used in call setup.

Steps 5 and 6. The 200 OK message is sent from the S-CSCF to the I-CSCF, and then from the I-CSCF to the UE, which indicates that the registration is complete.

The IMS incoming call setup defined in 3GPP [8, 7], referred to as the basic incoming call setup (B-ICS), is illustrated in Figure 3.2 with the following steps.

Step 1. The caller sends the Invite message to the I-CSCF. The initial media description offered in the *Session Description Protocol* (SDP) is contained in this message.

Step 2. The I-CSCF exchanges the Location-Info-Request (LIR) and Location-Info-Answer (LIA) message pair with the HSS to obtain the S-CSCF name for the destination UE.

Steps 3 and 4. The I-CSCF forwards the Invite message to the S-CSCF. Based on the user profile of the destination UE, the S-CSCF invokes whatever service logic is appropriate for this session setup attempt. Then it sends the Invite message to the UE (through the P-CSCF of the IMS network where the UE resides).

Steps 5-7. The UE responds with an answer to the offered SDP. This Offer Response message is passed along the established session path back to the caller.

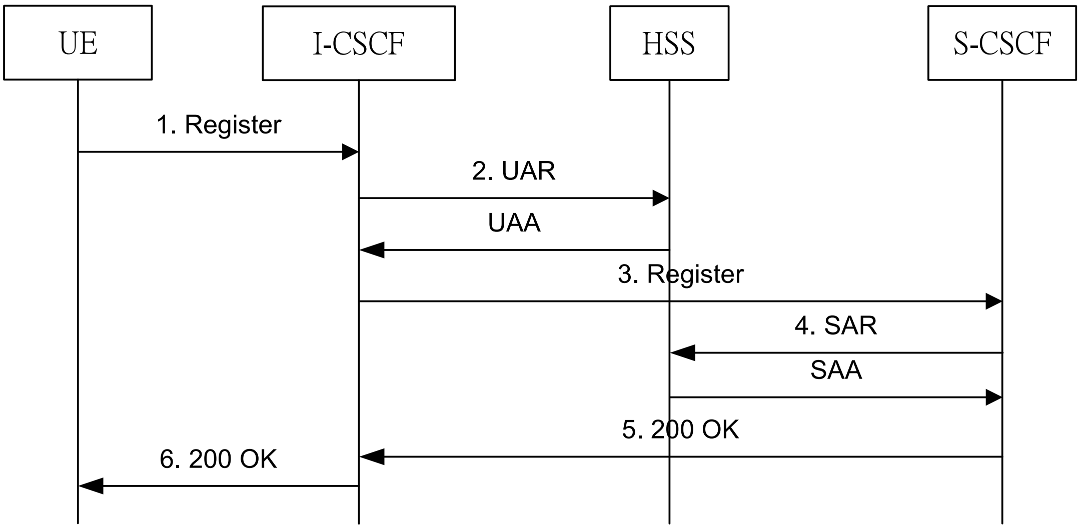

Figure 3.1: Basic Registration Procedure (B-RP)

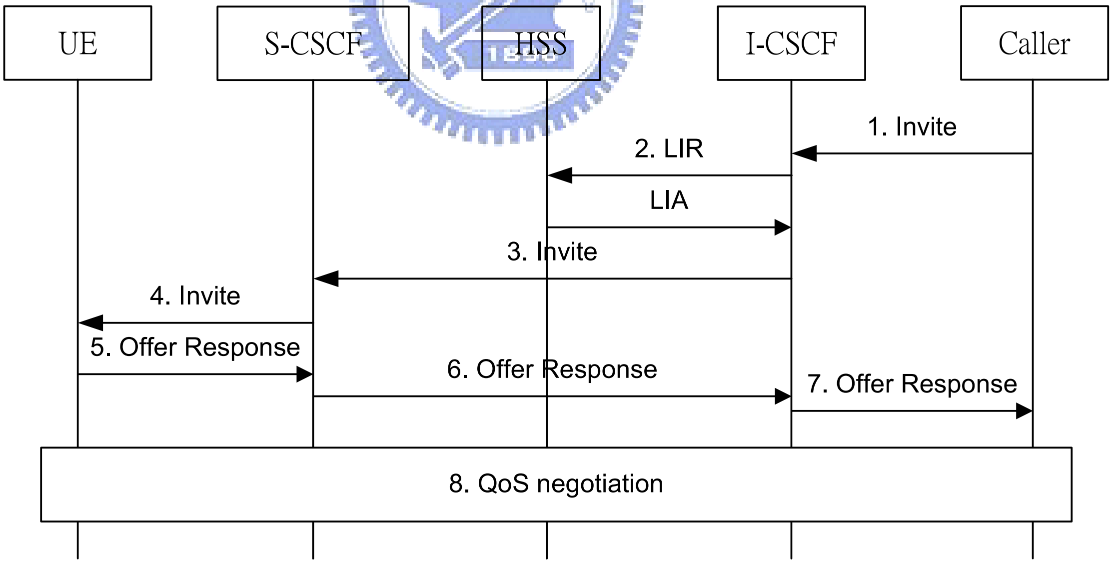

Figure 3.2: Basic Incoming Call Setup (B-ICS)

Step 8. The QoS for this call is negotiated between the originating network (of the caller) and the terminating network (of the UE), and the details are omitted.

3.2 The Cache Schemes

This thesis utilizes a cache at the I-CSCF to speed up the incoming call setup process. We first describe a basic cache scheme. To enhance availability and reliability, we then consider two checkpoint schemes that immediately recover the I-CSCF cache after an I-CSCF crash (failure).

The Basic Cache Scheme (The C Scheme): Figure 3.3 illustrates the registration message flow for the C scheme (called C-RP). C-RP is the same as B-RP except that when the 200 OK is sent from the S-CSCF to the I-CSCF, the (UE, S-CSCF) mapping (called the S-CSCF record) is saved in the cache (Step 6 in Figure 3.3). The incoming call setup for the C scheme (C-ICS) is illustrated in Figure 3.4. In C-ICS, the LIR and LIA message pair exchanged (Step 2 of B-ICS in Figure 3.2) is replaced by a cache retrieval (Step 2, Figure 3.4) to obtain the S-CSCF address. If an I-CSCF failure occurs and the whole cache content is lost, then the S-CSCF records are gradually re-built through the IMS registration procedure. If an incoming call arrives earlier than the registration, then B-ICS must be executed to set up the call.

The Checkpoint Scheme 1 (The C1 Scheme): To immediately recover the I-CSCF cache after a failure, we may save the content of the cache (only for the modified records) into a backup storage. In the C1 scheme, we periodically save the cache into the backup. When an I-CSCF failure occurs, the cache content is restored from the backup. Therefore, in the normal operation, the registration procedure and

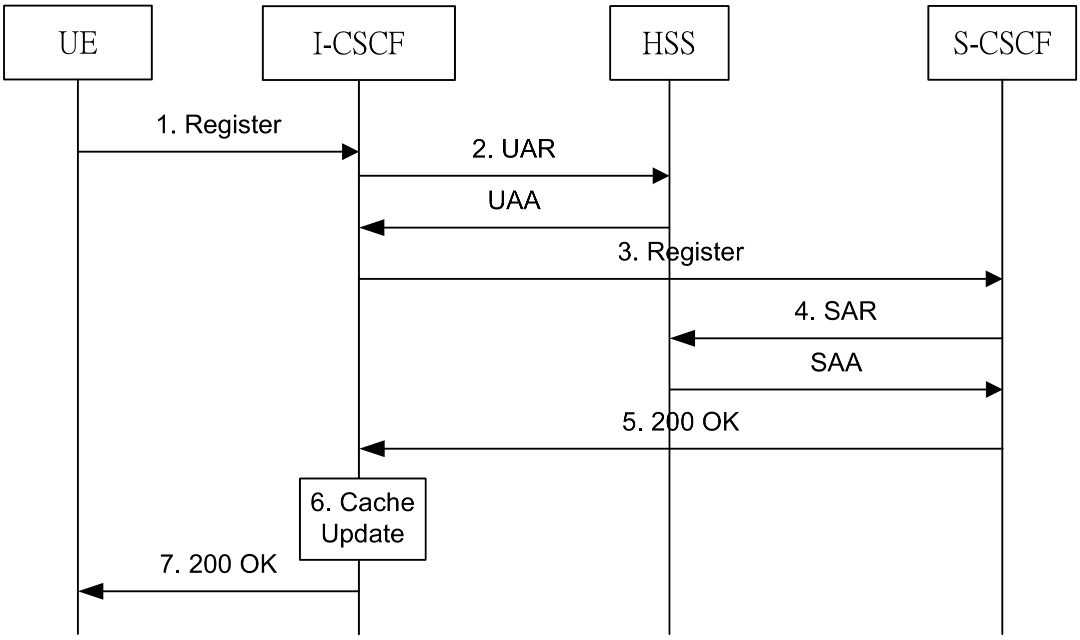

Figure 3.3: Registration with Cache Update (C-RP)

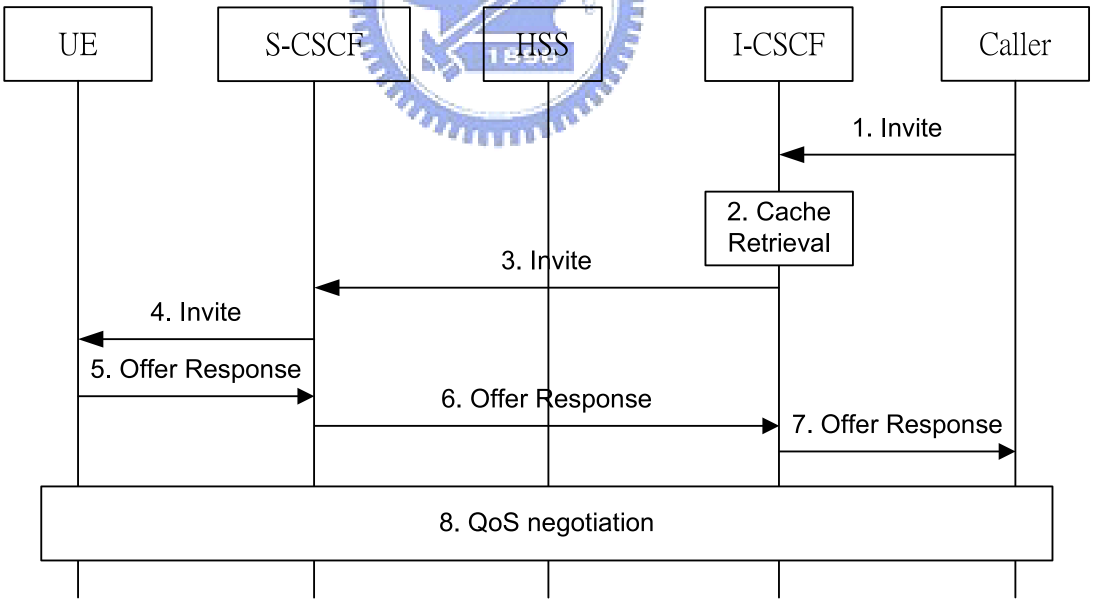

Figure 3.4: Incoming Call Setup with Cache Retrieval (C-ICS)

the incoming call setup procedure for the C1 scheme is the same as that for the C scheme.

After a failure, the incoming call setup procedure is the same as C-ICS (see Figure 3.4) if the S-CSCF is up to date (called a *cache hit*). Note that between a failure and the previous checkpoint, the S-CSCF record of an UE may be modified. In this case the S-CSCF may be obsolete when an incoming call arrives (called a *cache miss*), and the call setup message flow is illustrates in Figure 3.5. The first three steps of this message flow are the same as C-ICS. Since the UE already moves from the old S-CSCF to the new S-CSCF, at the end of Step 3, the old S-CSCF replies the 404 Not Found message to the I-CSCF. The I-CSCF then retrieves the new S-CSCF information from the HSS and sets up the call following Steps 2-8 of B-ICS in Figure 3.2.

The Checkpoint Scheme 2 (The C2 Scheme): It is clear that after an I-CSCF failure, the call setup cost for the C1 scheme is very expensive if a cache miss occurs.

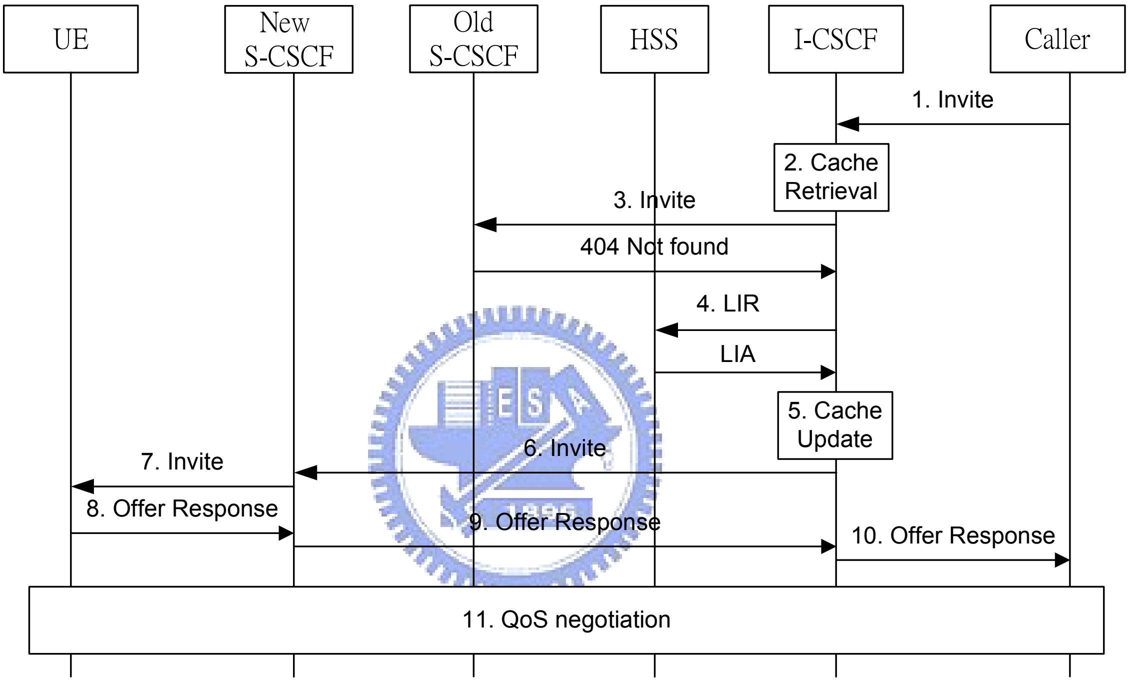

Figure 3.5: First Incoming Call Setup after I-CSCF-Failure: Cache Miss for the Checkpoint 1 Scheme

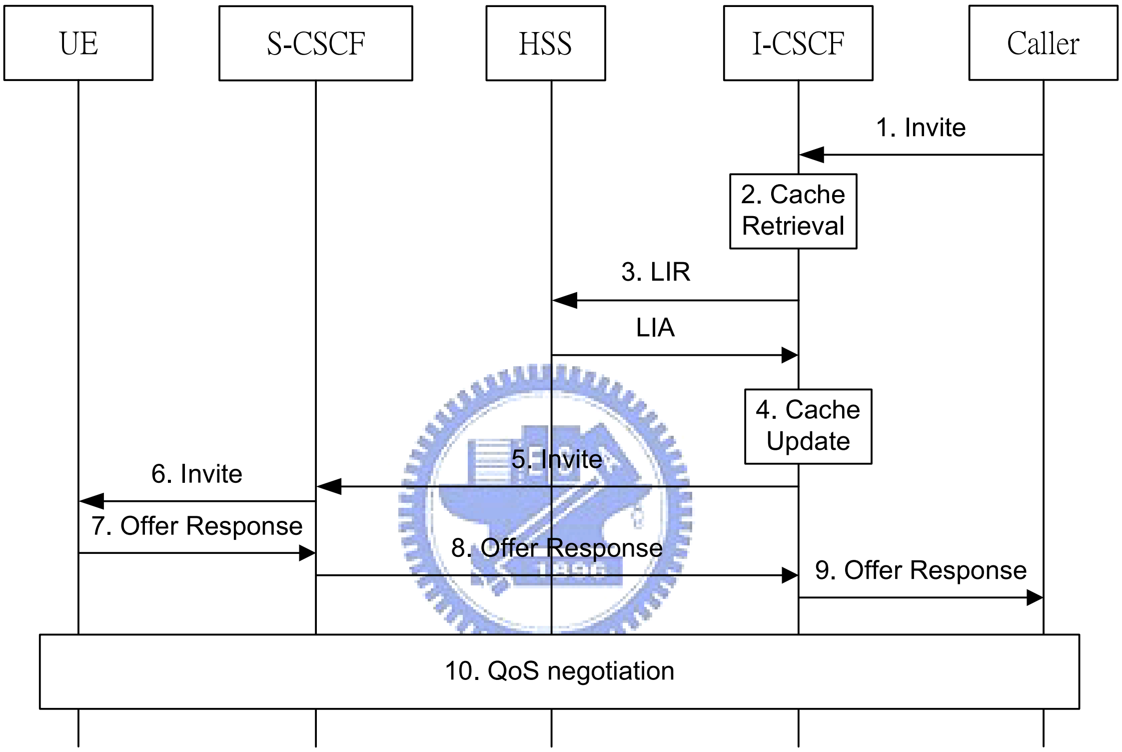

Figure 3.6: First Incoming Call Setup after I-CSCF-Failure: Cache Miss for Checkpoint 2 Scheme

Table 3.1: Caching and Checkpointing Operations

Scheme	Cache Retrieval for incoming call	Cache Restoration after I-CSCF Failure	Backup Record Invalidation
Basic	no	no	no
Cache	yes	no	no
Checkpoint 1	yes	yes	no
Checkpoint 2	yes	yes	yes

We resolve this issue by introducing the C2 scheme. Like the C1 scheme, this scheme periodically checkpoints the cache content into the backup. Furthermore, an S-CSCF record in the backup is invalidated if the corresponding record in the cache is modified. The C2 registration procedure is the same as C-RP except for Step 6 in Figure 3.3. In this step, we check if the S-CSCF record at the backup has been invalidated since the last checkpoint. If so, no extra action is taken. If not, the record in the backup is invalidated. Therefore if multiple registrations for the same UE occur between two checkpoints, the S-CSCF record in the backup is only invalidated for the first registration. After an I-CSCF failure, the C2 scheme knows exactly which S-CSCF records are invalid. For the first incoming call after the failure, if the S-CSCF record is valid, then the call setup procedure follows C-ICS in Figure 3.4. On the other hand, if the S-CSCF record is invalid, the procedure (see Figure 3.6) follows B-ICS in Figure 3.2.

Features of the B, C, C1 and C2 schemes are summarized in Tables 3.1 and 3.2. In the remainder of this thesis, we will analyze the registration and incoming call setup by using analytic and simulation models.

Table 3.2: IMS Registration and Call Setup

Scheme	Registration	Normal Incoming Call Setup	First Incoming Call Setup after Failure
Basic	B-RP	B-ICS	B-ICS
Cache	C-RP (B-RP + cache update)	C-ICS (B-ICS without HSS query)	B-ICS
Checkpoint 1	C-RP	C-ICS	Cache hit: C-ICS; Cache miss: B-ICS + cache update + extra access to S-CSCF
Checkpoint 2	C-RP + possible backup record invalidation	C-ICS	Cache hit: C-ICS; Cache miss: B-ICS + cache update

Chapter 4

Overhead of Checkpointing

This chapter investigates the costs for the C1 and the C2 schemes. Figure 4.1 illustrates the timing diagram for the registration and checkpointing activities of a UE . At t_0, t_2, and t_4, the UE issues registration requests either because it attaches to the network, or it moves from one service area to another service area. The inter-registration intervals $t_2 - t_0$, $t_4 - t_2$, etc., are represented by a random variable t_m. In this figure, periodic checkpoints are performed at t_1 and t_3, where the checkpointing interval is represented by a random variable t_c. The interval τ_m between a checkpoint and the next registration (e.g., $t_2 - t_1$) is called the *excess life* of the inter-registration interval. At a checkpoint,

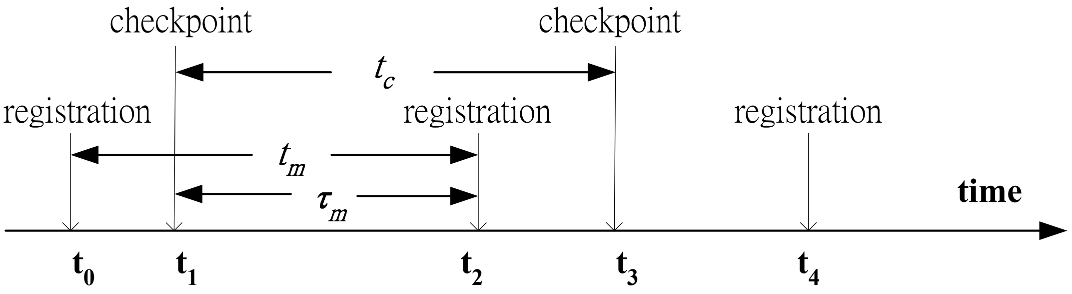

Figure 4.1: Timing Diagram for Registration and Checkpointing

only the modified S-CSCF records are saved into the backup. Let p_u be the probability that the S-CSCF record for the UE is saved at a checkpoint, then

$$p_u = \Pr[t_c > \tau_m]$$

It is clear that the checkpoint cost increases as p_u increases. Two types of checkpoint intervals are often considered. *Fixed* checkpointing performs checkpoints with fixed period $1/\mu$. In *exponential* checkpointing, the inter-checkpointing interval has the exponential distribution with the mean $1/\mu$. Assume that the inter-registration intervals t_m have the exponential distribution with the mean $1/\lambda$ (i.e., the registration stream forms a Poisson process). For an arbitrary time interval T, the number X of registrations occurring in this period has a Poisson distribution. That is

$$\Pr[X = x, T = t] = \left[\frac{(\lambda t)^x}{x!}\right] e^{-\lambda t} \tag{4.1}$$

and

$$\Pr[t_c > \tau_m] = 1 - \Pr[X = 0, T = t_c] \tag{4.2}$$

From (4.2), the probability p_u for fixed checkpointing is expressed as

$$p_u = 1 - e^{-\frac{\lambda}{\mu}} \quad \text{(fixed checkpointing)} \tag{4.3}$$

Similarly, the probability p_u for exponential checkpointing is expressed as

$$p_u = 1 - \int_{t_c=0}^{\infty} e^{-\lambda t_c} \mu e^{-\mu t_c} dt_c = \frac{\lambda}{\lambda + \mu} \quad \text{(exponential checkpointing)} \tag{4.4}$$

Figure 4.2 plots p_u for fixed and exponential checkpointing approaches based on (4.3) and (4.4). The figure indicates that p_u for fixed checkpointing is larger than that for exponential checkpointing (i.e., exponential checkpointing yields better performance than fixed checkpointing). In the remainder of this thesis, we only consider exponential checkpointing. General conclusions drawn from this thesis also apply to fixed checkpointing.

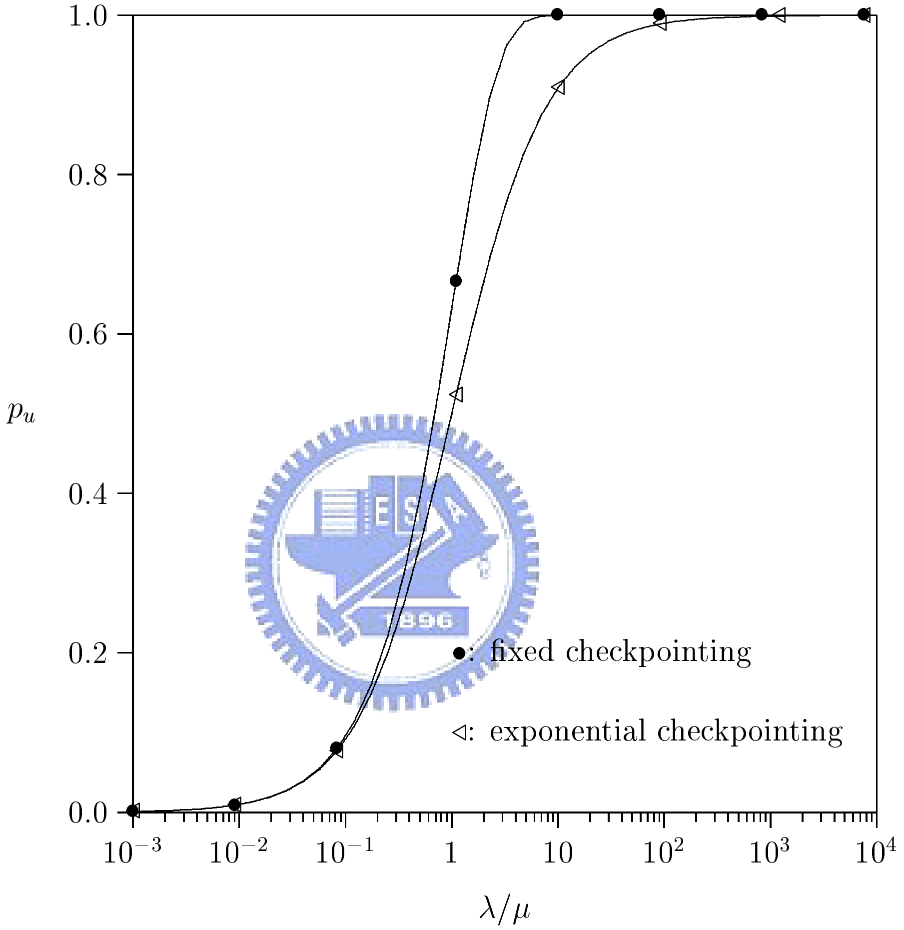

Figure 4.2: Comparing Fixed and Exponential Checkpointing (Poisson Registration Stream with the Rate λ)

Consider the inter-registration interval random variable t_m with the mean $1/\lambda$, the density function $f(\cdot)$ and the Laplace transform $f^*(s)$. The excess life τ_m has the distribution function $R(\cdot)$, density function $r(\cdot)$ and the Laplace transform $r^*(s)$.

Since exponential checkpointing is a Poisson process, t_1 in Figure 4.1 is a random observer of the t_m intervals. From the excess life theorem [19],

$$r^*(s) = \left(\frac{\lambda}{s}\right)[1 - f^*(s)] \tag{4.5}$$

Based on (4.5) we derive p_u as

$$\begin{aligned}
p_u &= \Pr[t_c > \tau_m] \\
&= \int_{t_c=0}^{\infty}\int_{\tau_m=0}^{t_c} r(\tau_m)\mu e^{-\mu t_c} d\tau_m dt_c \\
&= \int_{t_c=0}^{\infty} R(t_c)\mu e^{-\mu t_c} dt_c \\
&= \left.\frac{\mu r^*(s)}{s}\right|_{s=\mu} \\
&= \left(\frac{\lambda}{\mu}\right)[1 - f^*(\mu)]
\end{aligned} \tag{4.6}$$

Assume that t_m is a Gamma random variable with the mean $1/\lambda$, the variance V and the Laplace transform

$$f^*(s) = \left(\frac{1}{V\lambda s + 1}\right)^{\dfrac{1}{V\lambda^2}} \tag{4.7}$$

Then (4.6) is re-written as

$$p_u = \left(\frac{\lambda}{\mu}\right)\left[1 - \left(\frac{1}{V\lambda\mu + 1}\right)^{\dfrac{1}{V\lambda^2}}\right] \quad \text{(for Gamma distributed } t_m\text{)} \tag{4.8}$$

When t_m is exponentially distributed, $V = 1/\lambda^2$, and (4.8) is re-written as $p_u = \lambda/(\lambda+\mu)$, which is the same as (4.4). Figure 4.3 plots p_u for Gamma inter-registration intervals

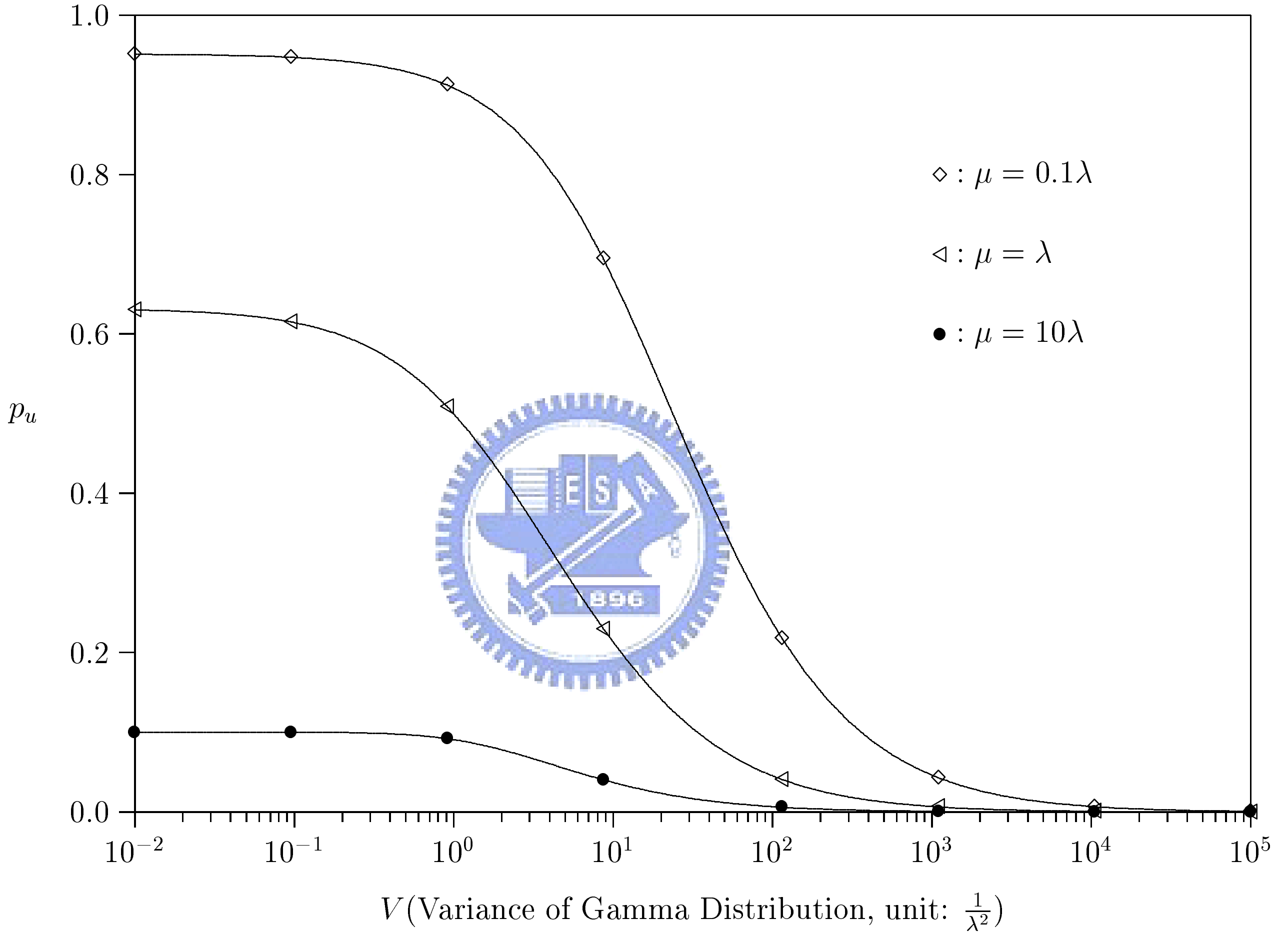

Figure 4.3: Effects of the Variance of the Inter-registration Intervals on p_u

with different variance values. The figure indicates that p_u decreases as the variance V increases. This phenomenon is explained as follows. When the registration behavior becomes more irregular, we will observe more checkpoint intervals with many registrations and more checkpoint intervals without any registration. In other words, smaller p_u is observed. Therefore the checkpointing performance is better when the registration activity becomes more irregular (i.e., V is larger).

Suppose that N UEs have registered to the IMS network, then there are N S-CSCF records in the I-CSCF cache. Let $\Pr[K = k]$ be the probability that k records are modified between two checkpoints. Then

$$\Pr[K = k] = \binom{N}{k} p_u^k (1 - p_u)^{N-k} \tag{4.9}$$

is a binomial probability mass function, and the random variable K has the mean $E[K] = Np_u$ and the variance $V[K] = Np_u(1 - p_u)$. A small $V[K]$ value implies that the S-CSCF record saving overheads for the checkpoint intervals are roughly the same (which provides stable, i.e., better performance for the checkpointing system). The $E[K]$ curves have the same shapes as that for the p_u curves (see Figure 4.3). That is, the S-CSCF record saving cost at a checkpoint decreases as the variance of t_m increases. The $V[K]$ curves are illustrated in Figure 4.4. For small μ values, (e.g., $\mu \leq \lambda$), the variance of K increases and then decreases as the variance of t_m increases. For large μ (i.e., $\mu \geq 10\lambda$), the variance of K decreases as the variance of t_m increases.

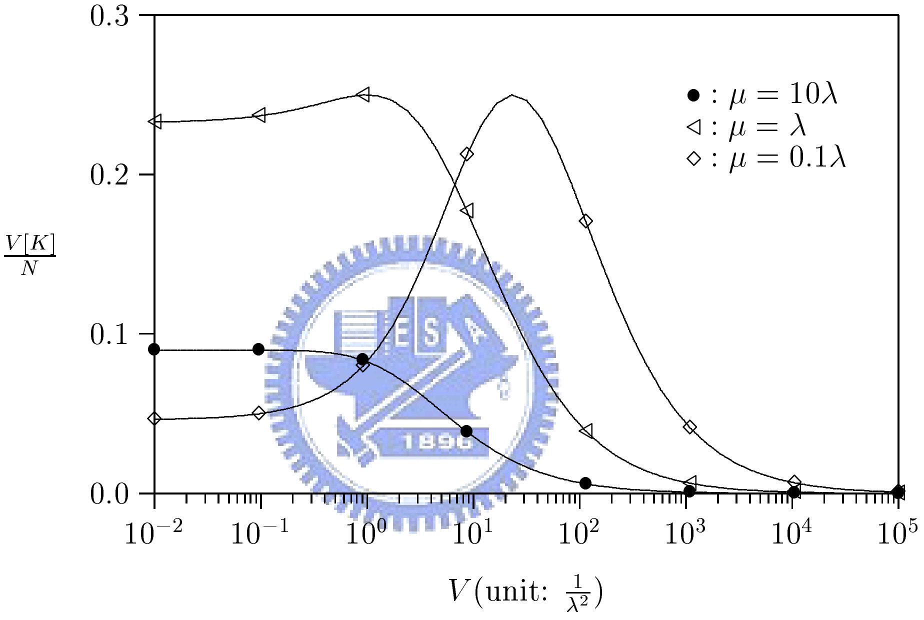

Figure 4.4: The Variance of the K Distribution

Chapter 5

Costs for Incoming Call Setup

This chapter investigates the incoming call setup costs. We first study the normal incoming call setup. Then we analyze the first incoming call setup after I-CSCF failure. We note that the checkpoint action is a background process, and the cost for retrieving the cache (e.g., Step 6 in Figure 3.3) and the cost for saving an S-CSCF record into the backup is negligible as compared with the communications cost between I-CSCF and HSS (the I-CSCF cache operation is typically 1000 times faster than the inter I-CSCF and HSS communications). Therefore we will ignore the I-CSCF cache operation costs in the incoming call setup study.

5.1 Normal Incoming Call Setup

Let t_H be the round-trip transmission delay between the I-CSCF and the HSS, t_S be the round-trip delay between the I-CSCF and the S-CSCF, and t_M be the round-trip delay between the S-CSCF and the UE. Let T_x be the incoming call setup delay from the I-CSCF to the UE (without QoS negotiation) for the "x" scheme (where $x \in \{B, C, C1, C2\}$).

Consider the B scheme. In Figure 3.2, t_H is the delay for Step 2; t_S is the delay for Steps 3 and 6; and t_M is the delay for Steps 4 and 5. We have

$$T_B = t_H + t_S + t_M$$

In Figure 3.4, t_S is the delay for Steps 3 and 6; and t_M is the delay for Steps 4 and 5. We have

$$T_C = T_{C1} = T_{C2} = t_S + t_M$$

Suppose that t_H, t_S, t_M have the same distribution with the density function $f_d(\cdot)$ and the mean $1/\delta$. It is clear that

$$E[T_C] = E[T_{C1}] = E[T_{C2}] = \frac{2E[T_B]}{3}$$

In other words, the cache/checkpoint schemes can save 33% of the incoming call setup overhead (between the I-CSCF and the UE). Furthermore, a timeout timer is typically maintained in the I-CSCF. For a call setup, if the I-CSCF does not receive the Offer Response message within a timeout period, the call is considered lost in the I-CSCF (i.e., the call is aborted). If the timeout period is set too short, then many normal incoming call setups may be misleadingly terminated due to timeouts. If the timeout threshold is set too long, then many incomplete call setups will not be detected early. Let θ_x be the timeout threshold for the "x" scheme (where $x \in \{B, C, C1, C2\}$), and

$$p_{\theta,x} = \Pr[T_x > \theta_x] \tag{5.1}$$

is the probability that a call setup is misleadingly aborted because its transmission delay is longer than the timeout period. Suppose that t_M, t_S and t_H have the same Gamma density function $f_d(\cdot)$ with the mean $1/\delta$. We utilize the simulation approach to compute $p_{\theta,x}$. Specifically, we repeatedly generate the sum of two gamma random numbers (for

T_C) and the sum of three gamma random numbers (for T_B). Then we derive $p_{\theta,B}$ and $p_{\theta,C}$ by using (5.1). Figure 5.1 compares $p_{\theta,B}$ with $p_{\theta,C}(= p_{\theta,C1} = p_{\theta,C2})$.

The figure shows the intuitive results that when the variance $V1$ of the transmission delay is small, the performance of the timeout mechanism is better (i.e., $p_{\theta,x}$ is small). The figure also indicates that to ensure the same $p_{\theta,x}$ values, the timeout period for the B scheme is much longer than the C (C1 and C2) schemes. For example, when $V1 = 100/\delta^2$, to ensure $p_{\theta,B} = p_{\theta,C} = 5.8\%$, $\theta_B = 9/\delta$ and $\theta_C = 3/\delta$ (i.e., the timeout threshold for the B scheme must be set three times as large as that for the C scheme).

5.2 First Incoming Call Setup after Failure

For the "x" scheme (where $x \in \{B, C, C1, C2\}$), let T_x^* be the round-trip transmission delay of the first incoming call setup after an I-CSCF failure. The delay T_x^* are derived as follows. For the B scheme, the first incoming call setup is not affected by the I-CSCF failure. That is,

$$T_B^* = T_B = t_H + t_S + t_M \tag{5.2}$$

For the C scheme, the cache in the I-CSCF is cleared after the failure. If the first event after the failure is an incoming call, then $T_C^* = T_B^*$. If the first event is a registration event, then the S-CSCF record is restored in the cache before the first incoming call arrives. When the incoming call arrives, $T_C^* = T_C$. Let α be the probability that the first event after I-CSCF failure is a registration. Then

$$T_C^* = \alpha T_C + (1-\alpha)T_B = T_C + (1-\alpha)t_H \tag{5.3}$$

The probability α is derived as follows. Consider the timing diagram in Figure 5.2. Suppose that an I-CSCF failure occurs at time t_2. For a UE, the first registration after

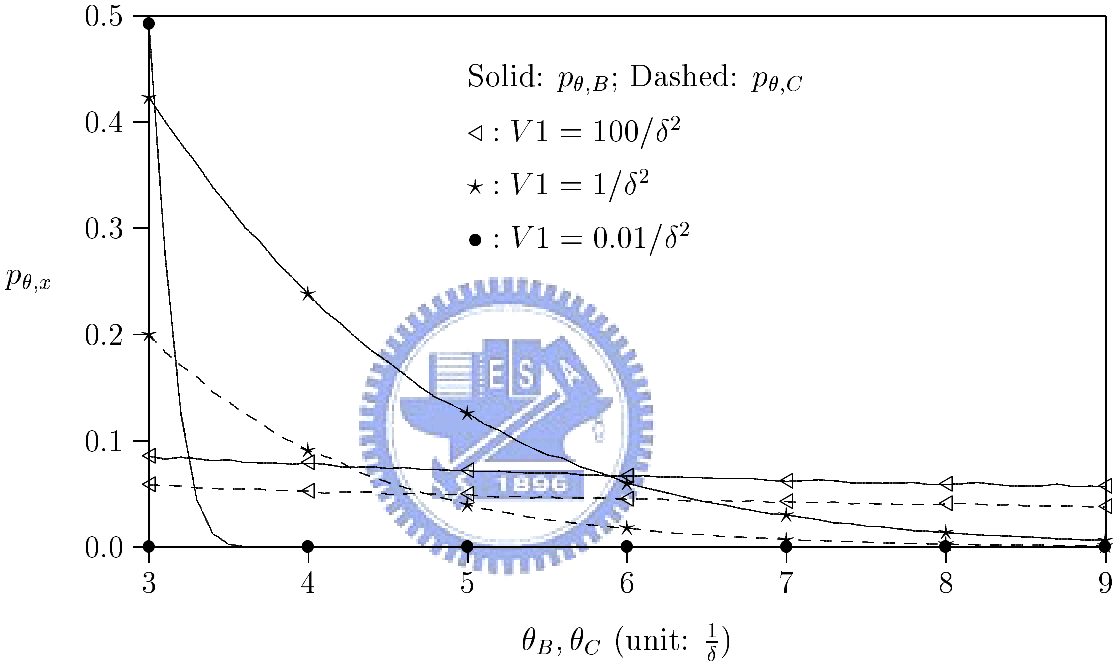

Figure 5.1: Comparing the Timeout Thresholds for the B and the C (C1 and C2) Schemes ($V1$: the variance of the Gamma Transmission Delay)

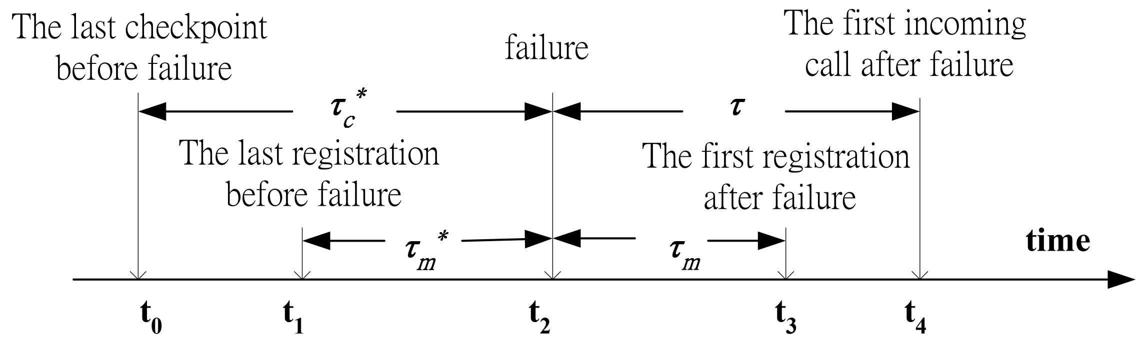

Figure 5.2: Timing Diagram Before and After an I-CSCF Failure

the failure occurs at t_3 and the first incoming call after the failure occurs at t_4. Let $\tau = t_4 - t_2$ and $\tau_m = t_3 - t_2$. Since the failure occurring time t_2 is a random observer of the inter-call arrival times and the inter-registration times, τ is the excess life of an inter-call arrival time. Also, τ_m is the excess life of an inter-registration time. Suppose that the call arrivals to the UE are a Poisson process with the rate γ. Then from the excess life theorem [19], τ has the exponential distribution with the mean $1/\gamma$. Similarly, τ_m has the density function $r(\cdot)$ and the Laplace transform $r^*(s)$ as expressed in (4.5). Therefore, similar to the derivation for (4.6),

$$\alpha = \Pr[\tau > \tau_m] = \left(\frac{\lambda}{\gamma}\right)\left[1 - f^*(\gamma)\right] \tag{5.4}$$

For the C1 scheme, two cases are considered when the first incoming call after the failure occurs.

Case I. The S-CSCF record restored from the backup is invalid (with probability β) and the first event after the failure is an incoming call (with probability $1-\alpha$). In this case (see Figure 3.5), $T^*_{C1} = T_B + t_S$.

Case II. The S-CSCF record restored from the backup is valid (with probability $1-\beta$), or the restored record is invalid (with probability β) and the first event after the failure is an IMS registration (with probability α). In this case, $T^*_{C1} = T_C$.

Based on the above two cases, we have

$$T^*_{C1} = T_C + (1-\alpha)\beta(t_H + t_S) \tag{5.5}$$

Probability β is derived as follows. In Figure 5.2, the last checkpoint before the I-CSCF failure occurs at time t_0. The last registration before the failure occurs at time t_1. From the reverse excess life theorem [19], $\tau^*_c = t_2 - t_0$ has the exponential distribution with the mean $1/\mu$, and $\tau^*_m = t_2 - t_1$ has the density function $r(\cdot)$ and the Laplace transform $r^*(s)$. Similarly to the derivation for (4.6),

$$\beta = \Pr[\tau^*_c > \tau^*_m] = \left(\frac{\lambda}{\mu}\right)\Big[1 - f^*(\mu)\Big] = p_u \tag{5.6}$$

For the C2 scheme (see the message flow in Figure 3.6), we have

$$T^*_{C2} = T_C + (1-\alpha)\beta t_H \tag{5.7}$$

If $f^*(s)$ is a Gamma Laplace transform as expressed in (4.7), then from (5.2), (5.3), (5.5), and (5.7), we have

$$\begin{aligned}
E[T^*_B] &= \frac{3}{\delta} \\
E[T^*_C] &= \frac{3}{\delta} - \left(\frac{\lambda}{\gamma\delta}\right)\left[1 - \left(\frac{1}{V\lambda\gamma+1}\right)^{\frac{1}{V\lambda^2}}\right] \\
E[T^*_{C1}] &= \frac{2}{\delta} + \left(\frac{2\lambda^2}{\mu\gamma\delta}\right)\left[1 - \left(\frac{1}{V\lambda\mu+1}\right)^{\frac{1}{V\lambda^2}}\right]\left[\frac{\gamma}{\lambda} - 1 + \left(\frac{1}{V\lambda\gamma+1}\right)^{\frac{1}{V\lambda^2}}\right] \\
E[T^*_{C2}] &= \frac{2}{\delta} + \left(\frac{\lambda^2}{\mu\gamma\delta}\right)\left[1 - \left(\frac{1}{V\lambda\mu+1}\right)^{\frac{1}{V\lambda^2}}\right]\left[\frac{\gamma}{\lambda} - 1 + \left(\frac{1}{V\lambda\gamma+1}\right)^{\frac{1}{V\lambda^2}}\right]
\end{aligned}$$

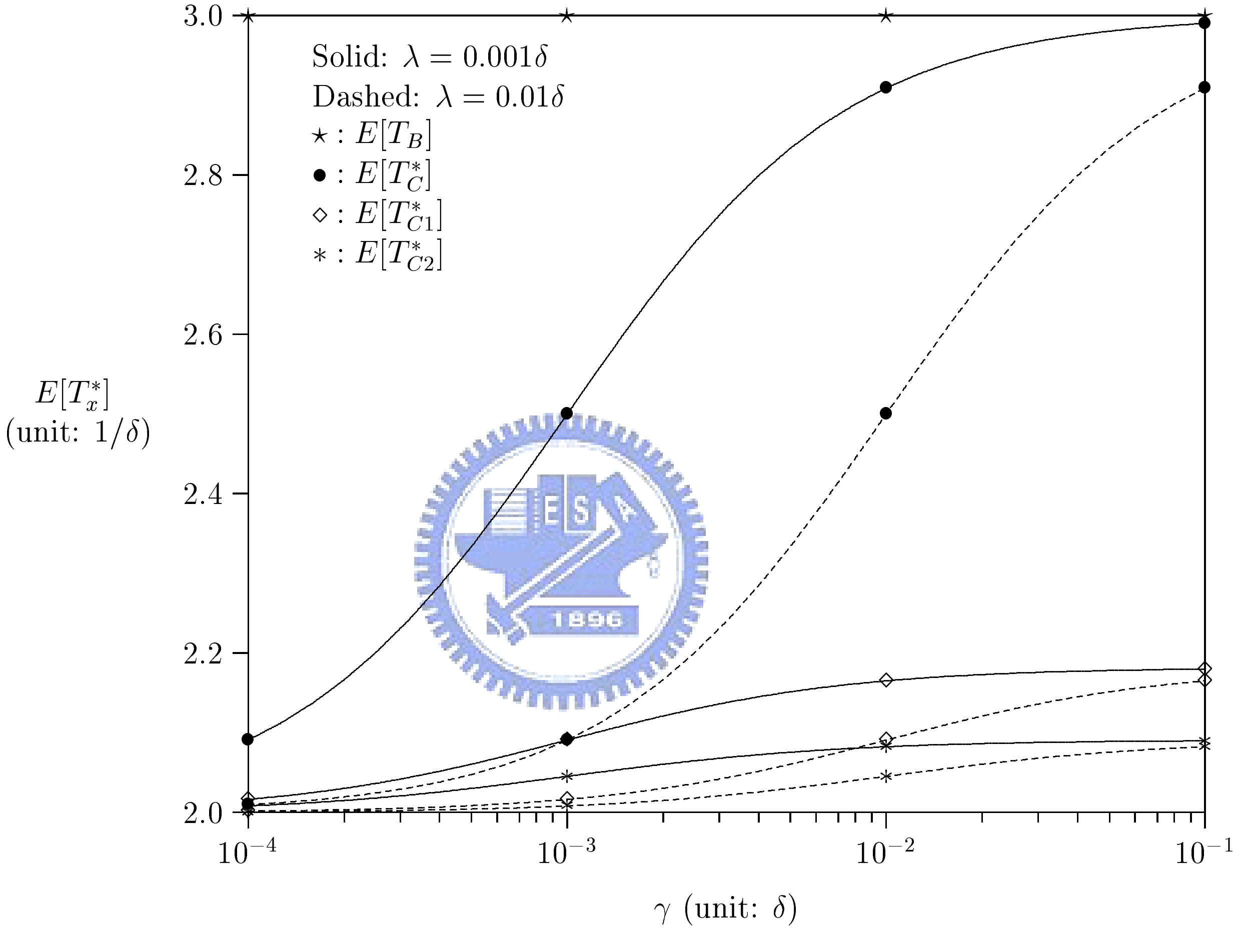

Figure 5.3: Transmission Delays for the First Incoming Call After an I-CSCF Failure ($\mu = 10\lambda$, $V = 1/\lambda^2$)

Figure 5.3 plots the $E[T_x^*]$ curves were $\mu = 10\lambda$ and $V = 1/\lambda^2$. Similar results are observed for different μ and V values, which will not be presented in this thesis. The figure indicates that for C, C1 and C2, $E[T_x^*]$ increases as γ (the incoming call arrival rate) increases. In this scenario, $E[T_{C1}^*]$ is limited to $2.2/\delta$ (less than 10% extra overhead for the normal incoming call setup of the C1 scheme), and $E[T_{C2}^*]$ is limited to $2.1/\delta$ (less than 5% extra overhead for the normal incoming call setup of the C2 scheme). For the C scheme, $E[T_C^*]$ approaches $E[T_B^*]$ as γ increases. The figure also indicates that as the registration rate λ increases, the call setup time decreases for C, C1, and C2. This phenomenon is due to the fact that α increases as λ increases, and it is more likely that the S-CSCF record is valid when the first incoming call arrives.

Chapter 6

Conclusions

The IMS network provides multimedia services for UMTS. This thesis investigated the performance of the IMS incoming call setup, and proposed cache schemes with fault tolerance to speed up the incoming call setup process. Our study indicated that by utilizing the I-CSCF cache, the average incoming call setup time can be effectively reduced, and smaller I-CSCF timeout threshold can be set to support early detection of incomplete call setups. To enhance fault tolerance, the I-CSCF cache is periodically checkpointed into a backup storage. When an I-CSCF failure occurs, the I-CSCF cache content can be restored from the backup storage. Since the checkpointing process is conducted in background, this activity does not affect the incoming call setup delays. As a final remark, if both the I-CSCF and the HSS fail, the S-CSCF records can only be recovered from the backup. In this case, our checkpoint schemes can significantly enhance the availability and fault tolerance of the IMS network.

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Appendix A

Simulation Codes

The simulation codes for Figure. 5.1 is listed in this appendix. The library of random number generator is proprietary and is not listed.

```
/*****************************************************************/
/* 2003/9/16 built by tsaimh@csie.nctu.edu.tw                    */
/*    p_{\theta , x} = Pr[ Tx > \theta_x]} , where x =  {B, C}   */
/* Description:                                                  */
/*    This program is used to compute p_{\theta, B} and          */
/*    p_{\theta, C} with Gamma transmission delay under          */
/*    different variances.                                       */
/*****************************************************************/

#include    <stdlib.h>
#include    "random_2.h"
#include    "random_tsaimh.h"

/* Assume t_H, t_S and t_M are all Gamma dist.                   */
Gamma t_H(1,1), t_S(1,1), t_M(1,1) ;
/* t_H: transmission delay between HSS and I-CSCF                */
/* t_S: transmission delay between I-CSCF and S-CSCF             */
/* t_M: transmission delay between UE and S-CSCF                 */

double r = 1 ;     /* mean = 1/r. We will not change the value   */
```

```
                   /* in this experiment.                        */
double T_B, T_C ;  /* T_B: total transmission time in B scheme   */
                   /* T_C: total transmission time in C scheme   */
                   /* (T_B = t_H + t_S + t_M, T_C = t_S + t_M)   */
long i, j ;
double theta_B, theta_C ;
/* theta_B: timeout threshold of B scheme   */
/* theta_C: timeout threshold of C scheme   */

long TotalNumTest, CurNumTest, NumDrop ;
/* TotalNumTest: total no. of tests to be performed              */
/* CurNumTest: current no. of tests                              */
/* NumDrop: no. of dropped call                                  */
/*    => p_{\theta, x} = NumDrop / TotalNumTest                  */

/***************************************************************/
/* compute_p_theta_b() is used to compute p_{\theta,B}.          */
/***************************************************************/
void compute_p_theta_b()
{
     /* print information about input parameter                  */
     printf("** T_B ** Var = %f , Total no. of tests = %d\n",
                t_H.GetVar(), TotalNumTest) ;

     /* compute p_{\theta, B} when timeout threshold "theta_B"   */
     /* is between 3/r and 9/r                                   */
     for(theta_B = 3/r; theta_B < 9.1/r; theta_B += 0.1/r)
     {
        NumDrop = 0 ;
        for (CurNumTest=0;CurNumTest < TotalNumTest; CurNumTest++)
        {
            T_B = t_H++ + t_S++ + t_M++ ;   /* get T_B           */

            /* If T_B is larger than timeout threshold, the call */
            /* is dropped.                                       */
            if(T_B > (theta_B))
                NumDrop++ ;
```

```
        }
        /* print (theta_B, p_{\theta,B}) pairs for plotting      */
        printf("%f\t%f\n", theta_B,
                ((double)NumDrop)/TotalNumTest) ;
    }
    return ;
}

/*****************************************************************/
/* compute_p_theta_c() is used to compute p_{\theta,C}.          */
/*****************************************************************/
void compute_p_theta_c()
{
    /* print information about input parameter                   */
    printf("** T_C ** Var = %f , Total no. of tests = %d\n",
                t_H.GetVar(), TotalNumTest) ;

    /* compute p_{\theta, C} when timeout threshold "theta_C"    */
    /* is between 3/r and 9/r                                    */
    for(theta_C = 3/r; theta_C < 9.1/r; theta_C += 0.1/r)
    {
        NumDrop = 0 ;
        for (CurNumTest=0;CurNumTest < TotalNumTest; CurNumTest++)
        {
            T_C = t_S++ + t_M++ ;   /* get T_C                   */

            /* If T_C is larger than timeout threshold, the call */
            /* is dropped.                                       */
            if(T_C > (theta_C))
                NumDrop++ ;
        }
        /* print (theta_C, p_{\theta,C}) pairs for plotting      */
        printf("%f\t%f\n", theta_C,
                ((double)NumDrop)/TotalNumTest) ;
    }
    return ;
}
```

```

/******************************************************************/
/* main function:                                                 */
/******************************************************************/
int main(int argc,char* argv[])
{
    if (argc != 2)
    {
       printf("\nUsage : %s <total no. of tests>\n", argv[0]);
       return -1 ;
    }

    /* Get "total no. of tests" from command line                  */
    TotalNumTest = atol(argv[1]);

    /* Set the means of t_H, t_S and t_M to 1/r, which are not    */
    /* changed in this experiment.                                */
    t_H.SetMean(1/r);
    t_S.SetMean(1/r);
    t_M.SetMean(1/r);

    /* ********************************************************** */
    /* Variance = 100/r^2, compute p_{\theta,x}                   */
    /* ********************************************************** */
    t_H.SetVar(100/(r*r));
    t_S.SetVar(100/(r*r));
    t_M.SetVar(100/(r*r));

    compute_p_theta_b();
    compute_p_theta_c();

    /* ********************************************************** */
    /* Variance = 1/r^2, compute p_{\theta,x}                     */
    /* ********************************************************** */
    t_H.SetVar(1/(r*r));
    t_S.SetVar(1/(r*r));
    t_M.SetVar(1/(r*r));
```

```

    compute_p_theta_b();
    compute_p_theta_c();

    /* ********************************************************** */
    /* Variance = 0.01/r^2, compute p_{\theta,x}                  */
    /* ********************************************************** */
    t_H.SetVar(0.01/(r*r));
    t_S.SetVar(0.01/(r*r));
    t_M.SetVar(0.01/(r*r));

    compute_p_theta_b();
    compute_p_theta_c();

    return 0 ;
}
```

Appendix B

Effects of the Distributions for Transmission Delay

In Chapter 5, we present the results for Gamma transmission delay distribution. In this appendix, we provide the results for transmission delays with Normal and Pareto distributions.

Figure B.1-B.6 show the effects of the three different distributions (including Gamma, Normal, and Pareto) on $p_{\theta,x}$ under the same input parameters. These three distributions have similar shape with small variance (i.e. $V1 = 1/\delta^2$ and $V1 = 0.01/\delta^2$). When the variance is large, Normal distribution has much larger $p_{\theta,x}$ than Gamma and Pareto distributions, which implies worse performance.

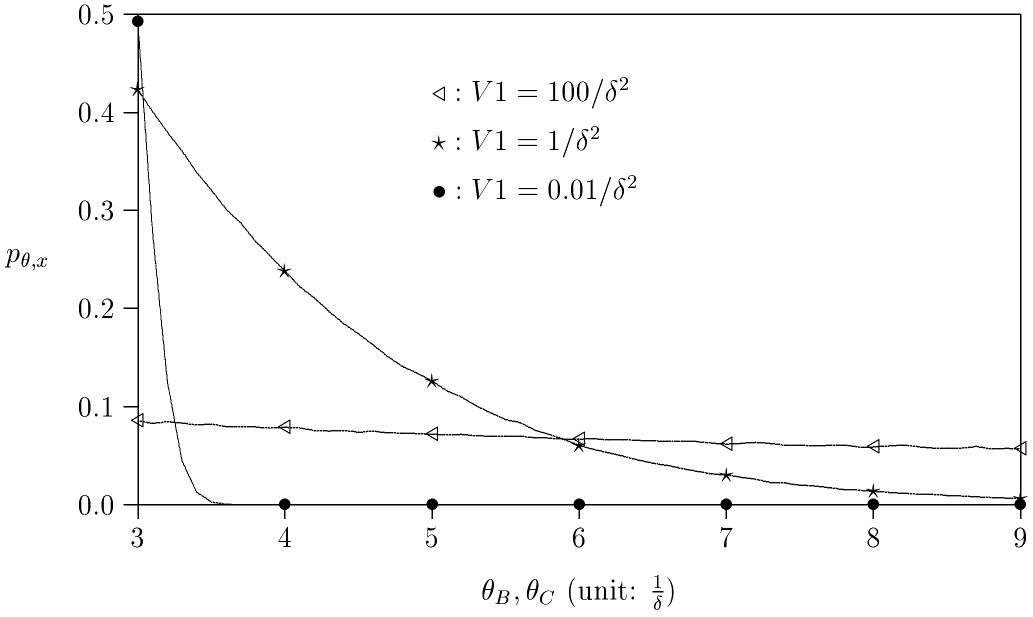

Figure B.1: Effects of Timeout Thresholds for B Scheme with Gamma Transmission Delay

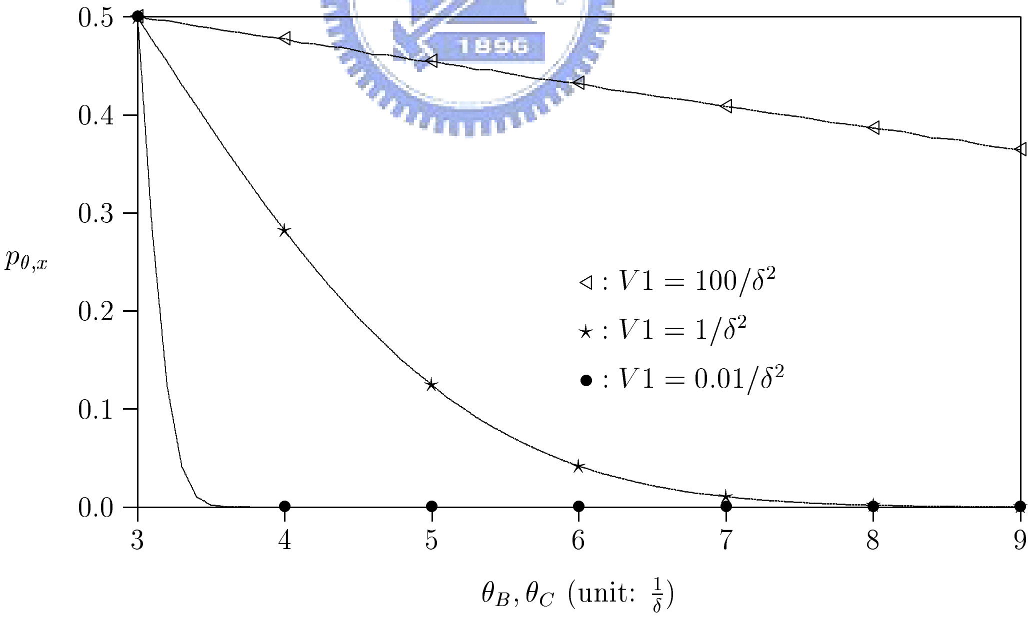

Figure B.2: Effects of Timeout Thresholds for B Scheme with Normal Transmission Delay

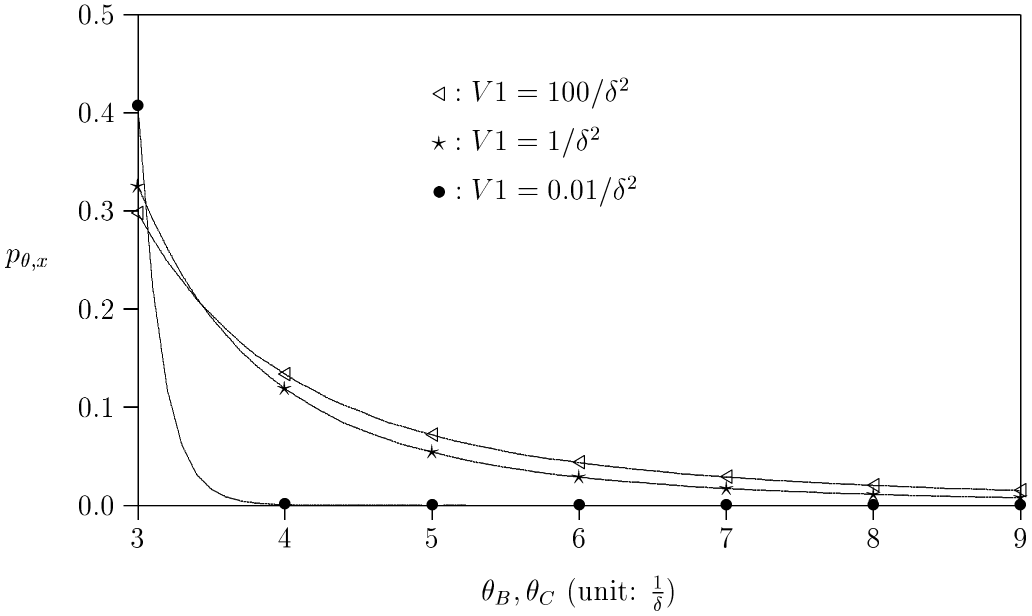

Figure B.3: Effects of Timeout Thresholds for B Scheme with Pareto Transmission Delay

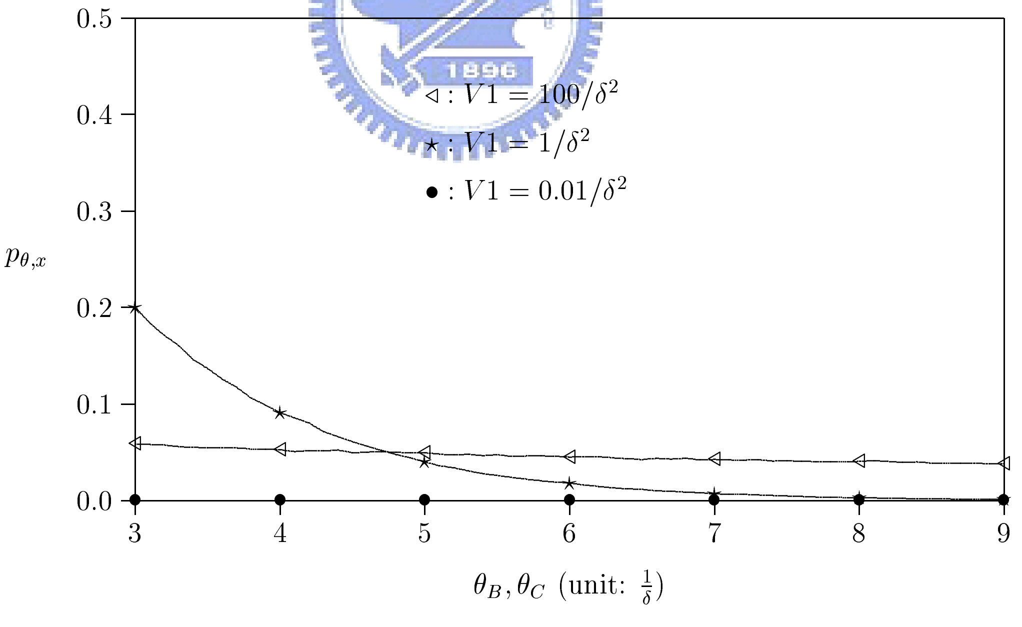

Figure B.4: Effects of Timeout Thresholds for C (C1 and C2) Scheme with Gamma Transmission Delay

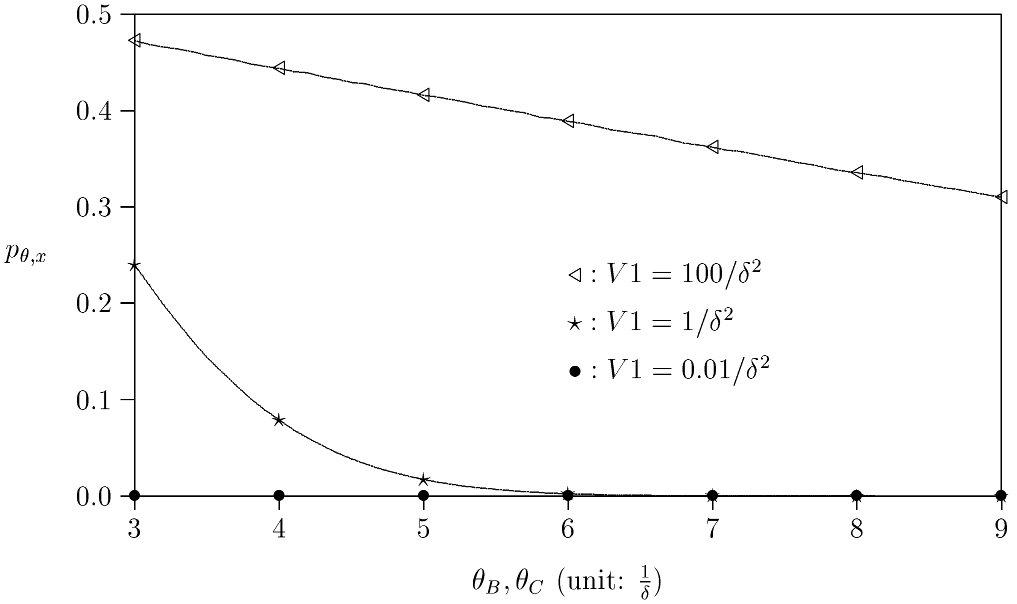

Figure B.5: Effects of Timeout Thresholds for C (C1 and C2) Scheme with Normal Transmission Delay

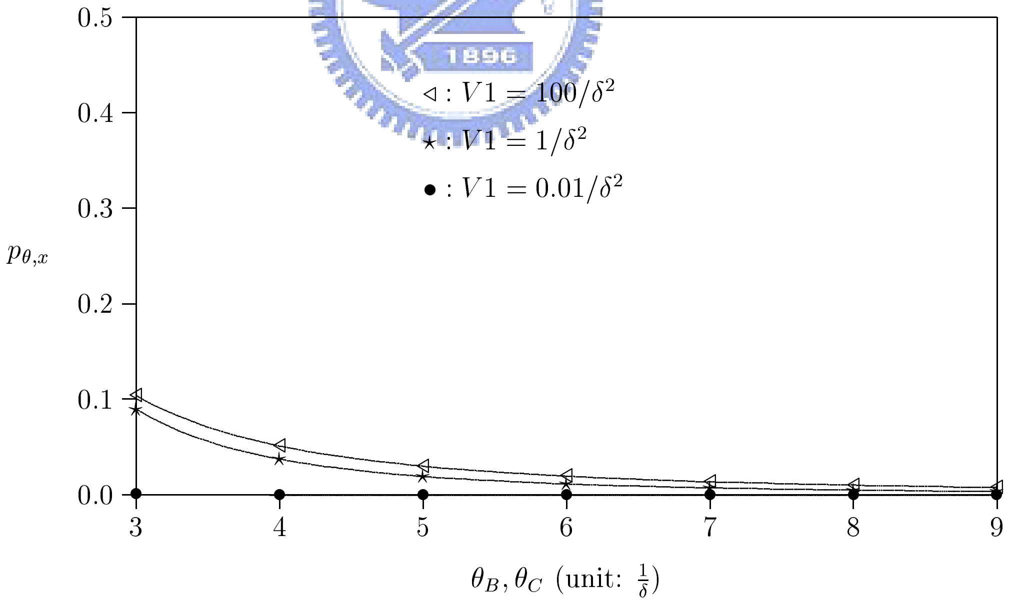

Figure B.6: Effects of Timeout Thresholds for C (C1 and C2) Scheme with Pareto Transmission Delay