國立交通大學

網路工程研究所

碩士論文

長期演進技術之電路交換回退效能研究

Performance of CS Fallback for Long Term Evolution Mobile Network

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摘　　要

當電信營運商將原有的第三代行動通訊網路 (3rd Generation；3G) 升級至長期演進技術 (Long Term Evolution；LTE) 時，LTE 網路和 3G 網路會共存一段時間。因為 3G 的語音通話服務比 LTE 的網路電話語音服務 (Voice over IP；VoIP) 還要成熟而且覆蓋範圍較大，在 LTE 佈建初期，營運商可能考慮使用電路交換回退 (Circuit-Switched fallback；CS fallback) 的技術，來提供 LTE 系統的語音通話服務。根據第三代合作夥伴計劃 (3rd Generation Partnership Project；3GPP) 的電路交換回退流程，當使用者設備 (User Equipment) 在 LTE 網路需要使用語音通話服務時，使用者設備會從 LTE 網路回退到 3G 網路。當通話結束後，使用者設備會立刻回到 LTE 網路。如果接下來要進行另一通語音電話，使用者設備與網路端必須再執行一次電路交換回退，造成通話建立效率不佳。為了解決這個問題，我們提出延遲返回 (Delayed-Return) 的方法，此方法延遲使用者設備從 3G 返回到 LTE 以避免不必要的電路交換回退流程。我們提出了數學分析來探討延遲返回的效能。本論文後續研究亦探討 CS fallback 以導入軟體定義網路 (Software-Defined Networking; SDN) 實做的 3G、LTE 架構和 CS fallback 流程供後續研究。研究結果指出，根據實際 3G 和 LTE 網路的測量數據，延遲返回的方法可以減少高達 60% 的電路交換回退成本。

關鍵字: 電路交換回退，延遲返回，長期演進技術，軟體定義網路

Performance of CS Fallback for Long Term Evolution Mobile Network

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ABSTRACT

When a mobile operator migrates its network from the *3rd Generation* (3G) system to *Long Term Evolution* (LTE), both 3G and LTE will co-exist for a period of time. Since the 3G *Circuit-Switched* (CS) voice mechanism is more mature and available than that for LTE *Voice over Internet Protocol* (VoIP), the operator may consider CS fallback as a solution to provide reliable voice calls. According to the *3rd Generation Partnership Project* (3GPP) CS fallback procedure, when a mobile user in the LTE network has an incoming or an outgoing call, the *User Equipment* (UE) falls back from LTE to *Universal Mobile Telecommunications System* (UMTS). When the call is complete and released, the UE immediately returns to LTE. If the next activity for the UE is another voice call, immediately switching from UMTS to LTE may not be efficient. In this case, the UE has to perform another CS fallback. To resolve this issue, we suggest delaying the returns to avoid unnecessary CS fallbacks, which is called *delayed-return* (DR). Based on the measurements from the real UMTS and LTE networks, we develop analytic model to investigate the performance of the CS fallback with DR. We also present the *Software-Defined Networking* (SDN) implementation for CS fallback for further studying. The study indicates that the DR scheme can effectively reduce the CS fallback costs up to 60%.

Keywords: CS fallback, delayed-return scheme (DR), long term evolution (LTE), Software-Defined Networking (SDN)

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Notation

The notation used in this thesis is listed below.

- p: the probability that when a voice call arrives, the UE can be connected at UMTS without CS fallback due to DR
- p_1: the probability that no data session is in progress when the previous call is released
- p_2: the probability that no data session arrives before the next voice call arrives
- α: the performance improvement of the DR scheme over the IR scheme
- t_c: the call holding time
- t_a: the inter-call arrival time
- t_s: the session holding time
- t_p: the inter-session arrival time
- t_f: the time that the UE falls back from LTE to UMTS
- t_d: the UMTS outgoing call setup delay without the CS fallback
- τ_p: the residual life of t_p
- $1/\mu = E[t_s]$: the mean session holding time
- λ: the rate parameter of the t_a distribution
- γ: the rate parameter of the t_p distribution
- k: the shape parameter of the t_a distribution

- m: the shape parameter of the t_p distribution
- $f_a(\cdot)$: the density function for the t_a distribution
- $f_p(\cdot)$: the density function for the t_p distribution
- $r_p(\cdot)$: the density function for the τ_p distribution
- $F_a(\cdot)$: the distribution function for the t_a distribution
- $R_p(\cdot)$: the distribution function for the τ_p distribution
- V_a: the variance for the t_a distribution
- V_p: the variance for the t_p distribution
- $f_a^*(s)$: the Laplace transform for the t_a distribution
- $f_p^*(s)$: the Laplace transform for the t_p distribution
- $r_p^*(s)$: the Laplace transform for the τ_p distribution

Chapter 1

Introduction

The *3rd Generation Partnership Project* (3GPP) *Long Term Evolution* (LTE) [1] defines an all IP network architecture that evolves from the *Universal Mobile Telecommunications System* (UMTS) [2] to provide high-speed data services. When a mobile operator migrates its network from the *3rd Generation* (3G) system to LTE, both 3G and LTE will co-exist for a period of time, and initially, the 3G coverage is more complete than the LTE coverage. Since LTE is a *Packet-Switched* (PS) network, the *Circuit-Switched* (CS) voice service [3] is not supported as 3G does. Therefore the LTE voice service is offered through the *Voice over Internet Protocol* (VoIP) technology. Since the 3G CS voice mechanism is more mature and available than that for LTE VoIP, in the deployment of LTE, many operators consider CS fallback [4] as the solution to provide reliable voice calls. The CS fallback technique switches the *User Equipment* (UE; the mobile phone) from the LTE network to the 3G legacy system when a voice call is attempted. In order to use the CS domain in the UMTS system when the UE resides in LTE, the LTE network needs to register the UE with both the LTE and the UMTS CS domain and delivers the CS paging message from UMTS to the UE.

Figure 1.1 illustrates a simplified architecture of UMTS and *Evolved Packet System* (EPS) for LTE. This architecture includes two parts: the UMTS network and the LTE network. A UE (Figure 1.1 (1)) accesses UMTS and LTE services through the radio interfaces. In the UMTS network (Figure 1.1 (a)), the *UMTS Terrestrial Radio Access Network* (UTRAN) consists of NodeBs (Figure 1.1 (2)) and *Radio Network Controllers* (RNCs; Figure 1.1 (3)). A NodeB provides *Wideband Code Division Multiple Access* (WCDMA) radio connectivity between the UE and the corresponding RNC. The RNC connects to the UMTS core network. This core net-

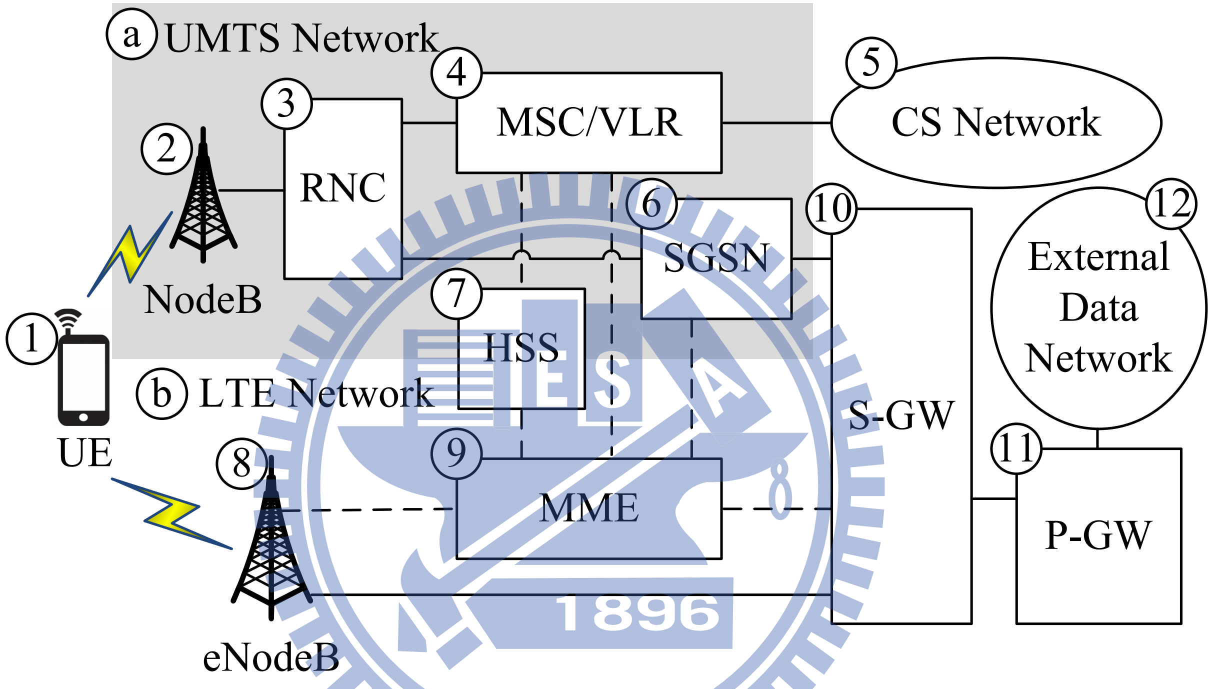


Figure 1.1: The EPS and UMTS Architecture for CS Fallback (dashed lines: signaling; solid lines: signaling/data)

work is partitioned into the CS and the PS domains. The CS domain includes *Mobile Switching Centers* (MSCs) and *Visitor Location Registers* (VLRs; Figure 1.1 (4)). An MSC is responsible for call control and connection between the UE and the external CS Network (Figure 1.1 (5)). A VLR is responsible for the mobility activities of the MSC. The PS domain consists of *Serving GPRS Support Nodes* (SGSNs; Figure 1.1 (6)) which provide the mobility and session services to the UEs. The *Home Subscriber Server* (HSS; Figure 1.1 (7)) is the master database containing all user-related subscription information, which supports mobility management of mobile users. In the LTE network (Figure 1.1 (b)), the *Evolved UMTS Terrestrial Radio Access Network* (E-UTRAN) consists of *evolved NodeBs* (eNodeBs; Figure 1.1 (8)) to offer LTE radio connectivity to the UE. The E-UTRAN connects to the LTE core network that includes the following components. A *Mobility Management Entity* (MME; Figure 1.1 (9)) interacts with the HSS to offer mobility management and session control. The *Serving Gateway* (S-GW; Figure 1.1 (10)) is responsible for routing data packets and is an anchor of the user plane data for intra- and inter-system handovers. The *Packet Data Network Gateway* (P-GW; Figure 1.1 (11)) provides the connectivity to the External Data Network (Figure 1.1 (12)) and the per-user based packet filtering. In the UMTS PS domain, the SGSNs connect to the External Data Network through the S-GW and the P-GW. According to the 3GPP CS fallback procedure [4], when a mobile user in the LTE network has an incoming or an outgoing call, the UE falls back from LTE to UMTS. When the call is complete and released, the UE immediately returns to LTE. If the next activity for the UE is another voice call, immediately switching from UMTS to LTE may not be efficient. In this case, the UE has to perform another CS fallback. To resolve this issue, we suggest delaying the returns to avoid unnecessary CS fallbacks.

This thesis is organized as follows. Chapter 2 describes the CS fallback procedures, the existing *Immediate-Return* (IR) scheme and the proposed *Delayed-Return* (DR) scheme for returning to LTE. Chapter 3 proposes an analytic model for the IR and the DR schemes. Chapter 4 studies the performance of IR and DR by numerical examples. Chapter 5 presents the *Software-Defined Networking* (SDN) implementation for CS fallback, and conclusions are given in Chapter 6.

Chapter 2

Network Architecture and Message Flow

This chapter describes the CS fallback procedures defined in the 3GPP, including call setup and call release with IR. We also report the measured processing times for the procedures collected in live 3G and LTE networks in [5, 6, 7]. Then we introduce the DR scheme, including call release and data session setup.

2.1 LTE Call Setup with CS Fallback

Figure 2.1 illustrates the CS fallback message flow when a UE makes a call in the LTE network. The following steps are executed:

Step 1. The UE sends the Extended Service Request message to the MME to initiate the CS fallback procedure.

Steps 2 and 3. The MME exchanges the UE Context Modification Request and Response message pair with the eNodeB to indicate that the UE should fall back to the UTRAN. Note that Steps 1-3 take about 0.3 seconds [5].

Step 4. The eNodeB sends the UE the *Radio Resource Control* (RRC) Connection Release with Redirection to UTRAN message to indicate that it may follow the cell identity and System Information to attach to the corresponding UTRAN cell.

Steps 5-9. Parallel to Step 4, the eNodeB sends the UE Context Release Request message to the MME to release the bearers between the eNodeB and the S-GW. Steps 4-9 take about 0.2 seconds [5].

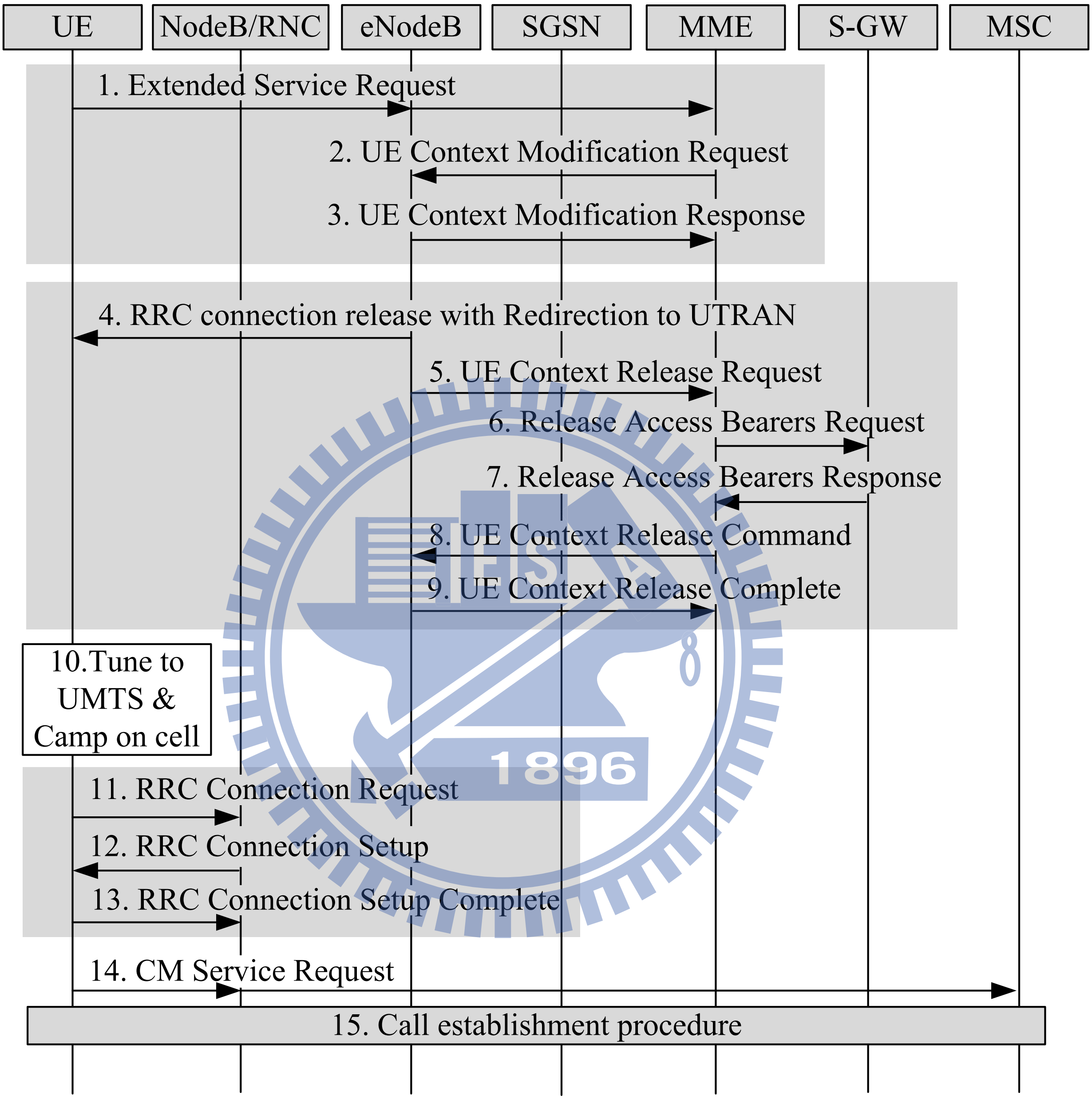


Figure 2.1: Call Setup with CS Fallback

Step 10. After Step 4, the UE tunes the radio to UMTS, and camps on the NodeB according to the System Information in the RRC Connection Release with Redirection to UTRAN message. Step 10 takes about 2.3 seconds for 3GPP R8 and 0.3 seconds for 3GPP R9 [5].

Steps 11-13. The UE exchanges with the NodeB the RRC Connection Request and Setup message pair to establish the radio connection. Then the UE sends the NodeB the RRC Connection Setup Complete message to acknowledge the RRC connection establishment. Steps 11-13 take about 0.3 seconds [5].

Steps 14 and 15. The UE sends the *Call Management* (CM) Service Request message to initiate the CS call establishment procedure. The UE includes the *Circuit-Switched Mobile Originated* (CSMO) flag to indicate that it is a CS fallback call. The CS call establishment at Step 15 follows the 3GPP standard, and the details can be found in [8]. Steps 14 and 15 take about 3.5 seconds [5].

Note that if the UE in LTE is engaged in a data session when a call arrives, then the PS connection (for the data session) is also switched to UMTS in the call setup of the CS fallback procedure. Details of PS connection switching can be found in [1].

2.2 Call Release with Immediate-Return

Figure 2.2 illustrates the call release procedure with *Immediate-Return* (IR). After a voice call is released, if no UMTS data session is in progress, the UTRAN moves the UE to the LTE network immediately with the following steps:

Step 1. The standard 3GPP call release procedure is executed [8].

Steps 2-5. The MSC sends the UTRAN the Iu Release Command message to release the bearer between the MSC and the RNC. This message contains the *End of CS Fallback* (CSFB) flag to indicate that the call which was released is a CS fallback call. Then the NodeB sends the UE the Radio Bearer Release message to release the radio bearer between the NodeB and the UE.

Steps 6-8. According to the End of CSFB flag, the NodeB knows that the UE is LTE capable. The NodeB sends the UE the RRC Connection Release with Redirection Info message to

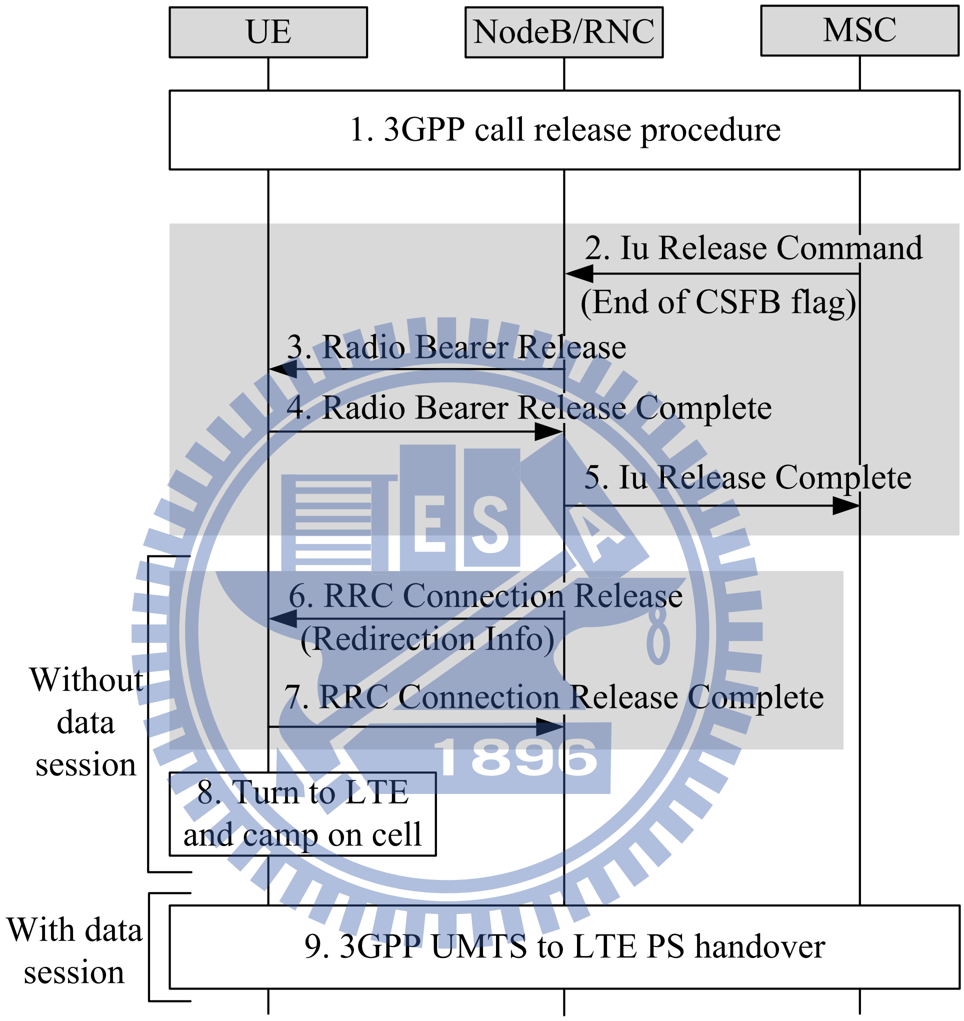


Figure 2.2: Call Release with IR

release the radio connection between the NodeB and the UE. Then the UE switches to the LTE network according the redirection information in the message.

If the UE is engaged in a data session when the voice call is released, then Steps 6-8 are replaced by the standard 3GPP UMTS to LTE PS handover (Step 9) [1], and the data session is moved to the LTE network.

2.3 Call Release with Delayed-Return

When a voice call is released, if the UE is engaged in a data session, then it is switched back to LTE as shown in Figure 2.2 (Steps 1-5 and 9). If the UE is not engaged in a data session, then it does not need to return to LTE immediately. Figure 2.3 illustrates the call release procedure with *Delayed-Return* (DR). The UE releases the radio connection and stays in UMTS in the idle mode.

Steps 1-5 of the message flow in Figure 2.3 is the same as the call release procedure with IR. At Step 6, the NodeB sends the RRC Connection Release without Redirection Info message. Because this message does not contain the optional Redirection Info, the UE will not switch to LTE. This message instructs the UE to release the RRC connection, stay in UMTS, and change its status to the idle mode. Compared with the CS fallback with IR, Steps 8 and 9 in Figure 2.2 are saved in the CS fallback with DR.

2.4 Data Session Setup in UMTS with Delayed-Return

Suppose that DR is applied, and the UE does not return to LTE after a voice call (i.e., there is no data session in progress when the voice call is released). If the next event to the UE is a data session arrival, then it will receive the PS paging message from the UMTS NodeB. The UE is switched to LTE to establish the PS connection. The detailed steps are described as follows (see Figure 2.4):

Step 1. The UE executes the 3GPP Inter-*Radio Access Technology* (RAT) cell reselection procedure from UTRAN [9] to perform the measurement process, and then selects a LTE cell.

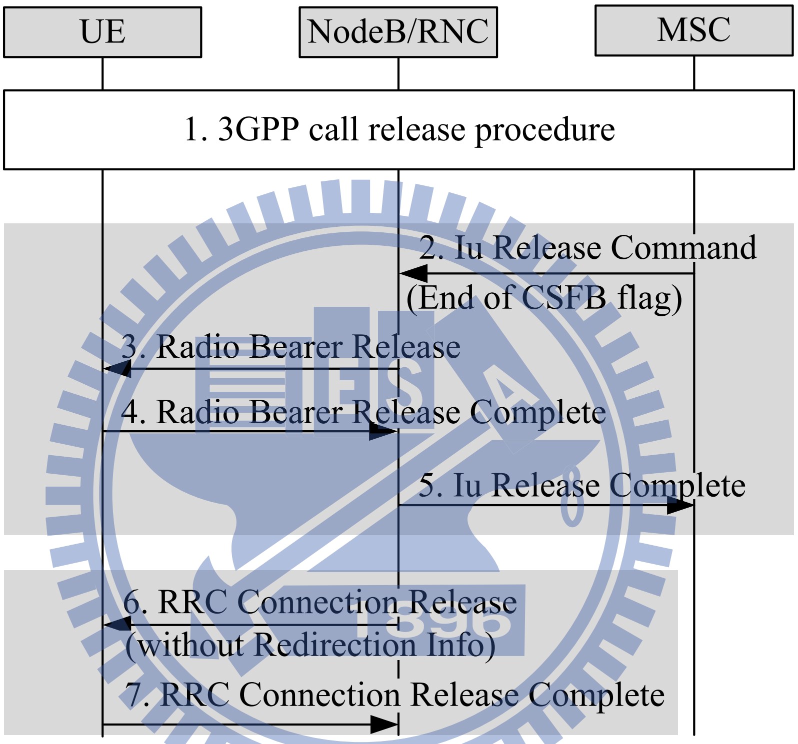


Figure 2.3: Call Release with DR

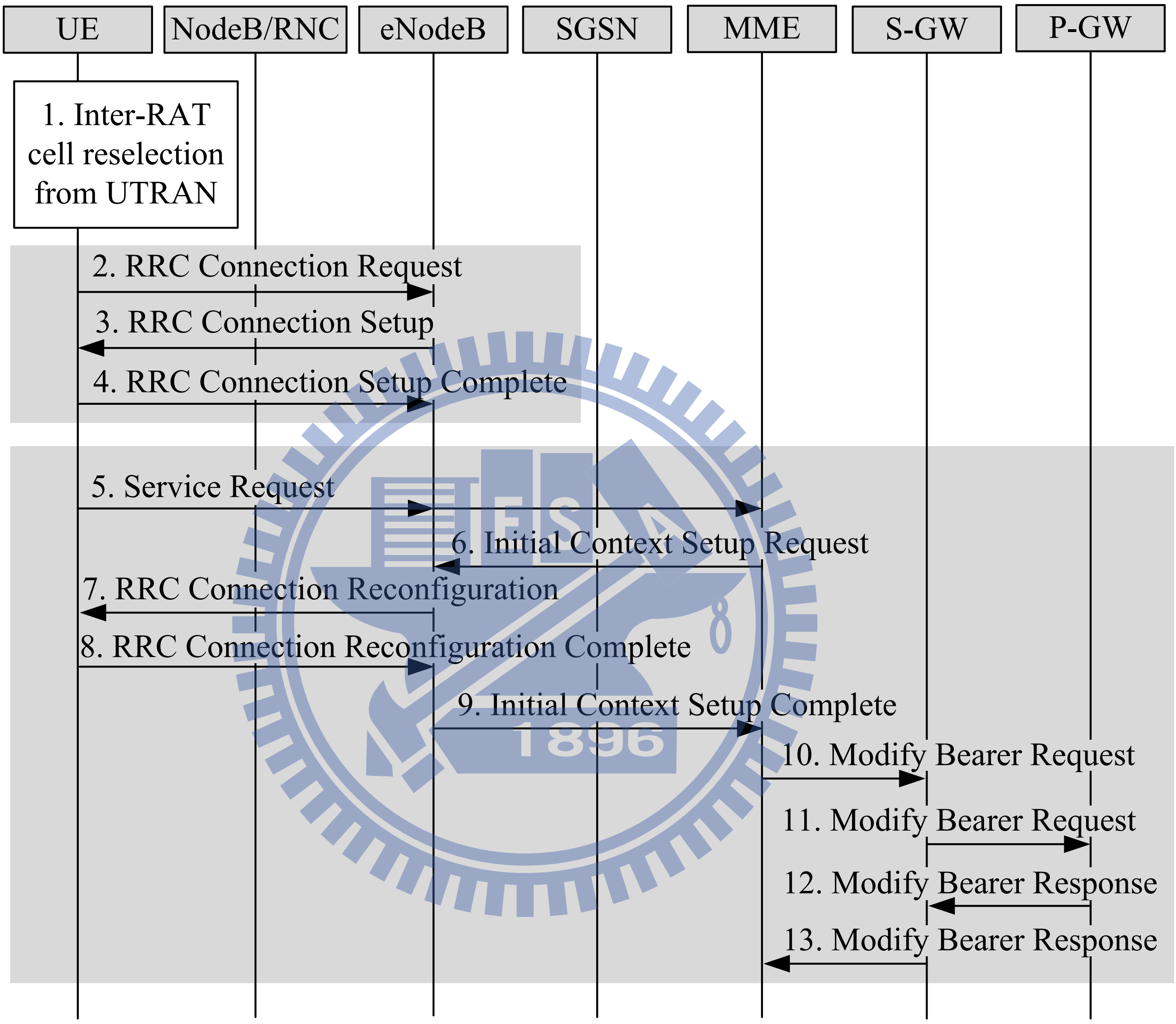


Figure 2.4: Date Session Setup in UMTS with DR

Steps 2-4. The UE exchanges with the eNodeB the RRC Connection Request and Setup message pair to establish the radio connection. Then the UE sends the eNodeB the RRC Connection Setup Complete message to acknowledge the RRC connection establishment procedure.

Step 5. The UE sends the MME the Service Request message to initial the establishment of the bearer for the PS connection.

Steps 6-9. The MME exchanges with the eNodeB the Initial Context Setup Request and Complete message to establish the radio bearer between the UE and the eNodeB. The Request message also contains the bearer information between the eNodeB and the S-GW. The eNodeB sends the UE the RRC Connection Reconfiguration message to modify the bearer information of the radio connection. Then the UE sends the eNodeB the RRC Connection Reconfiguration Complete message to acknowledge the radio bearer reconfiguration.

Steps 10-13. The MME sends the S-GW the Modify Bearer Request message to establish the bearer between the eNodeB and the S-GW and the bearer between the S-GW and P-GW.

We note that for data session setup, the CS fallback with DR does not incur extra overhead over IR from the network viewpoint. Specifically, Steps 10-13 in Figure 2.1 are executed by IR, which are the same as Steps 1-4 in Figure 2.4. IR also executes Steps 5-13 in Figure 2.4 when a data session arrives.

Chapter 3

Analytic Modeling

This chapter proposes an analytic model to study the performance improvement of the DR scheme over the IR scheme. Specifically, we derive the probability p that when a voice call arrives, the UE can be connected at UMTS without CS fallback due to DR. Figure 3.1 illustrates a timing diagram for voice call arrivals (at t_2 and t_5) and data session arrivals (at t_1 and t_6). Let $t_c = t_4 - t_2$ (also $t_7 - t_5$) be a voice call holding time. Let the inter-call arrival time $t_a = t_5 - t_4$ be a random variable with the density function $f_a(\cdot)$, the distribution function $F_a(\cdot)$, the variance V_a and the Laplace transform $f_a^*(s)$. Let the session holding time $t_s = t_3 - t_1$ (also $t_8 - t_6$) be a random variable with the mean $1/\mu$, and the inter-session arrival time $t_p = t_6 - t_3$ be a random variable with the density function $f_p(\cdot)$, the variance V_p and the Laplace transform $f_p^*(s)$. Suppose that the call release event at t_4 is a random observer of the period $[t_3, t_6]$. From the residual life theorem [10], the interval $\tau_p = t_6 - t_4$ is the residual life of t_p with the density function $r_p(\cdot)$, the distribution function $R_p(\cdot)$, and the Laplace transform $r_p^*(s)$. We define an *observation interval* as a period between when the previous call arrives and when the next call arrives (e.g., the interval $[t_2, t_5]$ in Figure 3.1). It is clear that the probability p described at the beginning of this chapter is the probability that no data session is in progress when the previous call is released (with probability p_1) and no data session arrives before the next voice call arrives (with probability p_2).

The sequence of t_s and t_p forms an alternating renewal process [11], and therefore $p_1 = \frac{E[t_p]}{E[t_p]+E[t_s]}$. Since a call release event is a random observer of t_s and t_p, p_2 can be expressed as $\Pr[t_a < \tau_p]$. According to the above description, we have

$$p = p_1 p_2 = \left(\frac{E[t_p]}{E[t_p] + E[t_s]} \right) \Pr[t_a < \tau_p] \tag{3.1}$$

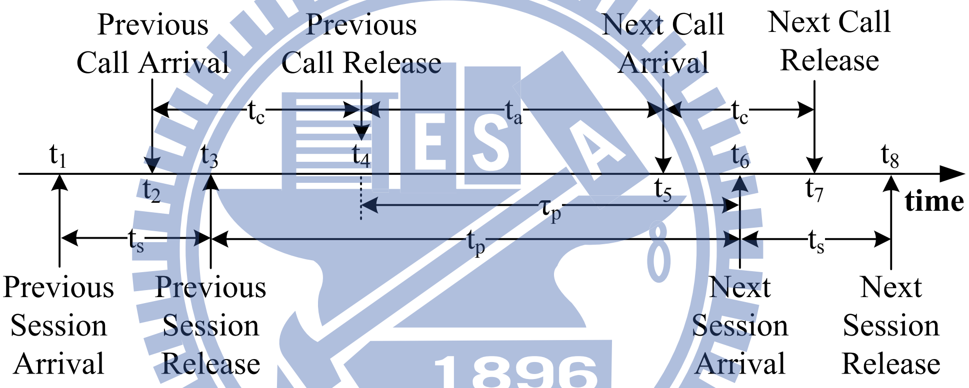


Figure 3.1: Timing Diagram for Voice Call and Data Session Arrivals

Based on the inverse Laplace transform formula and the residue theorem [12, 13], $\Pr[t_a < \tau_p]$ in (3.1) is derived as

$$
\begin{aligned}
\Pr[t_a < \tau_p] &= \int_{\tau_p=0}^{\infty} r_p(\tau_p) \int_{t_a=0}^{\tau_p} f_a(t_a) dt_a d\tau_p \\
&= \int_{\tau_p=0}^{\infty} r_p(\tau_p) F_a(\tau_p) d\tau_p \\
&= \left(\frac{1}{2\pi i}\right) \int_{\sigma-i\infty}^{\sigma+i\infty} \int_{\tau_p=0}^{\infty} r_p(\tau_p) e^{s\tau_p} \left[\frac{f_a^*(s)}{s}\right] d\tau_p ds \\
&= \left(\frac{1}{2\pi i}\right) \int_{\sigma-i\infty}^{\sigma+i\infty} r_p^*(-s) \left[\frac{f_a^*(s)}{s}\right] ds \\
&= -\sum_{z\in\sigma_p} Res_{s=z} r_p^*(-s) \left[\frac{f_a^*(s)}{s}\right] \qquad (3.2)
\end{aligned}
$$

where $i = \sqrt{-1}$, σ is a sufficiently small positive number, σ_p is the set of poles of $r_p^*(-s)$ in the right half of the complex plane, and $Res_{s=z}$ denotes the residue at the pole $s = z$. Alternatively, $\Pr[t_a < \tau_p]$ can also be derived as

$$
\begin{aligned}
\Pr[t_a < \tau_p] &= \int_{t_a=0}^{\infty} f_a(t_a) \int_{\tau_p=t_a}^{\infty} r_p(\tau_p) d\tau_p dt_a \\
&= \int_{t_a=0}^{\infty} f_a(t_a)[1 - R_p(t)] dt_a \\
&= 1 - \left(\frac{1}{2\pi i}\right) \int_{\sigma-i\infty}^{\sigma+i\infty} \int_{t_a=0}^{\infty} f_a(t_a) e^{st_a} \left[\frac{r_p^*(s)}{s}\right] dt_a ds \\
&= 1 + \sum_{z\in\sigma_a} Res_{s=z} f_a^*(-s) \left[\frac{r_p^*(s)}{s}\right] \qquad (3.3)
\end{aligned}
$$

where σ_a is the set of poles of $f_a^*(-s)$ in the right half of the complex plane.

For the demonstration purpose, we compute $\Pr[t_a < \tau_p]$ based on two cases of t_a and t_p distributions.

Case 1. t_a is a Gamma random variable with the shape parameter k and the rate parameter λ, and t_p is an Erlang random variable with the shape parameter m and the rate parameter γ. In this case, $k > 0$ is a real number and $m \geq 1$ is an integer.

Case 2. t_a is an Erlang random variable with the shape parameter k and the rate parameter λ, and t_p is a Gamma random variable with the shape parameter m and the rate parameter γ. In this case, $k \geq 1$ is an integer and $m > 0$ is a real number.

The Gamma distribution is considered because this distribution is widely used in telecom modeling [14]-[17]. We also select the Erlang distribution because this distribution can be easily extended into a hyper-Erlang distribution, which has been proven to be a good approximation to many other distributions as well as measured data [13, 18]. The Laplace transforms for the t_a and the t_p are

$$f_a^*(s) = \left(\frac{\lambda}{s+\lambda}\right)^k \text{ and } f_p^*(s) = \left(\frac{\gamma}{s+\gamma}\right)^m \tag{3.4}$$

For Gamma t_a and t_p, k and $m > 0$ are positive real numbers in (3.4). For Erlang t_a and t_p, k and m are positive integer numbers. From the residual life theorem [10] and (3.4), $r_p^*(s)$ is expressed as

$$r_p^*(s) = \left(\frac{\gamma}{sm}\right)\left[1 - f_p^*(s)\right] = \left(\frac{\gamma}{sm}\right)\left[1 - \left(\frac{\gamma}{s+\gamma}\right)^m\right] \tag{3.5}$$

For case 1, we substitute (3.4) and (3.5) into (3.2) to yield

$$\Pr[t_a < \tau_p] = \sum_{i=0}^{m-1}\sum_{j=0}^{i}\left[\frac{\gamma^{i-j}}{m\lambda^{i-j}(i-j)!}\right]\left(\frac{\lambda}{\gamma+\lambda}\right)^{k+i-j}\prod_{l=1}^{i-j}(k+l-1) \tag{3.6}$$

Note that in (3.6), when $i-j=0$, $\prod_{l=1}^{i-j}$ represents an empty product, and its value is 1. From (3.1) and (3.6), p is re-written as

$$p = \sum_{i=0}^{m-1}\sum_{j=0}^{i}\left[\frac{\mu\gamma^{i-j}}{(\gamma+m\mu)\lambda^{i-j}(i-j)!}\right]\left(\frac{\lambda}{\gamma+\lambda}\right)^{k+i-j}\prod_{l=1}^{i-j}(k+l-1) \tag{3.7}$$

On the other hand, for case 2, from (3.4) and (3.5), (3.3) is re-written as

$$\Pr[t_a < \tau_p] = 1 - \sum_{i=0}^{k-1}\left\{\frac{\gamma}{\lambda m} - \sum_{j=0}^{i}\left(\frac{\lambda^{j-1}}{j!m\gamma^{j-1}}\right)\left(\frac{\gamma}{\lambda+\gamma}\right)^{m+j}\prod_{l=1}^{j}(m+l-1)\right\} \tag{3.8}$$

From (3.1) and (3.8), p is re-written as

$$p = \left(\frac{m\mu}{\gamma+m\mu}\right)\left\{1 - \sum_{i=0}^{k-1}\left\{\frac{\gamma}{\lambda m} - \sum_{j=0}^{i}\left(\frac{\lambda^{j-1}}{j!m\gamma^{j-1}}\right)\left(\frac{\gamma}{\lambda+\gamma}\right)^{m+j}\prod_{l=1}^{j}(m+l-1)\right\}\right\} \tag{3.9}$$

Equations (3.7) and (3.9) are validated against the discrete event simulation experiments described in Appendix A, which shows that the discrepancies between the analytic and simulation results are within 0.5%.

Chapter 4

Numerical Examples

This chapter studies the call setup delays of DR and IR. Let t_f be the time that the UE falls back from LTE to UMTS (i.e., Steps 1-10 in Figure 2.1). Let t_d be the UMTS outgoing call setup delay without the CS fallback (i.e., Steps 11-15 in Figure 2.1). Then the performance improvement α of the DR scheme over the IR scheme can be defined as

$$\alpha = 1 - \frac{(1-p)E[t_f] + E[t_d]}{E[t_f] + E[t_d]} = \frac{pE[t_f]}{E[t_f] + E[t_d]} \tag{4.1}$$

In (4.1), $E[t_f] + E[t_d]$ is the expected total call setup delay for IR, and $(1-p)E[t_f] + E[t_d]$ is the expected total call setup delay for DR. The larger the α value, the better the performance of DR over IR. From the call setup delay measurement of Qualcomm (see Chapter 2), $E[t_f] = 2.5$ seconds for 3GPP R8, $E[t_f] = 0.5$ seconds for 3GPP R9, and $E[t_d] = 4$ seconds. From Huawei's measurements [6], $E[t_f] = 9$ seconds for 3GPP R8, $E[t_f] = 3$ seconds for 3GPP R9, and $E[t_d] = 5$ seconds. We also measured the call setup delay at Broadband Mobile Lab of National Chiao Tung University [7], where $E[t_f]$ is more than 10 seconds and $E[t_d] = 7$ seconds. Our measurement results are more consistent with Huawei's results than that of Qualcomm's results. In this thesis, we use Huawei's results to compute α in (4.1).

We also note that although an LTE data connection is ``always on'', the connection is in the idle mode (and is actually disconnected) if no data session is in progress. Because the expected session holding time is typically shorter than the expected inter-session arrival time [19, 20], we assume that $0.01E[t_p] \le E[t_s] \le 0.1E[t_p]$. We consider the effects of t_s (the session holding time), t_a (the inter-call arrival time), and t_p (the inter-session arrival time) on the probability p that a voice call can be connected without the CS fallback overhead. Note that the voice call holding time t_c does not affect p and is not considered. We also note that the α value is proportional to the p value (see (4.1)), and the effects on α are similar to those on p. Finally, to simplify our discussion, t_s and t_a are normalized by t_p.

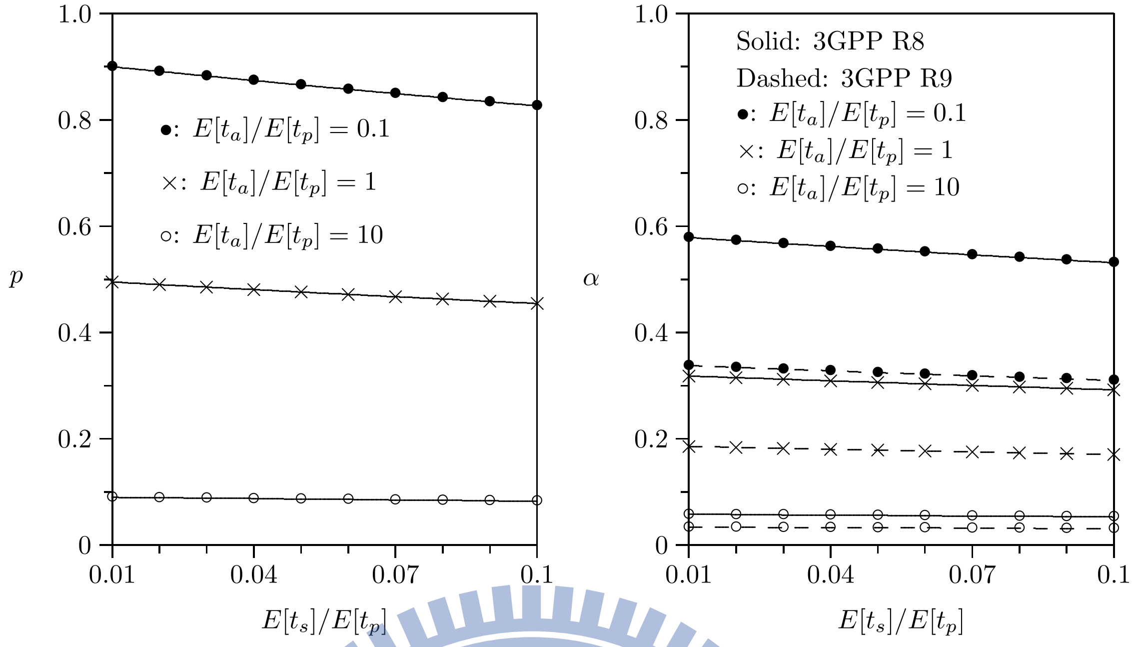
Effects of $E[t_s]/E[t_p]$: Figure 4.1(a) shows that p decreases as $E[t_s]/E[t_p]$ increases. When $E[t_s]/E[t_p]$ increases, a call is more likely to be released in the t_s interval. In this case, the UE will return to LTE immediately, and smaller p is observed. The non-trivial observation is that $E[t_s]/E[t_p]$ has insignificant impact on p for all $E[t_s]/E[t_p]$ values under our study. The probability p and the improvement α decrease by 8% when $E[t_s]$ increases from $0.01E[t_p]$ to $0.1E[t_p]$. In other words, in this operational range, we can ignore the effect of $E[t_s]/E[t_p]$ and can focus more on other parameters.

Effects of $E[t_a]/E[t_p]$: Figures 4.1(a), 4.2(a), and 4.3(a) indicate that p decreases as $E[t_a]/E[t_p]$ increases. When $E[t_a]/E[t_p]$ increases, the data session is more likely to arrive before the voice call arrives (i.e., the UE will return to LTE before the next call arrives). Thus, a smaller p is observed. Figures 4.2(a) and 4.3(a) show that the effects of $E[t_a]/E[t_p]$ become insignificant when V_a or V_p is large, where large p and α are always observed.

Effects of V_a: Figure 4.2(a) indicates that p increases as V_a increases. For a fixed $E[t_a]$ value, when V_a increases, there are much more short t_a intervals than long t_a intervals. For short t_a, it is very likely that $t_a < \tau_p$ (i.e., larger $\Pr[t_a < \tau_p]$ is observed). From (3.1) and (4.1), p and α increase as V_a increases.

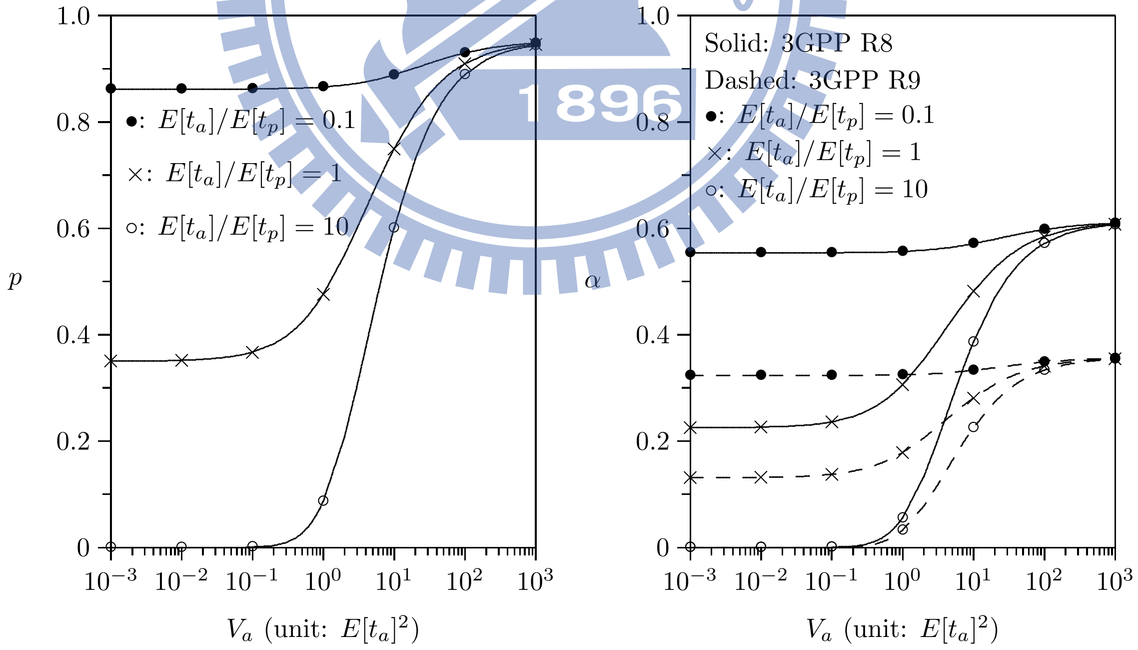
Effects of V_p: Figure 4.3(a) shows that p increases as V_p increases. When the inter-session arrival interval becomes more irregular (i.e., V_p increases), more long and short t_p intervals are observed. Since the call release events are more likely to fall in long t_p intervals and the next calls are likely to arrive before the next sessions arrive, larger p and α are observed.

Based on Figures 4.1(a), 4.2(a), 4.3(a), and Equation (4.1), Figures 4.1(b), 4.2(b), and 4.3(b) plot the α curves against $E[t_s]/E[t_p]$, V_a, and V_p. These figures show that with probability p, the CS fallback with DR can reduce up to 60% outgoing call setup delay over the CS fallback with IR. We note that the DR scheme can also reduce the incoming call setup delay (i.e., the delay between when the network pages the UE and when the UE rings). The incoming call setup delay is typically shorter than the outgoing call setup delay. From (4.1), the DR scheme has even better α performance for the incoming calls than that for the outgoing calls. Since the called party of a



(a) Effects on p (b) Effects on α

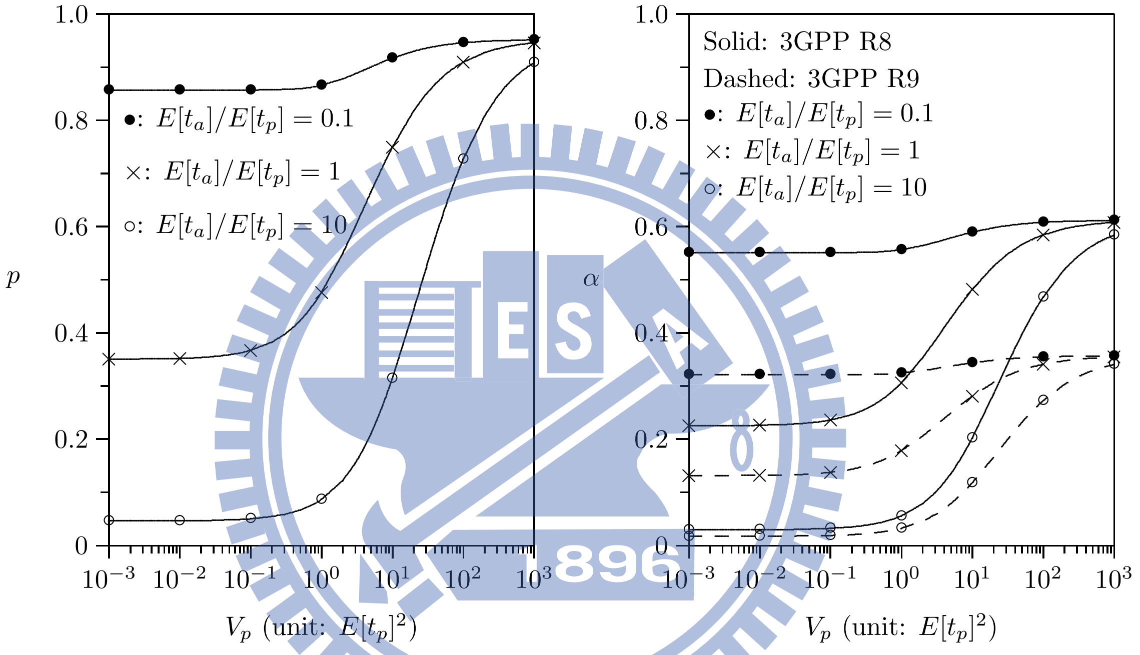
Figure 4.1: Effects of $E[t_s]/E[t_p]$ and $E[t_a]/E[t_p]$ on p and α ($V_a = E[t_a]^2$ and $V_p = E[t_p]^2$)



(a) Effects on p (b) Effects on α

Figure 4.2: Effects of V_a and $E[t_a]/E[t_p]$ on p and α ($E[t_s]/E[t_p] = 0.05$ and $V_p = E[t_p]^2$)

voice call does not experience call setup delay, the improvement α is only meaningful from the network cost viewpoint.



(a) Effects on p (b) Effects on α

Figure 4.3: Effects of V_p and $E[t_a]/E[t_p]$ on p and α ($E[t_s]/E[t_p] = 0.05$ and $V_a = E[t_a]^2$)

Chapter 5

SDN Implementation for CS Fallback

Analysis indicated that today's mobile networks experience significant signaling traffic [23]. To resolve this issue, Software-Defined Networking (SDN) has been introduced to the current LTE/UMTS architecture [24],[25]. SDN separates the control and data traffic in the mobile network. This can reduce the configuration complexity of adding new nodes into the mobile network and speed up the communication between mobile network elements to get better performance. This chapter introduces the SDN to the LTE and UMTS network architecture for CS fallback by replacing some network elements with the SDN controller Apps and the SDN switches. Since the SDN controller utilizes the OpenFlow protocol [26] to communicate with the SDN switches, they are usually called the OpenFlow controller and the OpenFlow switches, respectively. This chapter describes the SDN LTE and UMTS network architecture for CS fallback, and the call setup procedure.

5.1 SDN LTE and UMTS Network Architecture for CS Fallback

Figure 5.1 describes the simplified SDN LTE and UMTS architecture for CS fallback. We introduce the SDN architecture to the LTE and UMTS by separating the control plane and the user plane data of SGSN (e.g., SGSN-C and SGSN-D), S-GW and P-GW into Apps and OpenFlow Switches respectively. The SDN architecture includes two components: OpenFlow Controller and Switches. An OpenFlow Controller (Figure 5.1 (1)) provides the network topology and the packet information to Apps and sends the routing flow entry modification command from

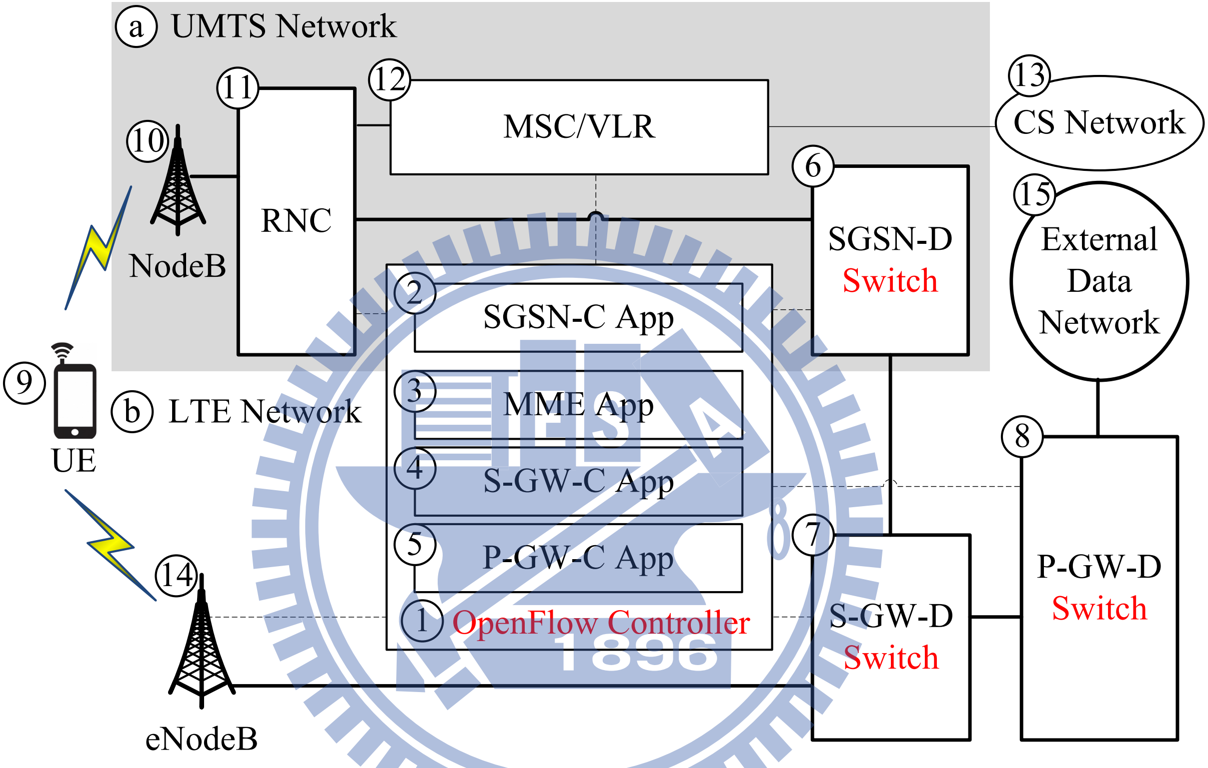


Figure 5.1: The simplified SDN LTE and UMTS architecture for CS fallback (dashed lines: signaling; solid lines: signaling/data)

Apps to the OpenFlow Switches. Apps (Figure 5.1 (2), (3), (4), (5)) are responsible for control plane. When the App receives the 3GPP signaling about establishing or redirecting the data path, it computes the routing flow entries which are set in Openflow Switches. An App can also communicate with other Apps or network elements via physical network interface. OpenFlow Switches (Figure 5.1 (6), (7), (8)) are responsible for forwarding the data packet by matching each packet against flow entries. OpenFlow Switches here have an advanced function that can encapsulate and decapsulate *GPRS Tunneling Protocol* (GTP) packets which are used to carry the packet in the UMTS and the LTE network.

This architecture includes two parts: the UMTS network and the LTE network. A UE (Figure 5.1 (9)) accesses the UMTS and LTE services through the radio interface. In the the UMTS network (Figure 5.1 (a)), *UMTS Terrestrial Radio Access Network* (UTRAN) consists of NodeBs (Figure 5.1 (10)) and *Radio Network Controllers* (RNCs; Figure 5.1 (11)). A NodeB provides *Wideband Code Division Multiple Access* (WCDMA) radio connectivity between the UE and the corresponding RNC. The RNC is responsible for radio resource management and connects to the UMTS core network. This core network is partitioned into the CS and PS domains. The CS domain includes *Mobile Switching Centers* (MSCs) and *Visitor Location Registers* (VLRs; Figure 5.1 (12)). The MSC is responsible for call control and connection between the UE and the external CS Network (Figure 5.1 (13)). The VLR is responsible for the mobility activities of the MSC. The PS domain consists of Serving GPRS Support Nodes which are separated into SGSN-C App and SGSN-D Switch (Figure 5.1 (2), (6)). The SGSN-C App is responsible for the mobility management and provides the session control to the UEs by controlling the SGSN-D Swtich.

In the LTE network (Figure 5.1 (b)), the *Evolved UMTS Terrestrial Radio Access Network* (E-UTRAN) consists of evolved NodeBs (eNodeBs; Figure 5.1 (14)) to offer LTE radio connectivity to UEs. The E-UTRAN connects to the LTE core network that includes the following components. The *Mobility Management Entity App* (MME App; Figure 5.1 (3)) provides the mobility management and session control to UEs. The *Serving Gateway* (S-GW) is separated into S-GW-C App and S-GW-D Switch (Figure 5.1 (4), (7)). The S-GW-C App is responsible for routing data packets by controlling the S-GW-D Switch and is an anchor of the user plane data for intra- and inter-system handovers. The *Packet Data Network Gateway* (P-GW) is separated into P-GW-C App and P-GW-D Switch (Figure 5.1 (5), (8)). The P-GW-C App provides the connectivity to the External Data Network (Figure 5.1 (15)) and the per-user based packet filtering by controlling the P-GW-D.

5.2 SDN LTE Call Setup with CS Fallback

Figure 5.2 illustrates the SDN CS fallback call setup with PS handover. Assume that S-GW is not changed in the procedure. When the UE makes a call and only if the UE is registered in UTRAN CS domain and is not registered in LTE IMS, the following steps are executed:

Step 1. The UE initiates the CS fallback procedure by sending the Extended Service Request message to the MME App through the eNodeB.

Steps 2 and 3. The MME App exchanges the UE Context Modification Request and Response message pair with the eNodeB to indicate that the UE should fall back to UTRAN. The UE Context Modification Request message includes the CS Fallback Indicator and the *Location Area Identification* (LAI) which identifies the CS domain registered by the UE.

Step 4. The eNodeB exchanges the Measurement Control and Report message pair with the UE in the Measurement Report Solicitation procedure to determine the target UTRAN cell.

Step 5. The eNodeB sends the Handover Required message to the MME App to initiate the handover procedure.

Step 6. The MME App sends the Forward Relocation Request message to the SGSN-C App to allocate resource in UMTS.

Step 7. The SGSN-C App sends the OFPT_FLOW_MOD (OFPFC_ADD) message to the SGSN-D Switch to add new flow entries for two uplink and downlink paired bearers. One pair is between the RNS and the SGSN-D Switch and the other pair is between the SGSN-D Switch and the S-GW-D Switch.

Steps 8 and 9. The SGSN-C App exchanges the Relocation Request and Acknowledge message pair with the RNC to establish the radio resource.

Setp 10. The SGSN-C App sends the Forward Relocation Response message to the MME App to indicate that the resource for the handover is prepared.

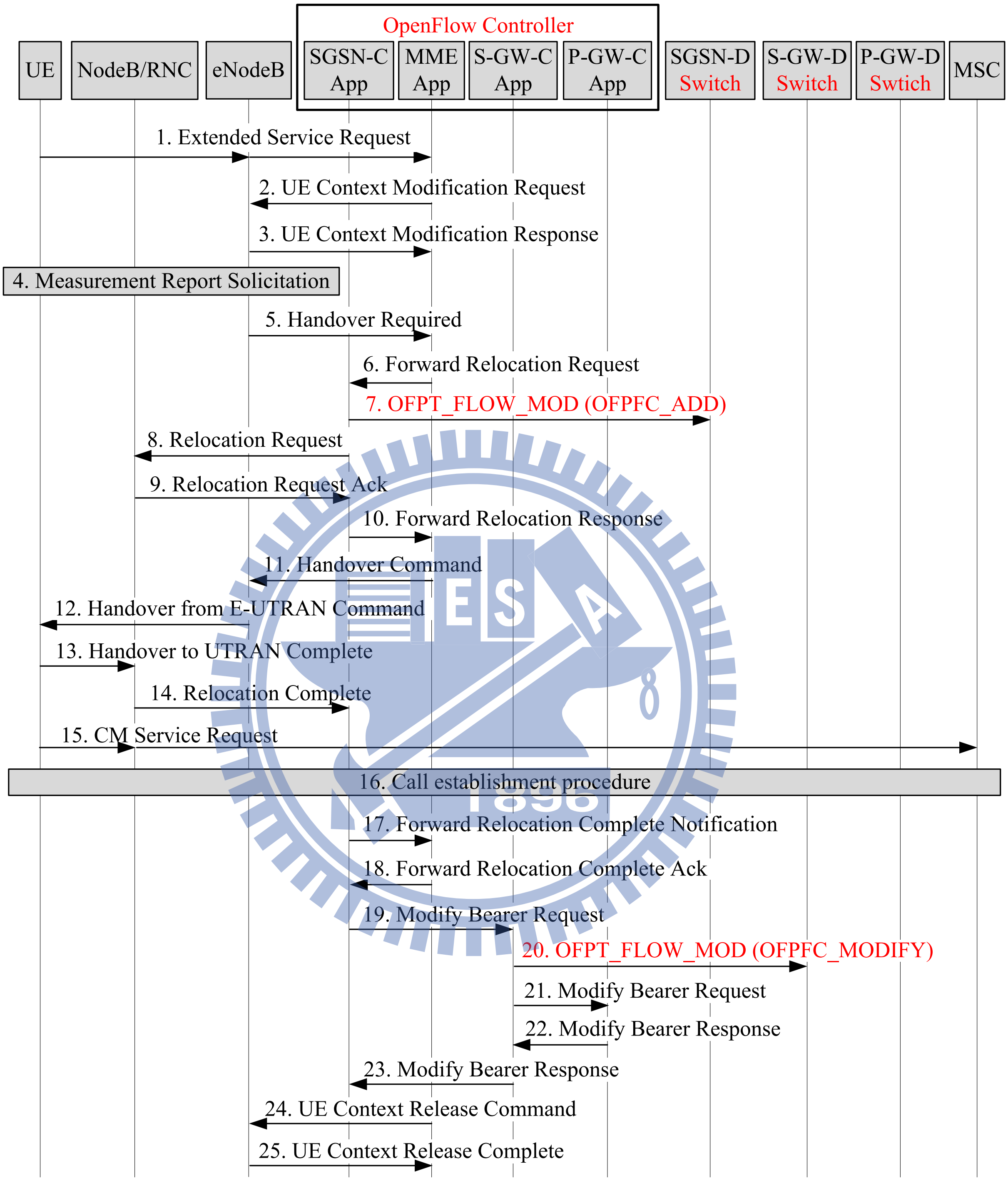


Figure 5.2: SDN LTE CS fallback call setup with PS handover

Setps 11 and 12. The MME App sends the Handover Command message to the eNodeB and the eNodeB sends the Handover from the E-UTRAN Command message to the UE to command that UE hands over to the target UTRAN cell. The UE suspends the uplink data transmission.

Step 13. The UE moves to the target UTRAN cell (i.e., the NodeB) and sends the Handover to UTRAN Complete message to the RNC. The UE resumes the uplink data transmission.

Step 14. The RNC sends the Relocation Complete message to the SGSN-C App to complete the relocation from E-UTRAN to UTRAN.

Steps 15 and 16. The UE initials the CS call establishment procedure by sending the CM Service Request message to MSC through the RNC. The UE includes the CSMO flag to indicate that it is a CS fallback call. The CS call establishment at Step 16 follows the 3GPP standard, and the details can be found in [8].

Steps 17 and 18. The SGSN-C App exchanges the Forward Relocation Complete Notification and Acknowledge message pair with the MME App to inform that the UE has arrived at UTRAN. The MME App starts a timer to release the resource for the uplink and the downlink bearers in eNodeB.

Setp 19. The SGSN-C App sends the Modify Bearer Request message to the S-GW-C App to inform that the SGSN-D Switch is now responsible for the bearers of the UE.

Step 20. The S-GW-C App sends the OFPT_FLOW_MOD (OFPFC_MODIFY) message to the S-GW-D Switch to modify flow entries. The other peer of the flow entries for the bearers is changed from the eNodeB to the SGSN-D Switch.

Steps 21 and 22. The S-GW-C App exchanges the Modify Bearer Request and Response message pair with the P-GW-C App to inform the change of the RAT type information for charging.

Step 23. The S-GW-C App acknowledges the SGSN-C App via the Modify Bearer Response message.

Steps 24 and 25. When the timer in Steps 17 and 18 expires, the MME App exchanges the UE Context Release Command and Complete message pair with the eNodeB to release the radio resource for the UE.

Chapter 6

Conclusions

This thesis proposed the DR scheme to avoid unnecessary CS fallbacks. Analytic model was developed based on the real LTE/UMTS network measurements to compare the DR scheme with the existing IR scheme. The performance is measured by the probability p that when a voice call arrives, the UE can be connected at UMTS without CS fallback, and therefore, non-necessary switching between UMTS and LTE is avoided. In other words, when a voice call arrives, the UE does not need to switch from LTE to UMTS, and when the call is complete, the UE does not need to switch from UMTS to LTE. Our study indicated that the DR scheme can effectively improve the CS fallback performance when

- the inter-call arrival time t_a is short (i.e., the voice calls arrive frequently),
- the variance of t_a is large (i.e., the inter-call arrival time is irregular), or
- the variance of the inter-session arrival time t_p is large (i.e., the inter-session arrival time is irregular).

The last two items of our conclusions are not trivial, and are used as guidelines to further investigate the user behavior by a commercial mobile operator. For users with long inter-call arrival time and regular call and data session arrivals, the CS fallback with IR is exercised, while for the users with short inter-call arrival time and irregular call and data session arrivals, the CS fallback with DR is exercised.

As a final remark, the DR scheme can be practically implemented in NodeB with a minor modification in the RRC Connection Release message. Therefore, the DR scheme is an effective approach for reducing the CS fallback costs. In the future, we will investigate the DR scheme by the call and data traffic statistics collected from the commercial mobile telecom network. We will also consider other approaches to avoid unnecessary CS fallbacks (e.g., a timer-based scheme that determines the optimal time interval for the UE to stay in UMTS based on different traffic rates). Moreover, because both CS fallback and *Enhanced Single Radio Voice Call Continuity* (eSRVCC) [21, 22] are voice call solutions in LTE, we will compare the call performance between these two solutions. We also present the SDN implementation for CS fallback for further studying.

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Appendix A

The Simulation Model for CS fallback with DR

This appendix describes the discrete event simulation model and the simulation code for CS fallback with DR. With minor modifications, the model can be extended for CS fallback with IR. The extension details are omitted. In our simulation model, an event e has two attributes:

- The *type* attribute indicates one of four event types. A **Call Arrival** event represents a voice call arrival. If this event occurs when the UE resides in LTE, the UE needs to trigger the CS fallback procedure to switch to UMTS. A **Call Release** event represents that a voice call is complete and is released. A **Session Arrival** event represents a data session arrival. If this event occurs when the UE is not engaged in a voice call, the UE needs to switch to LTE. A **Session Release** event represents that a session is released.
- The ts attribute indicates the timestamp when the event occurs.

In the simulation, the inter-call arrival times t_a and inter-session arrival times t_p are generated from random number generators G_a and G_p, respectively. The call holding times t_c and the session holding times t_s are generated from random number generators G_c and G_s, respectively. Two output statistics are collected in the simulation:

- N: the total number of the voice calls investigated in the simulation run
- N_U: the total number of the calls that arrive when the UE resides in UMTS

From the above outputs, we compute

$$p = N_U/N$$

In the simulation, a clock ck is maintained to indicate the simulation progress, which is the timestamp of the event being processed. Three flags are used in the simulation: $domain$, f_voice and f_data. The $domain$ flag indicates the domain (LTE or UMTS) where the UE currently resides. The f_voice flag indicates if the UE is engaged in a voice call and f_data indicates if the UE is engaged in a data session. All events are inserted into the event list, and are deleted from the event list in the non-decreasing timestamp order for execution. Figure A.1 illustrates the simulation flow chart with the following steps:

Step 1. Set all output variables (i.e., N and N_U) and the simulation clock ck to 0. Set $domain$ to LTE. Both f_voice and f_data are set to OFF.

Step 2. The first two events e_1 and e_2 are generated and inserted into the event list. For event e_1, $e_1.type$ is **Call Arrival** and $e_1.ts = ck + t_a$ where t_a is generated from G_a. For event e_2, $e_2.type$ is **Session Arrival** and $e_2.ts = ck + t_p$ where t_p is generated from G_p.

Step 3. The first event e in the event list is deleted, and is processed based in its $type$ in Step 4. The clock ck is set to $e.ts$.

Step 4. If $e.type$ is **Call Arrival**, then Step 5 is executed. If $e.type$ is **Call Release**, then Step 9 is executed. If $e.type$ is **Session Arrival**, then Step 14 is executed. If $e.type$ is **Session Release**, the simulation proceeds to Step 17.

Step 5. For a **Call Arrival** event, the UE needs to connect to the UMTS CS domain. If $domain$ is LTE, then Step 6 is executed. If $domain$ is UMTS, the simulation proceeds to Step 7.

Step 6. The UE is in LTE and the CS fallback procedure is performed. Set $domain$ to UMTS. Then the simulation goes to Step 8.

Step 7. The call is connected to the UE in UMTS. N_U is increased by one.

Step 8. Set f_voice to ON to indicate that UE is engaged in a voice call. The **Call Release event** e_3 is generated and inserted into the event list, where $e_3.type$ is **Call Release** and $e_3.ts = ck + t_c$. The value t_c is generated from G_c. Then Step 3 is executed.

Step 9. A **Call Release** event occurs. If f_data is ON, then the data session is in progress, and Step 10 is executed. If f_data is OFF, the simulation proceeds to Step 11.

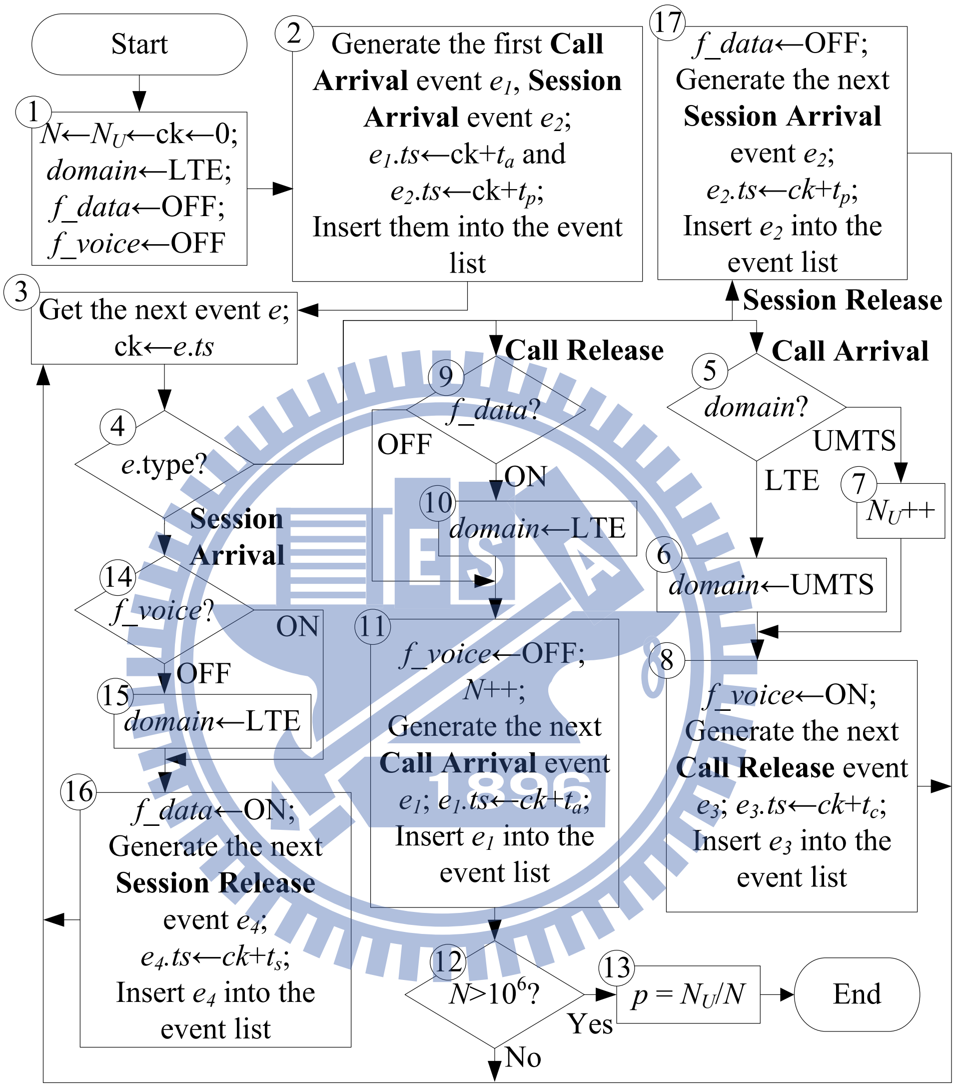

Figure A.1: Simulation Flow Chart for CS Fallback with DR

Step 10. The UE is switched from UMTS to LTE. Set $domain$ to LTE.

Step 11. Set f_voice to OFF to indicate that the call is released. Increase N by one. The next **Call Arrival** event e_1 is generated and inserted into the event list.

Step 12. If one million of the **Call Release** events have been processed, then stable result is produced. Step 13 is executed to exit the simulation. Otherwise, the simulation proceeds to Step 3.

Step 13. Probability p is computed, and the simulation is terminated.

Step 14. When a **Session Arrival** event occurs, this step checks if UE is engaged in a voice call. If so, Step 16 is executed. Otherwise, Step 15 is executed.

Step 15. The UE is idle and is established the PS connection in LTE. Set $domain$ to LTE.

Step 16. Set f_data to ON to indicate that the UE is engaged in a data session. The **Session Release** event e_4 is generated and inserted into the event list, where $e_4.ts = ck + t_s$. Then the simulation goes to Step 3.

Step 17. A **Session Release** event occurs. The UE releases the PS connection. Set f_data to OFF. The next **Session Arrival** event e_2 is generated and inserted into the event list. Then the simulation goes to Step 3.

Appendix B

The Simulation codes for CS fallback with DR

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

```
#include <iostream>
#include <event.h>
#include <e_list.h>
#include <random_2.h>
#include <random_tsaimh.h>
#include <ctime>

using namespace std;

//define numbers of call events have been processed
#define Iteration 1000000

#define Call_Arrival 1
#define Session_Arrival 2
#define Call_Release 3
#define Session_Release 4

int main(){

  int seed = (int)time(0);
```

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//flag to record the status of the UE
bool f_voice=false , f_data=false , domain_in_LTE=true;

//N: the total number of the calls
//N_U: the total number of the calls
//that arrive when the UE resides in UMTS
double  N=0, N_U=0;

//set the parameters of every distributions
int m=10;
double lambda=0.1,gamma,lambda_c=1,mu=1,k=5;
double mean_a,mean_c,mean_s,var_a;
double t=0,call_arrival_time ,session_arrival_time ,
        call_holding_time ,session_holding_time;

mean_a=1;
mean_c=10*mean_a;
mean_s=10*mean_a;
gamma=1.0/mean_a;
var_a=mean_a*mean_a;


Expon call_arrival(seed ,1.0/lambda);
//Gamma call_arrival(seed ,k/lambda, k/(lambda*lambda) );

Expon session_arrival(seed+1,1.0/gamma);
//Gamma call_arrival(seed+1, mean_a, var_a);
//Erlang session_arrival(seed+1, m/gamma, m/(gamma*gamma));

Expon call_holding(seed+2,mean_c);
Expon session_holding(seed+3,mean_s);


//set the event list and the first call and the session event
Event *EventNode;
E_List *EventList=new E_List;
Event * FirstEventOfEList;
```

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EventNode = new Event();
call_arrival_time = call_arrival++;
EventNode -> setTimeStamp(ck+call_arrival_time);
EventNode -> setEventType(Call_Arrival);
*EventList << *EventNode;

EventNode = new Event();
session_arrival_time = session_arrival++;
EventNode -> setTimeStamp (t+session_arrival_time);
EventNode -> setEventType (Session_Arrival);
*EventList << *EventNode;

while(N<Iteration){

  //get the first event in the event list
  *EventList >> FirstEventOfEList;
  ck=FirstEventOfEList->getTimeStamp();

  //check the event type and do something
  switch(FirstEventOfEList->getEventType()){

    case Call_Arrival:

      //if the UE is in LTE, set the domain to UMTS
      //if the UE is in UMTS, N_U++
      if(domain_in_LTE==true){
        domain_in_LTE=false;
      }else{
        N_U++;
      }

      //set the f_voice to ON and generate the next call release event
      f_voice=true;
      EventNode = new Event();
      call_holding_time = call_holding++;
      EventNode -> setTimeStamp(t+call_holding_time);
      EventNode -> setEventType(Call_Release);
```

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      *EventList << *EventNode;

      break;

    case Session_Arrival:

      //if no call is in progress, set the domain to LTE
      if(f_voice==false){
        domain_in_LTE=true;
      }

      //set the f_data to ON and generate the next session event
      f_data=true;
      EventNode = new Event();
      session_holding_time = session_holding++;
      EventNode -> setTimeStamp(t+session_holding_time);
      EventNode -> setEventType(Session_Release);
      *EventList << *EventNode;

      break;

    case Call_Release:

      //if a session is in progress, set the domain to LTE
      if(f_data==true){
        domain_in_LTE=true;
      }

      //add the N by one, set the f_voice to OFF and
      //generate the next call arrival event
      N++;
      f_voice=false;
      EventNode = new Event();
      call_arrival_time = call_arrival++;
      EventNode -> setTimeStamp(t+call_arrival_time);
      EventNode -> setEventType(Call_Arrival);
      *EventList << *EventNode;

```

```
        break;

      case Session_Release:

        //set the f_data to OFF and generate
        //the next session arrival event
        f_data=false;
        EventNode = new Event();
        session_arrival_time = session_arrival++;
        EventNode -> setTimeStamp(t+session_arrival_time);
        EventNode -> setEventType(Session_Arrival);
        *EventList << *EventNode;

        break;
    }
    delete FirstEventOfEList;
  }

  //compute the probability p that when a call arrives,
  //the UE can be connected in UMTS with out CS fallback
  cout<<”p=”<<N_U/N<<endl;

}
```