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QOS PATH PROVISIONING IN INTER-DOMAIN NETWORK WITH GAME THEORY

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การรับประกันคุณภาพการให้บริการในโครงข่ายระหว่างโดเมน เป็นปัญหาที่ท้าทาย เนื่องจากผู้ให้บริการอินเทอร์เน็ตไม่มีความร่วมมือกัน วิทยานิพนธ์นี้เสนอกรอบความคิดใหม่บนพื้นฐานของโครงข่ายที่ผู้ให้บริการอินเทอร์เน็ตไม่มีความร่วมมือกัน เพื่อแบ่งความรับผิดชอบในคุณภาพการให้บริการของแต่ละโดเมน กรอบความคิดใหม่นี้คือวิธีการจัดกลุ่มเส้นทางตามจุดสมดุลของแนช โดยการคัดแยกเส้นทางตามระดับคุณภาพของเส้นทาง และการเลือกเส้นทางที่มีระดับคุณภาพการให้บริการตามจุดสมดุลของแนช โมเดลของโครงข่ายสูญเสียสร้างขึ้นเพื่อคำนวณค่าความน่าจะเป็นของการรับของการเรียกและค่าผลประโยชน์ที่คาดหวังจากผลเฉลยของเกมที่จุดสมดุลของแนช วิธีการจัดกลุ่มเส้นทางตามจุดสมดุลของแนชได้ถูกประเมินด้วยการวิเคราะห์ทางคณิตศาสตร์และเปรียบเทียบกับนโยบายดั้งเดิมสามวิธี (การเลือกเส้นทางคุณภาพสูงที่สุด, เส้นทางคุณภาพต่ำสุด และ เส้นทางคุณภาพเทียบเท่ากันทุกโดเมน) ผลการวิเคราะห์แสดงความถูกต้องของค่าความน่าจะเป็นการรับของการเรียกที่ได้จากการวิเคราะห์ทางคณิตศาสตร์ เปรียบเทียบกับการวิเคราะห์ ด้วยโปรแกรมคอมพิวเตอร์ที่ช่วงความมั่นใจ 95 เปอร์เซ็นต์ ผลการทดลองแสดงว่าวิธีการจัดกลุ่มเส้นทางตามจุดสมดุลของแนชให้ค่าผลประโยชน์สูงกว่าวิธีดั้งเดิมทั้งสามวิธี สำหรับโมเดลทางธุรกิจสามแบบ (ได้แก่ แบบไม่เก็บค่าผ่านทาง, แบบขายปลีก และ แบบขายส่ง) อย่างไรก็ตาม นโยบายการเลือกเส้นทางคุณภาพสูงสุดและการเลือกเส้นทางคุณภาพต่ำสุด ให้ค่าผลประโยชน์ใกล้เคียงกับวิธีการจัดกลุ่มเส้นทางตามจุดสมดุลของแนชเมื่อพิจารณาในกรณีของโมเดลทางธุรกิจทั้งสามแบบ ในโครงข่ายที่มีคุณภาพของเส้นทางเหมือนกันทุกโดเมน นอกจากนี้ ผลประโยชน์ที่ได้รับจากนโยบายดั้งเดิมทั้งสามแบบ มีค่าน้อยกว่าผลประโยชน์ที่ได้รับจากวิธีการจัดกลุ่มเส้นทางตามจุดสมดุลของแนชในโครงข่ายที่มีคุณภาพของเส้นทางแตกต่างกัน ดังนั้นวิทยานิพนธ์นี้สรุปว่าวิธีการจัดกลุ่มเส้นทางตามจุดสมดุลของแนชมีประโยชน์มากในการใช้ทดสอบวิธีการจัดสรรคุณภาพการให้บริการสำหรับโครงข่ายระหว่างโดเมนในทางปฏิบัติในอนาคต

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Providing a guarantee for end-to-end QoS in inter-domain networks is a challenging problem due to the lack of cooperation among ISPs. In this dissertation, a new framework based on a network environment with non-cooperative ISPs has been proposed for apportioning of ISP's responsibility in an end-to-end QoS request. The newly proposed QoS provisioning framework with Path-Classification scheme under Nash equilibrium (PC-Nash) is obtained by classifying the paths according to the QoS-level and optimally selecting the QoS-level apportioning at the Nash equilibrium. A loss network model has been formulated to promptly calculate the call acceptance probabilities as well as the resultant expected utility value of the game solution at Nash equilibrium indicating the optimal QoS-level apportionment of ISPs. PC-Nash has been analytically evaluated and compared with three conventional policies (most-effort, least-effort and equal-distribution). The results show the conformity of call acceptance probabilities between mathematical analysis and simulation at 95% confidence interval. Based on the utility functions of practical ISP business models (i.e., peer, retail and wholesale service models), the experiments demonstrate that PC-Nash outperforms the conventional policies. However, most-effort and least-effort policies provide comparable utilities to PC-Nash with respect to peer and retail/wholesale service models, respectively, for the network with the same path quality. Further, the utilities of all conventional policies are significantly less than the utility of PC-Nash for the networks with different path qualities. By these evidences, the framework of PC-Nash is expected to be most useful in QoS provisioning trials of practical inter-domain networks in the future

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CHAPTER I

INTRODUCTION

1.1 Research Motivation

Internet service providers (ISPs) face challenges stemming from the advent of ubiquitous communication services and convergent networks. In today's highly competitive telecommunication markets, ISPs have to provide smooth transmissions to their customers, who expect to benefit from end-to-end connections with a guaranteed quality of service (QoS). To support this growing demand, ISPs need an efficient methodology to meet their customers' requirements while optimising their network resources.

The difficulty is that an ISP has the authority to control traffic flows in only its own network– so called "domain" (e.g., a network under a unique autonomous system number), but an end-to-end connection often needs to pass through inter-domain networks consisting of several connected domains. Since inter-domain networks are administered by multiple ISPs, the success of end-to-end connections relies on the subtle interactions of provisioning policies in place by those ISPs. These policies must be good enough to facilitate an establishment of end-to-end QoS connection. Such establishment, while requiring ISP mutual cooperation, must allow reasonable mutual ISP competition to serve their own best interests. Due to these complexities, efficient provisioning of guaranteed QoS connections across inter-domain networks remains an open challenge [1].

Proper cooperation among ISPs has been seen as a solution for providing end-to-end QoS. The conventional approaches in the research literature often require each ISP or domain to exchange internal network information using a common protocol [2–5]. To reserve paths for connection-oriented services, traffic engineering (TE) information must be announced across the domains by using a common protocol, e.g., a resource reservation protocol-TE (RSVP-TE) [2], border gateway protocol-TE (BGP-TE) [3, 4], multiprotocol label switching-TE (MPLS-TE) [5] and generalised MPLS-TE (GMPLS-TE) [2]. Existing studies [4, 6–11] have extended these protocols to efficiently solve the end-to-end QoS provisioning problem. Kumar and Saraph [6] use the concept of sharing QoS information among alliance networks via a routing control platform coexisting with the BGP. Other studies [4, 7–11] use the concept of a QoS tunnel or virtual trunk for QoS routing by an additional attribute to convey TE information. Although these schemes perform well when the ISPs cooperate, the apportionment of the QoS responsibilities of ISPs has yet to be studied.

A trade-off between path reservation efficiency and the dissemination of internal network information renders the optimally cooperative environment amongst ISPs often unreachable in many practical cases. For instance, individual ISPs are usually not willing to disclose internal network information, such as a complete topology and link state information, for reasons of security or business competitiveness. This situation poses a challenging problem for ISPs that exercise fully independent management [12–14].

Some studies assume a non-cooperation among ISPs, [12–14]. Ogino and Nakamura [12] propose an adaptive QoS-class allocation scheme to estimate the level of QoS assigned by the downstream domains. An ISP uses the estimated level to determine its QoS class to successfully establish the connection. However, such a scheme works properly only if the TE signals are forwarded across domains. In contrast, the most-effort (ME), least-effort (LE) and equal-distribution (ED) policies, proposed by Pongpaibool and Kim [13], do not require internal topology or TE information from other domains; only the QoS constraints must be sent to downstream domains. However, these policies force ISPs to be in charge of the highest, lowest and moderate responsibilities in a QoS request. Their investigation does not consider the purported efficiency if the level of responsibility in a QoS request is instead freely selected by individual ISPs to optimise their own objectives. In practice, it is difficult to force all ISPs to select the paths at the same QoS level.

Without ISP cooperation, the key to offering end-to-end QoS services must therefore rely on dynamic apportionment of QoS responsibilities among ISPs. Such a non-cooperative problem underlines the need for an analysis with a non-cooperative game theory [15–17]. This thesis focuses on investigating the optimal apportionment of QoS for providing end-to-end QoS across multiple domains in the framework of a non-cooperative game with respect to Nash equilibrium. A QoS provisioning framework with a Path-Classification scheme under the Nash equilibrium (PC-Nash) is proposed to facilitate the management of multiple QoS levels or path qualities in each domain. In PC-Nash, an ISP is not forced to disclose the network topology nor forward TE across domains. The only requirement is that the ISP classifies its paths according to their qualities. In addition, PC-Nash can be considered a generalisation and a unified representation of the three policies, i.e., ME, LE and ED [13] with maximum, minimum and moderate QoS levels, respectively. Such unification makes it possible to analyse how the ISPs interact with their freedom of choice in the QoS apportionment by using various levels of QoS stringency.

1.2 Literature Review

One essence of requirement for today's telecommunication services is an end-to-end QoS guarantee. This critical issue has been motivating researchers in seeking for new techniques to deliver end-to-end QoS. Some possible approaches are to enhance a process of the standard inter-domain routing protocols, e.g., BGP-TE and RSVP-TE, to add a new mechanism or to bide a service level agreement among the ISPs.

1.2.1 Enhanced BGP-TE

BGP-4 [18] is a path vector protocol that allows each domain or Autonomous System (AS) to adopt the local policy in route selection and route propagation to the destination prefixes. BGP-4 exchanges the reachability information between adjacent domains via UPDATE messages. The information in the UPDATE messages is used to establish the topology representing the relationships of the ASs. The destination prefixes, AS_PATH and NEXT_HOP in the UPDATE message, are provided for advertised routes. Basically, an edge router is set its policy to select a path which provides the minimum number of hops in the AS_PATH. Due to a lack of QoS information forwarding across the domain boundary, QoS guarantee cannot be done over the multiple domains. Consequently, many studies [3, 4, 8, 19, 20] propose mechanisms to extend the QoS information in the BGP for QoS routing. Xiao et al. [3, 19] have proposed a scheme to advertise the statistical QoS information through the BGP routers. They define the new QoS metrics, such as the Available Bandwidth Index (ABI), Delay Index (DI), Available Histogram (AH) and Delay Histogram (DH), which are presented as statistical metrics instead of the deterministic metrics. Using the statistical reported in these metrics to select the proper router provides the performance of the network closer to the optimality than to select the router following static metrics. Meanwhile, the system suffers from increased overheads. Cristallo and Jacquent [20] propose a new attribute, QOS_NLRI in UPDATE messages in BGP, for the many types of QoS information. However, this work does not present how the information is used in the path selection. M. Boucadair [21] proposes a new feature for BGP enhancements. The technique does not change the BGP state machine but allows for different treatments of the received announcements depending on the conveyed QoS information. In doing so, two message attributes, i.e. QoS Service Capability and QoS_NLRI, are added to BGP-4 in order to forward the traffic according to the QoS guarantee. The QoS Service Capability is an optional parameter of the OPEN message and it allows peering entities to learn each other's QoS Service Capabilities. The QoS_NLRI is used to convey QoS-related information in UPDATE messages. The simulation results conducted in [8] confirm that the end-to-end QoS is improved by the path selection based on two QoS attributes, i.e. QoS Service Capabilities and QoS_NLRI. Due to the lack of a mechanism to enforce the necessary information update in the BGP entities, the path selection might not reach an optimal. Prior and Sargeto [4] improved the QoS extension technique to BGP by delivering three QoS metrics with UPDATE messages. They define the QoS_INFO for carrying three QoS metrics, namely, the light load delay, assigned bandwidth and congestion alarm. These extensions are designed while taking into account the need to minimizing the overhead in the signalling messages and the path re-computation. In order to prove that using this technique can make the system reach the optimal path selection, the simulation experiments comparing QoS_NLRI with the common BGP depict using QoS_INFO in BGP can provide the system with a near optimum path selection over both a common BGP and a BGP with added QoS_NLRI.

1.2.2 Enhanced RSVP-TE

Apart from the QoS extension to BGP-4, the RSVP-TE [22] is created to support the QoS requirement over a MPLS/GMPLS network. Several new objects are added in the RSVP path message [22]. The SESSION object and the SENDER_TEMPLATE object uniquely identify the Label Switch Path (LSP) tunnels with or without the QoS requirement. The EXPLICIT_ROUTE object (ERO) specifies the route which meets the QoS requirement as a sequence of abstract nodes. To prevent a routing loop, the RECORD_ROUTE object (RRO) is added in the path message to specify the actual route that the LSP tunnel traverses. The SESSION_ATTRIBUTE object is for the session identification and diagnostics. For policy control, routers along the path use the setup and hold priorities along with SENDER_TSPEC and POLICY_DATA objects in the path message. With RSVP-TE protocol, an LSP tunnel with the QoS requirement can be obtained for intra-domain traffic [22]. However, this information cannot be sent across multiple domains because of the confidentiality. QoS delivery across multiple domains can be achieved by using the inter-AS LSP proposed in [23]. The establishment of the inter-LSP is based on an AS number and a prefix destination. Only the head-end Label Switch Router (LSR) is permitted to fill ERO with nodes that belong to the same AS and the AS that will be traversed by the Path message. At the entrance of each AS, the border router computes an LSP path towards the downstream AS and specifies the ERO accordingly. The inter-domain path selection may rely on the QoS extension to BGP. As a result, the local path optimization depends on each AS. Although, these studies suggest how to extend QoS over inter-domain network, they do not mentioned how each AS should efficiently select the local paths.

1.2.3 Cooperative QoS Routing Approach

Kumar and Saraph [6] have proposed a new Alliance Network model for supporting the end-to-end QoS services. An alliance network consists of a set of interconnected ASs forming an alliance. These ASs must share their QoS information through the alliance network. The premium traffic will be served by the MPLS tunnel establishment. To do this, the BGP routers in each AS must be upgraded to be a Routing Control Platform (RCP) [6]. The RCP centralises the BGP import and export policy implementation for the AS administrator and frees up other routers for the forwarding tasks. Thus, the new alliance network model is compatible with the existing BGP. The RCP learns the BGP advertised paths from the border routers through the iBGP session [6]. The RCP selects the best path and sends the selected path to all routers in the AS. For extension to other AS, the RCP in each AS learns multiple routes through eBGP [6]. Then, the alliance network is constructed by communication between RCPs via the TCP. This approach uses an overlay model to co-exist with the BGP. From the simulation results, the alliance network can support premium services while the common BGP can not. Since this success requires cooperation with the ISPs or central control system over the inter-domain networks, this idea might be abandoned by the ISPs because of the adverse business conditions in real practice.

Other approaches [4, 7–10] use the concept of a QoS tunnel or a virtual trunk establishment for the QoS routing. These works are based on the assumption that providing end-to-end QoS across the Internet needs the co-operation of multiple ISPs. Georgatsos et al. [7] uses a local Quality Classes (l-QCs) in each domain and an extended Quality Classes (e-QCs) between two domains for supporting end-to-end QoS requests. Meanwhile, Griffin et al. [8] used the concept of the mata-QoS class plane (the details can be found in [10]). ASs can freely choose the preferred method for engineering the QoS. Although these previous approaches can perform well in co-operative manner, the responsibility in the QoS apportionment has not been studied.

1.2.4 QoS Path Provisioning Approach

Several QoS path provisioning approaches (e.g., [12, 13, 24]) deal with how to allocate a path to support an end-to-end QoS in inter-domain networks. These researches focus on seeking an appropriate QoS level that each domain should offer for a QoS request. Tham and Liu [24] have proposed a Reinforcement Lerning-based Adaptive Marking (RLAM) scheme to achieve the cost effective based on an end-to-end QoS requirement. This scheme is applied for a Differentiated Service (DiffServ) network [25] of which incoming packets are marked at the ingress router with (DiffServ Code Point)

DSCP value. The RLAM scheme lets the system learn an optimal QoS level via the states of congestion in the other domains by using reinforcement learning technique [26]. Based on dynamically path provisioning QoS, the optimal QoS level of each domain must be periodically adjusted following the penalty of the loss rate and the end-to-end delay. Even the RLAM scheme provides a cost effective according to changing traffic pattern, this scheme requires some feedback messages in order to achieve the convergence of optimal QoS level.

The other example of adaptive path QoS provisioning scheme is proposed by Ogino and Nakamura [12]. Unlike the RLAM scheme, Ogino and Nakamura [12] have proposed an adaptive QoS-class allocation scheme based on the Markov decision theory [27] to estimate the level of QoS assigned by the downstream domains. To determine a proper QoS class to successfully establish the connection, the probability of every possible state must be pre-calculated. This scheme requires to periodically recalculate corresponding to the traffic pattern variation. As the same as the RLAM scheme, an adaptive QoS-class allocation scheme also works properly only if the signalling messages are forwarded across domains. In contrast, the most-effort (ME), least-effort (LE) and equal-distribution (ED) policies, proposed by Pongpaibool and Kim [13], do not require internal topology or TE information from other domains; only the QoS constraints must be sent to the downstream domains. For ME, the highest QoS that a domain can support at the current state of the network must be allocated to a call request. In contrast, LE is similar to greedy scheme which the lowest QoS of path in a domain satisfying a QoS request is always allocated. ED is established to compromise between ME and LE schemes; that is, all domains must allocate their QoS as equal as possible. However, ED requires an extra information about the number of domains connecting the end-to-end route. These policies force ISPs to be in charge of the highest, lowest and moderate responsibilities in a QoS request. Their investigation does not consider the purported efficiency if the level of responsibility in a QoS request is instead freely selected by individual ISPs to optimise their own objectives. In practice, it is difficult to force all ISPs to select the paths at the same QoS level.

1.2.5 Game Theoretic Approach

Other approaches, which differ from the enhancement of the existing inter-domain routing protocols, are rooted in a game theory. Due to the nature of behaviours of the ISPs, e.g., the ownership operation, business competition and selfishness, a game theory is a suitable tool for analysing the inter-domain routing problem. In addition, this behaviour leads most practical ISPs to uncooperative. Recent work by [15–17, 28–30] studied the issue of an incentive utility for the ISPs based on a non-cooperative framework. Those studies provide the direction for how to select the optimal inter-connection link. In particular, some studies [17, 28–30] analyse the incentive model for the routing policy in BGP. The analysis shows that the incentives of rational ISPs are aligned with the call accomplishment. Thus, the ISPs have no incentive to deviate from the prescribed behavior. Other studies [31, 32] focus on the price setting to the peering links of the transit domains. Using the BGP UPDATE message, Barth et al, [32] have proposed the game theoretical framework to determine the optimal price that the ISPs should charge their peers.

Unlike the works in [16, 32], Jesus et al., [31] analyse the peering bilaterally with respect to the pair-wise Service Level Agreements (SLA) by using the game theory according to the realistic model. The capacity constraint of the transit link is integrated into a price setting criteria in order to control the inter-domain traffic. The optimal price setting for an inter-connection link can be found with respect to the ISP business relationships. Apart from the non-cooperative game, some literature formulates the inter-domain routing problem as a cooperative game. For example, Shrimali et al., [33] have focused on a benefits of bilateral cooperation among ISPs. Qian et al., [34] have proposed an economic model for tiered network services and used game-theoretic techniques to find the optimal price for each service tier.

Even though many studies note that the solution provided by the cooperative game theoretical framework is superior to that from the non-cooperative game solution, the non-cooperation is in real practice suitable for the problem with the ISPs based on the aforementioned reasons. Therefore, this thesis formulates the problem based on the non-cooperative game theory. While those studies propose several pricing mechanisms to cope with the inter-domain routing problem, none of them takes into consideration the routing with end-to-end QoS guarantee.

1.3 Thesis Objective

This dissertation aims at proposing a new scheme to efficiently provision an end-to-end QoS path along the inter-domain network. The proposed scheme employs the game theoretical framework to reach the optimal operating point of individual inter-acting domains.

1.4 Scope of Thesis

1. Review the previous inter-domain routing policies proposed in [13], i.e. most-effort, least-effort and equal-distribution policies.

2. Propose an end-to-end QoS path provisioning scheme

- Consider two constraints, namely, maximum bandwidth and availability requests.
- Propose a method for policy implementation.

3. Study the effect of the proposed scheme and provide the comparative study with the benchmark schemes.
4. Develop utility functions according to business relationship models for preventing the selfishness of inter-domain path provisioning.
5. Propose a mathematical analysis for performance evaluation based on Continuous Time Markov Chain (CTMC).
6. Study the effect of policy implementation of two domains through analysis and numerical experiments.
7. Study the effect of policy implementation of three domains using a cascade model and a triangle model by conducting numerical experiments.

1.5 Methodology

1. Review the previous inter-domain routing policies, i.e. most-effort, least-effort and equal-distribution policies.
2. Propose an end-to-end QoS path provisioning scheme
   - Consider two constraints, namely, maximum bandwidth and availability requests.
   - Propose a method for policy implementation.
3. Study the effect of the proposed scheme and provide the comparative study with the benchmark schemes.
4. Develop utility functions according to business relationship models for preventing the selfishness of inter-domain path provisioning.
5. Propose a mathematical analysis for performance evaluation based on Continuous Time Markov Chain (CTMC).
6. Study the effect of policy implementation of two domains by simulation and numerical experiments.

7. Study the effect of policy implementation of three domains with a cascade model and a triangle model by numerical experiments.

1.6 Original Contributions

Main contributions of this thesis are as follows.

- This thesis proposes a new framework to solve the problem of end-to-end QoS provisioning in inter-domain networks (Chapter III). This framework comprises three stages: 1) the Path-Classification scheme to help in efficient QoS provisioning; 2) a loss network model is proposed for evaluating the QoS-level selection and to also be generalised to the three conventional policies, i.e., ME, LE and ED; 3) a non-cooperative game theory is applied to analyse the optimal QoS level apportionment of ISPs with respect to the utility function based on practical business models.

- Based on the non-cooperative problem, this work differs from others [15–17] in several key aspects. The main difference is that some of these studies [15–17] focus on the problem of inter-domain network routing in the inter connection level, while this work considers a QoS level apportionment for inter-domain traffic control in both the internal and inter connection levels.

- The investigations in this thesis is conducted by computer simulation. This thesis also extends the limit of that study by using mathematical analysis.

- This thesis rigorously investigates accuracy of the proposed loss network model with a discrete-time simulation and a performance evaluation of PC-Nash compared with the conventional policies ME, LE and ED. The results of all experiments show that PC-Nash outperforms these conventional policies. The discussion also provides a guideline of proper QoS level or conventional policies suitable in different scenarios.

1.7 Structure of Thesis

This thesis is organised as follows. Chapter II provides the necessary background of this thesis, which includes the basic considered QoS, the network model and the conventional path provisioning policies. Chapter III presents our proposed QoS provisioning framework with the Path-classification scheme under the Nash equilibrium (PC-Nash). Chapter IV evaluates the effectiveness of the path provisioning policies based on the topologies of two concatenated domains. In Chapter IV, Section 4.1 verifies the accuracy of the proposed loss network model, and Sections 4.2 and 4.3 evaluate the performance of the proposed framework and the conventional policies based on two domains without an interconnection link and two domains with an interconnection link, respectively. Chapter V presents the investigation of the path provisioning policies based on the hierarchical network. Chapter VI presents the extension of PC-Nash. Chapter VII concludes the main findings in this dissertation and discusses about the future work.

CHAPTER II

BACKGROUND

This chapter provides the fundamental principles supporting the end-to-end QoS path provisioning in inter-domain network. The focus of this section lines on the considered QoS parameters offered to end-customers, the conventional QoS path provisioning policies and the principle of non-cooperative game theory. The knowledge background and the deep discussion lead to a guideline and motivation for the proposed scheme in Chapter III.

2.1 Considered QoS parameters

The term QoS is defined by ITU-T Rec. E.800 as "*The collective effect of service performance which determines the degree of satisfaction of a user of the service.*" [35]. The goal of QoS offering is to provide end users a good experience when using a particular service. In fact, the QoS parameters depend on each application's requirement. In this thesis, only the main parameters offered by the ISP according to a per-connection basis, such as the effective bandwidth and minimum connection availability, are provisioned across multiple domains.

2.1.1 Bandwidth Guarantee

An important QoS parameter for which various services running on the Internet require is the bandwidth guarantee [35]. The network layer must play a critical role in the QoS provisioning process to achieve bandwidth guarantee. The existing studies adopt path provisioning protocols, e.g., Resource Reservation Protocol-Traffic Engineering extension (RSVP-TE) [22], Constraint-Based Label Distribution Protocol (CR-LDP) [36], and Border Gateway Protocol-TE (BGP-TE) [8], to achieve the end-to-end bandwidth guarantee. With the TE extension, routers whose role is a path decision selector calculate the appropriate route according to the bandwidth request of each service. For instance, MPLS-TE routes traffic flows across the network by dynamically allocating required resources within a given network capacity and topology [37]. The RSVP-TE reserves the needed resources in every intermediate router along the end-to-end path. The selected path is reserved for the streaming service according to the bandwidth request of the service [22]. For BGP-TE, the Bandwidth QoS Attribute (BWQA) is used to specify the bandwidth available in the Network Layer Reachability Information

(NLRI) field in order to ensure that the assigned route has a sufficient amount of bandwidth [8]. One can therefore use these extended protocols to provide end-to-end bandwidth guarantee. Nevertheless, these approaches are based on the maximum bandwidth reservation for every request. Doing this might cause inefficient network utilization because the sources often do not send the traffic at the peak load all the time. Therefore, the improved provisioning should rely on statistically multiplexing the shared connections in the same network equipment. In this regard, to encapsulate the packet-level QoS parameters, e.g. the packet loss ratio, latency, and jitter, in the call-level QoS, the required bandwidth can be mapped to the effective bandwidth or equivalent capacity [38, 39]. The reason for doing this is to ensure an efficient call-level bandwidth allocation and a packet-level guarantee.

2.1.2 Availability Guarantee

Network providers normally report the availability property of their transport networks to customers for the purpose of presenting the ability to withstand certain types of failures. It implies the length of the service outages. For example, three nines of physical unprotected availability or 99.9% means approximately nine hours of outage per year while five nines or 99.999% means approximately five minutes of outages per year [40]. This implies that an availability is a long-run average characterisation of a large pool of transport network devices. Let us define availability as the probability that a piece of network equipment is in the up-state at a given time interval. The availability of a single component can be calculated by using $\mathrm{MTTF}/(\mathrm{MTTF}+\mathrm{MTTR})$, where MTTF is the mean time to failure, and MTTR is the mean time to repair [41]. To approximate end-to-end path availability, the analysis is based on the following assumptions. A two-state (working and failed) model describes the component status. Each component fails independently. The service-time and repair-time have the independent memoryless properties. And MTTR is much smaller than MTTF [41]. In addition, network providers can increase their end-to-end route availability by adding the redundant components in a proper standard technique such as one-for-one (1+1) protection, one-to-one (1:1) protection and one-for-N (N+1) protection [42]. In order to provision a route across multiple domains, the provisioning process is sequentially conducted by the domains from the sources to the destinations. The first domain has to offer the path with the availability of at least equal to the availability requested. Then, the availability target is updated to the second domain and so on. For a sequential path provisioning process associated with a target availability constraint, a proper end-to-end route must satisfy the availability request for a call.

2.2 Network Model

The inter-domain network model is defined as a directed graph $\mathcal{G}(\mathcal{V}, \mathcal{L})$, where $\mathcal{V}$ denotes the set of nodes and $\mathcal{L}$ is the set of links in a network. Let k_i denote a *path* of domain i connecting an ingress node to an egress node (referred to as the border node when the destination is outside domain i). The set of links in path k_i is referred to as $\mathcal{L}(k_i) \subset \mathcal{L}$. Here, $\mathcal{R}$ is defined as the set of routes for all possible origin-destination pairs in the network. Also, route r is expressed as the set of paths whereby a connection traverses from its origin to its destination. The route profile matrix $\mathbf{R} = [R_{r,l} : r \in \mathcal{R}, l \in \mathcal{L}]$ is defined as the matrix of route-link indices, where $R_{r,l} = 1$ if link l is on route r; otherwise, $R_{r,l} = 0$.

Suppose that a call of type $s \in S$, where S is the set of call types, requests the end-to-end QoS with required bandwidth b_s and availability a_s for its connection. The term *bandwidth* refers to the effective bandwidth or equivalent capacity [38, 39]. That is, if every call is supported at its effective bandwidth value, then all the packet-level QoS parameters (e.g. packet loss ratio, latency and jitter) of that call can be guaranteed.

The term *availability* refers to the probability that a route from its origin to destination is operable. Every call must be supported by the route of which availability is at least equal to the availability request of that call. In the path provisioning process, upon a new call arrival, the ISPs must check whether the remaining capacity and availability of their paths satisfy the requested QoS of the call. To define the remaining capacity and availability of path k_i, for link l, let its capacity and availability be c_l and $A(l)$, respectively.

The remaining capacity of path k_i depends on the number of ongoing connections in the links of path k_i. The system state is defined as $\mathbf{n} = [n_{r,s} : r \in \mathcal{R}, s \in S]$, where $n_{r,s}$ is the number of ongoing type-s connections on route r. The remaining capacity of path k_i, when the network is in state $\mathbf{n}$, is defined as

$$C(k_i, \mathbf{n}) = \min_{l \in \mathcal{L}(k_i)} \left[c_l - \sum_{r \in \mathcal{R}} R_{r,l} \sum_{s \in S} b_s n_{r,s} \right]. \tag{2.1}$$

The availability is measured in the steady state from $MTTF/(MTTF+MTTR)$ [41], where $MTTF$ is the mean time to failure and $MTTR$ is the mean time to repair. Given the assumption of independent link failure, the availability of path k_i depends on only the availability of links in path k_i as

$$A(k_i) = \prod_{l \in \mathcal{L}(k_i)} A(l). \tag{2.2}$$

Suppose that an inter-domain connection set-up request passes through domains $1, \ldots, h$ sequentially, and that domain i assigns path k_i^* to the request. Note that in this research the request is processed through the call admission control (CAC) agent of each domain sequentially, i.e., without the crank-back mechanism [43] or the QoS parameter renegotiation [44]. As a result, the connection can be established successfully if all the following constraints are satisfied:

$$C(k_i^*, \mathbf{n}) \geq b_s \quad \text{for } i = 1, \ldots, h, \tag{2.3}$$

$$A(k_1^*) \geq a_s, \tag{2.4}$$

$$A(k_i^*) \geq a_s / \prod_{j=1}^{i-1} A(k_j^*) \quad \text{for } i = 2, \ldots, h. \tag{2.5}$$

Based on (2.3)–(2.5), the CAC constraints are updated for each domain and necessary target values for the constraints must be forwarded from upstream domain $i-1$ to downstream domain i. Let $b_{i,s}^t$ and $a_{i,s}^t$ be the target bandwidth and availability values that must be satisfied by domain i for the establishment of a new type-s connection. Based on these sequentially updated target values, (2.3)–(2.5) can be rewritten as

$$b_{i,s}^t = b_s \quad \text{for } i = 1, \ldots, h, \tag{2.6}$$

$$a_{1,s}^t = a_s \tag{2.7}$$

$$a_{i,s}^t = a_s / \prod_{j=1}^{i-1} A(k_j), \quad \text{for } i = 2, \ldots, h. \tag{2.8}$$

Let $\mathcal{K}_i$ be the set of all possible paths in domain i. When the network is in state $\mathbf{n}$, the set of paths that can be provisioned to the type-s call arriving at domain i is then expressible as

$$\tilde{\mathcal{K}}_i(s, \mathbf{n}) = \left\{ k_i \in \mathcal{K}_i : C(k_i, \mathbf{n}) \geq b_{i,s}^t, A(k_i) \geq a_{i,s}^t \right\}. \tag{2.9}$$

Note that the paths in $\tilde{\mathcal{K}}_i(s, \mathbf{n})$ change in accordance with the type of connection request and the number of ongoing connections. A connection request is rejected if $\tilde{\mathcal{K}}_i(s, \mathbf{n}) = \emptyset$ for some $i \in \{1, \ldots, h\}$. In practice, no matter if the crank-back or QoS renegotiation is in place, $a_{i,s}^t$ increases with i and is always greater than a_s for all i for inter-domain QoS provisioning because the availability values a_s and $A(k_i)$ are always less than 1. The decision of a domain in assigning qualified paths to a connection request directly affects the remaining possible paths that can be assigned in subsequent domains.

2.3 Conventional Path Provisioning Policies

This section considers three conventional policies of apportioning the end-to-end QoS responsibility among transit networks, namely most-effort, least-effort and equal-distribution policies [13].

2.3.1 Most-Effort Policy: ME

In ME, an ISP always takes the highest responsibility for an availability request. The highest-availability path that justifies both the capacity and availability constraints is chosen by mutual agreement of each domain. Hence, with ME, the proper path selected by domain i for a connection request of type-s, when the network is in state **n**, can be expressed mathematically as

$$k_i^* = \arg\max_{k_i \in \tilde{\mathcal{K}}_i(s,\mathbf{n})} A(k_i). \tag{2.10}$$

2.3.2 Least-Effort Policy: LE

In LE, in contrast to ME, an ISP may want to act upon the availability request in the opposite way. In LE, the lowest-availability path that justifies both the capacity and availability constraints is chosen by each domain. Mathematically, with LE, one can then write

$$k_i^* = \arg\min_{k_i \in \tilde{\mathcal{K}}_i(s,\mathbf{n})} A(k_i). \tag{2.11}$$

2.3.3 Equal-Distribution Policy: ED

For ME and LE, the relative responsibility in availability assignment is of higher burden towards the upstream and downstream domains, respectively. This can cause an imbalance in QoS apportioning, especially when the upstream or downstream domains cannot match their candidate paths with the requested target values of availability. To alleviate such a problem, ED attempts to allocate the level of responsibility equally among ISPs along the route. Suppose that there are h ISPs or domains along the route. For ED, define

$$k_i^* = \arg\min_{k_i \in \tilde{\mathcal{K}}_i(s,\mathbf{n})} \left\{ A(k_i) : A(k_i) \geq a_{i,s}^{ED} \right\}, \tag{2.12}$$

where

$$a_{1,s}^{ED} = \sqrt[h]{a_s} \tag{2.13}$$

and, for $i = 2, \ldots, h$,

$$a_{i,s}^{ED} = \min \left\{ \sqrt[h]{a_s}, \left(\frac{a_s}{\prod_{j=1}^{i-1} A(k_j)} \right)^{1/(h-i+1)} \right\} \tag{2.14}$$

$$= \left(\frac{a_s}{\prod_{j=1}^{i-1} A(k_j)} \right)^{1/(h-i+1)} \tag{2.15}$$

In (2.13) and (2.14), the term $\sqrt[h]{a_s}$ is meant for ensuring that, in the worst case scenario, each domain must try to maintain the assigned path availability such that the overall end-to-end availability of the connection to be established can meet the requested target of a_s. However, if the upstream domains have already assigned their path availability, which is better than $\sqrt[h]{a_s}$, then it should be possible that the later domains can assign the path with smaller availability as long as its assignment does not result in the accumulative burden of availability assignment, which is more difficult than the value agreed by ED. This is expressed in the second term in the $\min$ operator of (2.14). Since the denominator $\prod_{j=1}^{i-1} A(k_j)$ of this second term is always less than 1, one can obtain (2.15).

2.4 Principle of Game Theory

Among the conflicts of interest and the highly competitive nature of telecommunications industry, game theory plays an important role in widely substantive telecommunication problems, e.g., resource sharing among wireless devices [45], call admission control for mobile multimedia communications [46], traffic flow control in wire network [47], [48] and the interconnection charge between two domains [16]. Game theory is widely used to model such conflicts. In order to formulate the problem of conflicts with a game theoretical framework, one needs to define the players of the game and all the possible strategies for each player. Thus, the decision makers are mapped to the players, and their possible actions are considered as their strategies. The game's outcome or payoff refers to the output after the actions are taken. In addition, game theory assumes that all the players are rational and strive to maximize their outcome. Of course, the outcome might sometimes be difficult to evaluate. Instead of a direct analysis via the game outcome, the outcome is usually transformed into a utility which represents the players' preference to their outcomes. For example, let $\ddot{a}$ and $\ddot{b}$ be the game outcomes of player i when the player has applied strategies $\ddot{A}$ and $\ddot{B}$ to the game, respectively. Assume that player i prefers outcome $\ddot{b}$ to outcome $\ddot{a}$ or mathematically written as $\ddot{b} \succ \ddot{a}$, if and only if, the utility of outcome $\ddot{b}$ is greater than the utility of outcome $\ddot{a}$ ($u_i(\ddot{b}) > u_i(\ddot{a})$). Hence, with the utility transformation, the game can be analysed on mathematical basis. Since the outcomes of a game depend on the strategic actions and reactions of all the players, such a game is called a strategic-game.

There are two types of strategic-games, i.e., "non-cooperative" and "cooperative" [49]. A non-cooperative game is a game associated with a strong assumption of no pre-play communication between players or no agreement in order to force each player to make a specific action. On the other hands, a cooperative game allows all players to negotiate and make binding agreements. From the nature of the inter-domain network problem, autonomous systems are often not willing to make a binding agreement or share any internal information. Therefore, such a problem should be modelled by a game in a non-cooperative manner. Moreover, the inter-domain problem can be seen as a non-zero-sum non-cooperative game because it is not "a win-lose strategic game". This game is that one can lose while the others may not gain.

To analyse how other players would react to one player's move, one needs take into account all the possible reactions to future actions as far ahead as possible. One has to look as far into the game as possible, and then, reason backward to figure out which action is best for each player should select. Such a solution to a non-zero-sum non-cooperative game can be found by solving for a Nash equilibrium. A finite n-person of non-zero-sum non-cooperative game is given n-finite-pure-strategy sets ($X_1, X_2, \ldots, X_n$). Define $u_j(x_1, \ldots, x_{j-1}, x_j, x_{j+1}, \ldots, x_n)$ as the utility of player j when the deployed pure-strategies of players are $x_1, \ldots, x_{j-1}, x_j, x_{j+1}, \ldots, x_n$ with $x_j \in X_j$ for $j = 1, 2, \ldots, n$ [50]. A vector of pure strategy choices $(x_1, \ldots, x_{j-1}, x_j, x_{j+1}, \ldots, x_n)$ is said to be a Nash equilibrium, if and only if, for all $j = 1, 2, \ldots, n$ and for all $\ddot{x}_j \in X_j$,

$$u_j(x_1, \ldots, x_{j-1}, x_j, x_{j+1}, \ldots, x_n) \geq u_j(x_1, \ldots, x_{j-1}, \ddot{x}_j, x_{j+1}, \ldots, x_n). \tag{2.16}$$

By definition, the Nash equilibrium is a point where all the players play the game with their best strategy against another. However, the pure-strategy Nash equilibrium may not exist in some games.

In fact, the players might learn to play the game by choosing the best pure-strategy against other players' actions. The best strategy might change in each turn if there is no pure-strategy Nash equilibrium in the game. The accumulated number of times each strategy is chosen divided by the total number of turns referring to the probability that the strategy should be used. In this case, a Nash equilibrium is said to be mixed strategies. Suppose vector $X_j = (1, 2, \ldots, m_j)$ denotes the pure strategies of player j. Let $P_j = (p_{j,1}, p_{j,2}, \ldots, p_{j,m_j})$ be the probability vector of player j for m_j strategies, where $p_{j,k} \geq 0$ and $\sum_{k=1}^{m_j} p_{j,k} = 1$. Player j can apply the probability vector P_j in a set of mixed strategies $\mathcal{P}_j$ to react to other players. The average utility of player j is given by [50]

$$U_j(P_1, P_2, \ldots, P_n) = \sum_{k_1=1}^{m_1} \sum_{k_2=1}^{m_2} \cdots \sum_{k_n=1}^{m_n} p_{1,k_1} p_{2,k_2} \cdots p_{n,k_n} u_j(k_1, k_2, \ldots, k_n). \tag{2.17}$$

A vector of mixed strategies $(P_1, P_2, \ldots, P_n)$ with $P_j \in \mathcal{P}_j$ for $j = 1, 2, \ldots, n$ is said to be a Nash equilibrium, if and only if, for all $j = 1, 2, \ldots, n$, and for all $P \in \mathcal{P}_j$,

$$U_j(P_1, P_2, \ldots, P_{i-1}, P_i, P_{i+1} \ldots, P_n) \geq U_j(P_1, P_2, \ldots, P_{i-1}, P, P_{i+1}, \ldots, P_n). \tag{2.18}$$

Thus, the vector of probabilities of all players which satisfies (2.18) is the best response to each other. A Nash equilibrium can always be found by using a mixed-strategy approach [49].

2.5 Summary

This chapter provides the necessary background of this dissertation by drawing an attention to the end-to-end QoS guarantee. Based on the basic technique of QoS support, the considered QoS parameters include two common QoS parameters, namely, bandwidth and availability requests. The approaches in this dissertation take into consideration the term bandwidth which refers to the effective bandwidth or equivalent capacity. With that amount of reserved bandwidth, each request can be guaranteed its necessary QoS parameters on the packet level. The sections that follow present the network model and describe the process of provisioning the end-to-end QoS in the inter-domain networks. To approach the problem of this dissertation, the difficulty of the end-to-end QoS support in the inter-domain networks is pinpointed. This dissertation focusses on the conventional path provisioning policies (ME, LE and ED) which are presented in detail here. The approach of this dissertation concentrates on the problem of end-to-end QoS path provisioning for the non-cooperation among multiple domains. Therefore, the principle of game theory is provided. Now that the necessary background for understanding the end-to-end QoS path provisioning problem has been discussed, the next chapter proposes the new scheme for handling this problem.

CHAPTER III

PROPOSED QOS PROVISIONING FRAMEWORK WITH PATH-CLASSIFICATION SCHEME UNDER NASH EQUILIBRIUM: PC-NASH

In practice, ISPs have several choices of proper paths for constructing an end-to-end QoS connection together. These choices have a variety of QoS levels. Challenges arise when ISPs must try to achieve their efficiency in resource usage and, at the same time, satisfactory QoS for the inter-domain request. By the equity or net neutrality principle, a regulation is usually in place to prevent an ISP from treating the traffic of the same type differently according to their originating domains (e.g. from their own customers as well as from the other domains of competing ISPs). As a result, if that principle is strictly implemented, then the suggested selection of paths for all traffic may need to be done randomly, regardless of their ownership. In doing so, the overall efficiency of a network, however, can be adversely affected.

This chapter proposes a QoS provisioning framework with the so-called Path-Classification scheme under Nash equilibrium (PC-Nash) to help facilitate the trade-off between such equity treatment as well as the resultant expected efficiency. The essence of PC-Nash is to partition the set of all possible paths of each domain into *path groups* according to their QoS levels. Upon a connection request, a path group with a proper QoS level is first chosen for the request, and the actual path to be tried by the request is chosen uniformly randomly from all paths within that group. The effect of random path selection is thus confined to how possible paths are grouped together.

PC-Nash is defined in three stages: (1) QoS provisioning with Path-Classification scheme, (2) evaluation of QoS-level selection and (3) game-theoretical analysis of optimal QoS-level selection. In the first stage (given in Subsection 3.1), all possible paths are sorted in ascending order by their path availabilities, which are then quantised into QoS levels. In the second stage (given in Sections 3.2 and 3.3), the selected QoS levels are evaluated in terms of utility functions. In the third stage (given in Sections 3.4 and 3.5), the optimal QoS level of path group selection is identified by using a non-cooperative game theoretical framework.

3.1 QoS Provisioning with Path-Classification Scheme

Suppose a type-s call traverses h domains, with the sequence of domains $(1,\ldots,h)$, and domain i adopts the Path-Classification scheme. After the upstream domains $j = 1,\ldots,i-1$ have assigned their paths, the bandwidth and availability targets for domain i are updated by $b^t_{i,s}$ and $a^t_{i,s}$, respectively. The proposed QoS provisioning framework is comprised of three steps

Step 1: QoS Ranking: All the paths in $\tilde{\mathcal{K}}_i(s,\mathbf{n})$ are sorted in ascending order by using the logarithm of their availability values from $\min_{k_i\in\tilde{\mathcal{K}}_i(s,\mathbf{n})}\log(A(k_i))$ to $\max_{k_i\in\tilde{\mathcal{K}}_i(s,\mathbf{n})}\log(A(k_i))$.

Step 2: Path Classification: Apply a linear quantisation to the QoS scale between the minimum and maximum log availability values. For domain i, their paths in $\tilde{\mathcal{K}}_i(s,\mathbf{n})$ are then classified into D_i path groups, each corresponding to the equally quantised QoS level.

Step 3: Path Selection: With a pre-specified QoS level d_i, this QoS provisioning framework allows domain i to select any path from group d_i, where $d_i \in \{1,\ldots,D_i\}$ and D_i is the highest QoS level in domain i. Thus, let us denote the set of paths that can be assigned to a type-s call with the QoS level $d_i = 1,\ldots,D_i$ of domain i when the network is in state $\mathbf{n}$ as $\Gamma_i(s,\mathbf{n},d_i) \subset \tilde{\mathcal{K}}_i(s,\mathbf{n})$. The paths in $\Gamma_i(s,\mathbf{n},d_i)$ will be randomly selected for a type-s call with probability $1/|\Gamma_i(s,\mathbf{n},d_i)|$. Note that if $\Gamma_i(s,\mathbf{n},d_i) = \emptyset$ and $\tilde{\mathcal{K}}_i(s,\mathbf{n}) \neq \emptyset$, then domain i is allowed to choose a path in the next lower level with maximum availability. This relaxation can decrease the unnecessary call rejection. Note also that whichever QoS level d_i is selected, the assigned paths always satisfy both the bandwidth and availability targets.

Figure 3.1 shows an example of this QoS provisioning framework with the Path-Classification scheme when $\tilde{\mathcal{K}}_i(s,\mathbf{n}) = \{1,2,\ldots,7\}$ and $D_i = 3$.

The proposed QoS provisioning framework with the Path-Classification scheme can be considered as a general representation of all three existing path provisioning policies: ME, LE and ED. In particular, our framework results in ME, LE and ED with d_i being set to D_i, 1 and a proper intermediate value between 1 and D_i, respectively. This generalised expression becomes exact at the limit with a large number of QoS levels ($D_i \to \infty$).

In practice, the Path-Classification scheme can usually be implemented independently by each domain. ISPs adjust their selection to achieve their own objectives, such as maximum chance of call success or least bandwidth consumption. In the long run, if ISPs can learn of the returned reward upon the completion of their selections and try to adapt their QoS-level selection strategies rationally,

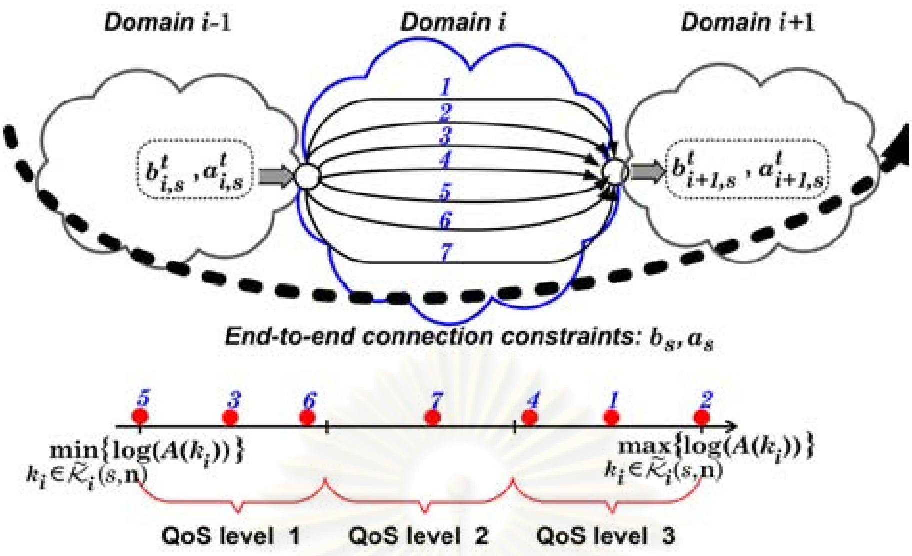


Figure 3.1 Example of Path-Classification scheme: $\tilde{\mathcal{K}}_i(s, \mathbf{n}) = \{1, 2, \ldots, 7\}$ and $D_i = 3$

one may expect convergence to the best QoS provisioning solution. With PC-Nash, we allow such adaptation to occur in the constrained environment of non-cooperative Nash equilibrium. To identify the equilibrium, one needs first to find an efficient way of evaluating the long-run averages of performance or utility values of interest. In this regard, an analytical model is herein proposed within the loss network framework [51].

3.2 Evaluation of QoS-level Selection

3.2.1 Assumptions

- The network is modelled as a loss network [51] with alternative routing. The incoming call can access any route that satisfies the QoS requirement and corresponds to the routing policy. If a call request cannot be accepted because the corresponding route is not available, then the call will be blocked.

- Poisson arrivals and exponentially distributed holding times are assumed for every origin-destination pair. The mean call arrival rate and the mean call holding times do not depend on the system state. This property can be useful in justifying the Markovian assumption in the Continuous Time Markov Chain (CTMC) model. Hence, the number of calls in the system is modelled by a stationary and ergodic Markov chain.

- The state space of possible network states is finite because every route has a finite capacity and every call will be assigned a certain amount of bandwidth associated with its request.

3.2.2 Loss Network Model of Proposed Framework with Path-Classification Scheme

Let v_o and v_t be the originating and terminating nodes for a call request in $\mathcal{V}$. Thus, node v_o is in domain 1 and node v_t is in domain h. Let the mean arrival rate and the mean holding time of type-s calls from nodes v_o to v_t be $\lambda_s(v_o, v_t)$ and $1/\mu_s(v_o, v_t)$, respectively. A state of the Markov chain can be defined as the matrix of the number of calls from every type and on every route, $\mathbf{n} = [n_{r,s} : r \in \mathcal{R}, s \in S]$. The state space, which represents the states in which the reserved bandwidth in every link is not greater than the link capacity, is denoted as

$$\Omega = \left\{ \mathbf{n} : \mathbf{R}^T \mathbf{n} \mathbf{b} \leq \mathbf{C} \right\}, \tag{3.1}$$

where column vectors $\mathbf{b} = [b_s : s \in S]$ and $\mathbf{C} = [c_l : l \in \mathcal{L}]$.

Assume that all domains along the end-to-end connection implement the proposed QoS provisioning framework with the Path-Classification scheme and domain i selects QoS level d_i. At state $\mathbf{n}$, domain i classifies its paths in $\tilde{\mathcal{K}}_i(s, \mathbf{n})$ into D_i groups. With selected d_i, path $k_i^* \in \Gamma_i(s, \mathbf{n}, d_i)$, which satisfies the QoS request of type-s calls, will be randomly selected with the probability

$$\mathbb{P}_{k_i^*}(s, \mathbf{n}, d_i) = \begin{cases} 1/|\Gamma_i(s, \mathbf{n}, d_i)|, & k_i^* \in \Gamma_i(s, \mathbf{n}, d_i) \\ 0, & \text{otherwise}, \end{cases} \tag{3.2}$$

where $\Gamma_i(s, \mathbf{n}, d_i) \neq \emptyset$. Note that if $\Gamma_i(s, \mathbf{n}, d_i) = \emptyset$ and $\tilde{\mathcal{K}}_i(s, \mathbf{n}) \neq \emptyset$, then domain i selects path k_i^* in the next lower QoS level with maximum availability with probability 1.

Note that although the paths in $\tilde{\mathcal{K}}_i(s, \mathbf{n})$ and $\Gamma_i(s, \mathbf{n}, d_i)$ depend on the selected paths along the upstream domains ($j = 1, \ldots, i-1$), the events in which a path in $\Gamma_i(s, \mathbf{n}, d_i)$ is selected and a path in $\Gamma_j(s, \mathbf{n}, d_j)$ is selected are independent due to the randomisation principle of path selection within the selected path groups. As a result, given ($s, \mathbf{n}, d_j$ for all j's), the probability that paths $k_1^*, \ldots, k_i^*$ are selected is equal to

$$\prod_{j=1}^{i} \mathbb{P}_{k_j^*}(s, \mathbf{n}, d_j). \tag{3.3}$$

Consequently, the probability that route $r^* = \{k_1^*, \ldots, k_h^*\}$ will be selected for type-s calls arriving at state $\mathbf{n}$ is expressible as

$$\mathbb{P}_{r^*}(s, \mathbf{n}, \mathbf{d}) = \prod_{i=1}^{h} \mathbb{P}_{k_i^*}(s, \mathbf{n}, d_i), \tag{3.4}$$

where $\mathbf{d} = (d_1, \ldots, d_h)$.

Let $\mathbf{e}_{r,s}$ be the unit matrix with a 1 in the r-th row and s-th column. If route r^* is assigned for the incoming call of type-s from origin-destination pair (v_o, v_t) at state $\mathbf{n}$, the state transition rate from $\mathbf{n}$ to $\mathbf{n}+\mathbf{e}_{r^*,s}$ is obtained from

$$\mathbb{P}_{r^*}(s,\mathbf{n},\mathbf{d})\lambda_s(v_o,v_t), \tag{3.5}$$

where $\mathbf{n},\mathbf{n}+\mathbf{e}_{r^*,s}\in\Omega$. For the outgoing (completed) calls of type-s from origin-destination pair (v_o,v_t) on route r^* at state $\mathbf{n}$, the state transition rate from $\mathbf{n}$ to $\mathbf{n}-\mathbf{e}_{r^*,s}$ is obtained from

$$n_{r^*,s}\mu_s(v_o,v_t), \tag{3.6}$$

where $n_{r^*,s}$ is the number of ongoing type-s connections on route r^* and $\mathbf{n},\mathbf{n}-\mathbf{e}_{r^*,s}\in\Omega$.

With the transition rates from (3.5) and (3.6), the steady-state probability $\pi(\mathbf{n})$ associated with the implemented policy can be found by solving the normalisation condition and global-balance equations of the resultant Markov chain. Define the set of blocking states of type-s call for origin-destination pair (v_o,v_t) as

$$\Omega_B(s,v_o,v_t)=\{\mathbf{n}\in\Omega:\mathbf{n}+\mathbf{e}_{r,s}\notin\Omega,\forall r\in\mathcal{R}(v_o,v_t)\}\,. \tag{3.7}$$

where $\mathcal{R}(v_o,v_t)\subset\mathcal{R}$ is the set of possible routes for origin-destination pair (v_o,v_t).

Then, the acceptance probability of type-s calls in domain i for origin-destination pair (v_o,v_t) can be calculated as follows:

$$\mathbb{A}_{i,s}(v_o,v_t)=1-\sum_{\mathbf{n}\in\Omega_B(s,v_o,v_t)}\pi(\mathbf{n}). \tag{3.8}$$

The mean number of accepted type-s calls in domain i can be computed from

$$\sigma_{i,s}=\sum_{v_o,v_t}\mathbb{A}_{i,s}(v_o,v_t)\lambda_s(v_o,v_t)/\mu_s(v_o,v_t). \tag{3.9}$$

And the call-level mean bandwidth usage of domain i at its point of interconnection is given by

$$w_i=\sum_{s,v_o,v_t}\mathbb{A}_{i,s}(v_o,v_t)b_s\lambda_s(v_o,v_t)/\mu_s(v_o,v_t). \tag{3.10}$$

3.2.3 Loss Network Model of ME, LE and ED Policies

For completeness, this subsection extends the loss network model to analyse the ME, LE and ED policies since their original formulation appear only with a computer simulation model [13]. The method to construct corresponding Markov chains for these three policies is the same as in Subsection 3.2.2. The only difference is that (3.2) must be modified in accordance with each policy. For ME, LE and ED, parameter d_i in $\mathbb{P}_{k_i^*}(s,\mathbf{n},d_i)$ of (3.2) can be omitted. Similarly, parameter $\mathbf{d}$ in $\mathbb{P}_{r^*}(s,\mathbf{n},\mathbf{d})$ of (3.4) can also be omitted. Then, $\mathbb{P}_{k_i^*}(s,\mathbf{n},d_i)$ and $\mathbb{P}_{r^*}(s,\mathbf{n},\mathbf{d})$ can be rewritten here as $\mathbb{P}_{k_i^*}(s,\mathbf{n})$ and $\mathbb{P}_{r^*}(s,\mathbf{n})$, respectively.

- With all domains implementing ME, all ISPs select the path according to (2.10). Thus, (3.2) is replaced by

$$\mathbb{P}_{k_i^*}(s,\mathbf{n}) = \begin{cases} 1, & k_i^* = \underset{k_i \in \tilde{\mathcal{K}}_i(s,\mathrm{n})}{\arg\max} A(k_i) \\ 0, & \text{otherwise}. \end{cases} \tag{3.11}$$

- With all domains implementing LE, the paths are selected according to (2.11). Thus, (3.2) is replaced by

$$\mathbb{P}_{k_i^*}(s,\mathbf{n}) = \begin{cases} 1, & k_i^* = \underset{k_i \in \tilde{\mathcal{K}}_i(s,\mathrm{n})}{\arg\min} A(k_i) \\ 0, & \text{otherwise}. \end{cases} \tag{3.12}$$

- With all domains implementing ED, define the set of paths that satisfy ED policy as

$$\tilde{\mathcal{K}}_i^{ED}(s,\mathrm{n}) = \left\{ k_i \in \tilde{\mathcal{K}}_i(s,\mathrm{n}) : A(k_i) \geq a_{i,s}^{ED} \right\}. \tag{3.13}$$

Thus, (3.2) is replaced by

$$\mathbb{P}_{k_i^*}(s,\mathbf{n}) = \begin{cases} 1, & k_i^* = \underset{k_i \in \tilde{\mathcal{K}}_i^{ED}(s,\mathrm{n})}{\arg\min} A(k_i) \\ 0, & \text{otherwise}. \end{cases} \tag{3.14}$$

Finally, for ME, LE and ED, (3.4) can be replaced by

$$\mathbb{P}_{r^*}(s,\mathbf{n}) = \prod_{i=1}^{h} \mathbb{P}_{k_i^*}(s,\mathbf{n}). \tag{3.15}$$

The transition rates of the Markov chains for ME, LE and ED are the same as (3.5) with $P_{r^*,s}(s,n,d)$ being replaced by $P_{r^*,s}(s,n)$ and (3.6). Performance of ME, LE and ED can be evaluated from (3.8)–(3.10).

Note that the performance of ME, LE and ED can be directly obtained, while the performance of PC-Nash needs to be further searched in the utility space for Nash equilibrium. The utility definition and resultant game-theoretical analysis of the optimal QoS level is described in Sections 3.3–3.5.

3.3 Utility Function

This chapter has adopted the utility functions to express ISP profits and costs from the business models proposed by [13]. There are two types of business models at the point of interconnection, (1) peer and (2) customer-provider.

Peer model is used for adjacent ISPs that have agreed to trade their traffic flows equally. Hence, there is no exchange of payment between the ISPs. Therefore, only the cost of reserved bandwidth is reflected in the peer utility function. The utility value of domain i is

$$u_i = -\beta_i w_i, \tag{3.16}$$

where w_i is the mean bandwidth usage of domain i and each bandwidth unit costs β_i monetary units.

Customer-provider models represent the fee-charging agreement by adjacent domains for exchanging traffic flows. There are two models: (1) retail service and (2) wholesale service. In the retail service model, providers charge their customers in accordance with the requested type of service. For example, ISPs may charge on the basis of guaranteed availability. The utility function of the retail service model is

$$u_i = \sum_{s \in S} g_i(a_s)\sigma_{i,s} - \beta_i w_i, \tag{3.17}$$

where $\sigma_{i,s}$ is the mean number of accepted type-s calls in domain i and $g_i(a_s)$ is the revenue in monetary units per call, which depends on the availability request a_s. In the wholesale service model, customers are charged at the same price regardless of the guaranteed availability. Thus, the utility function is similar to that for retail service except for the revenue term. For the wholesale service model [13], the charge per connection is the same for all call types, i.e., $g_i(a_s)$ can be set to a constant that is not dependent on s.

3.4 Non-Cooperative Game in PC-Nash

In PC-Nash, a non-cooperative game is proposed for determining an optimal QoS level. The action of choosing the preferred QoS-level d_i for each domain i is defined as the game strategy of player i (referring to domain i). Each game player tries to maximise its own utility values based on the business models at its corresponding point of interconnections.

Given the nature of interactions between ISPs, an ISP can learn from the actions of other ISPs and adjust its strategy accordingly. This behavior is mapped to sequential actions and reactions between players. Strategies with appropriate probabilities are eventually selected. This type of probabilistic selection is called a mixed strategy (see [49]).

For this game formulation, let $u_i(\mathbf{d})$ denote the utility of domain i, given the QoS-level setting by all domains in **d**. Recall that domain i classifies the paths into D_i groups. The strategy space of domain i is defined to cover all possible path categories. QoS-level d_i, where $d_i = 1, \ldots, D_i$, is denoted as strategies of domain i. All possible combinations of strategies are then $\prod_{\forall i} D_i$. Domain i assigns the probability p_{d_i} to strategy d_i. Define the probability

$$\mathbb{P}(\mathbf{d}) = \prod_j p_{d_j}.$$

The expected utility for domain i is then obtainable from

$$E[U_i] = \sum_{\forall \mathbf{d}} \mathbb{P}(\mathbf{d}) u_i(\mathbf{d}), \tag{3.18}$$

for all $[p_{d_i} : d_i \in \{1 \ldots, D_i\}]$ for all i's. Suppose that the expected utility $E[U_i^*]$ can be obtained by applying probability vectors $[p^*_{d_i} : d_i \in \{1 \ldots, D_i\}]$ for all i's into (3.18). A mixed-strategy profile $\big([p^*_{d_i} : d_i \in \{1 \ldots, D_i\}], \forall i\big)$ is a Nash equilibrium if, and only if, $E[U_i^*] \geq E[U_i]$ for $[p_{d_i} : d_i \in \{1, \ldots, D_i\}]$ for all i's. The optimal point obtained by arriving at a Nash equilibrium in a mixed-strategy game can be used to represent the performance of PC-Nash.

3.5 Algorithm for Finding PC-Nash Performance

It is well known that there is a Nash equilibrium for this mixed-strategy game [49]. To find a Nash equilibrium, we have adopted a stochastic learning algorithm, called the method of successive averages (MSA) [52]. The essence of MSA is to emulate the learning behavior of game players in searching for their best expected utilities. The MSA algorithm can be summarised in the following steps.

Step 0: Initialise probability p_{d_i} to $1/D_i$ for all i's and set the current iteration number n to 1.

Step 1: Let each domain $i = 1, \ldots, h$ take turns in updating its strategy selection probability as follows. For a domain i, select the strategy $\widehat{d}_i$ that maximises the average utility of domain i:

$$\widehat{d}_i = \mathop{\arg\max}_{\tilde{d}_i \in \{1,\ldots,D_i\}} \left\{ \sum_{\forall \mathbf{d}: d_i = \tilde{d}_i} \mathbb{P}(\mathbf{d}) u_i(\mathbf{d}) \right\}. \tag{3.19}$$

Set η_{d_i} to 1 if strategy d_i is selected ($d_i = \widehat{d}_i$); otherwise, set it to 0. Then, update the probability of domain strategy: $p_{d_i} \leftarrow (1/n)\eta_{d_i} + (1 - (1/n))p_{d_i}$ for all $d_i \in \{1, \ldots, D_i\}$.

Step 2: Update iteration number $n \leftarrow n + 1$ and return to Step 1 unless utilities $E[U_i]$ of all i's converge.

If (3.19) in Step 1 gives multiple solutions, then the corresponding strategies are here randomly selected in a uniform manner. The Nash equilibrium is found at the end of this process. The obtained probability vectors, $[p^*_{d_i} : d_i \in \{1, \ldots, D_i\}]$ for all i's, represent the optimal probabilities of the strategies as recommended for individual domains in this proposed PC-Nash framework.

For practical implementation of PC-Nash, the call admission and routing decisions can be made in real-time because the decision maker at each domain can immediately assign a proper path (that satisfies the QoS criteria) within the domain to incoming calls according to the pre-chosen QoS level. Or if no such path is available, then the incoming call can be immediately rejected. In a longer time scale, based on the collective information of reward or penalty obtained from individual call admission and routing decisions, each domain then adjusts its proper QoS level by a stochastic learning process e.g. MSA.

Therefore, the optimal operating point of PC-Nash can be promptly used at the convergence time. The proof in [53] shows that the solution by MSA always converges to a certain point, which is an equilibrium point. The convergence time of Nash equilibrium depends on the size of strategy space—related to the number of domains and QoS levels of each domain. The convergence time of Nash equilibrium in the worst case is considered as in the order of polynomial time of the number of domains and strategies [54, 55]. However, the convergence speed can be improved by adjusting the step size ($1/n$) of MSA following the suggestion in [53]. Based on numerical results in this paper, MSA has been found to converge quickly within 10 iterations because the size of the strategy space for inter-domain networks is usually not very large. PC-Nash, therefore, can be applied for time-sensitive applications without any effect on routing decision delay.

Since PC-Nash is employed for end-to-end QoS path provisioning in inter-domain networks, the approach is intended to be scalable to the network dimension of individual domain as well as to the number of domains along the route. Instead of dealing with hugely detailed routing information when the network size is large, the router can take the advantage of aggregated routing information readily provided by the proposed path classification framework. As a result, the necessary signalling information for path selection of each domain only marginally grows with the number of QoS levels. In addition, PC-Nash does not require any additional TE signallings to be forwarded over the whole route of inter-domain networks. Only local information is sufficient for each domain running PC-Nash to perform the long-run QoS-level adjustment. For this reason, PC-Nash can be separately implemented by individual domains and its implementation is readily scalable.

CHAPTER IV

EFFECTIVENESS OF PATH PROVISIONING POLICIES

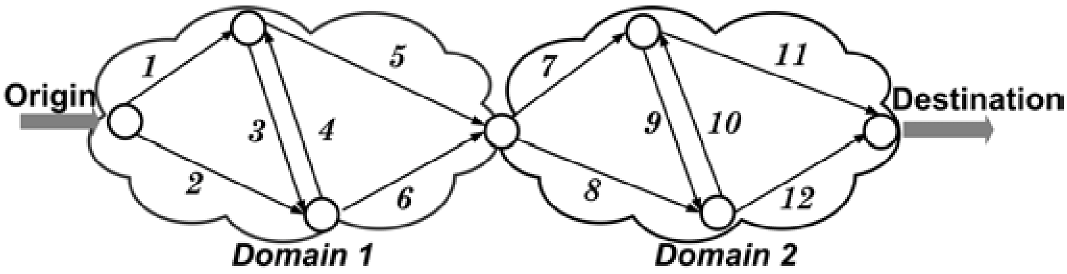
This chapter starts with the mathematical verification of the proposed loss network model. The experimental verification presents the accuracy of the proposed loss network model applied for three conventional policies (ME, LE and ED) and the newly proposed policy (PC-Nash). For the comparison of simulation and exact analysis results, the exact analysis is based on the proposed loss network model. The performance of all policies are investigated in the case studies of two-concatenated domains in order to provide insightful applicability of those policies. To achieve the purpose of performance evaluation, the effectiveness of PC-Nash is evaluated by comparing with ME, LE and ED. Two topologies have been used: the concatenation of two identical network topologies and the concatenation of two different network topologies. The investigation considers both inter-domain networks without and with an interconnecting link between the two domains. The summary of our finding in each experiment is provided with possible insights for practical inter-domain networks and the suggestion for further analyse in the next chapter.

4.1 Accuracy Evaluation of the Proposed Loss Network Model

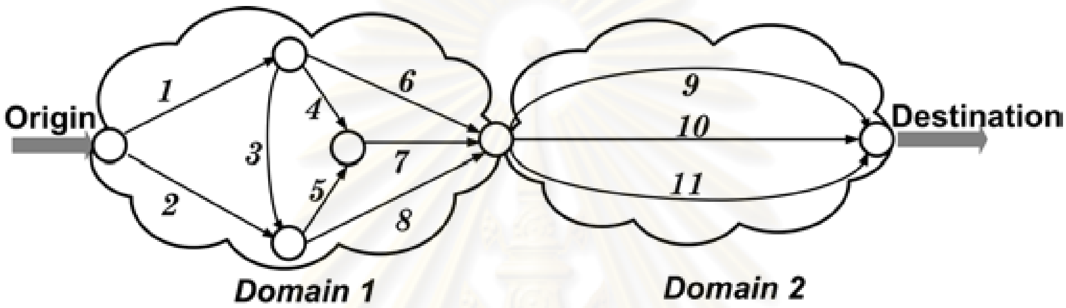
The goal of this section is to verify the correctness of the proposed mathematical model in Chapter 3. The proposed loss network model applied for ME, LE, ED and PC-Nash is first verified by a discrete-event simulation model in this section. To confirm the accuracy and applicability of the proposed loss network model, the experiments have been set in various network topologies and network characteristics. The important finding here is the accuracy confirmation of the proposed loss network model, which is used in the latter experiments.

4.1.1 Experimental Setting

Figure 6.11 illustrates the inter-domain networks of the same path quality (a) and of different path qualities (b). The topologies' profiles are presented in Tables 4.1 and 4.2. The experiments have been conducted on the topologies shown in Figure 6.11. For all experiments, let every call route from one origin-destination pair with independent Poisson call arrivals and exponentially distributed call holding times. The investigation considers multiple call types of which the constraints



(a) Topology 1 (concatenation of two identical network topologies), where label of link $l \in \{1, \ldots, 12\}$.



(b) Topology 2 (concatenation of two different network topologies), where label of link $l \in \{1, \ldots, 11\}$.

Figure 4.1 Network topologies

and load proportion are listed in Table 4.3. All simulation results presented in Section 4.1.2 have been obtained with 95% confidence intervals from 10 independent runs per point. The simulated time for each run has been set to 720 time units. The simulation program has been developed in MATLAB® and run on the computer cluster consisting of 3 computing nodes each with core-2-quad 2.0 GHz Xeon™processors and 4-GByte memory.

Table 4.1 Network profile of topology 1

Link (l)	$1, 5, 7, 11$	$6, 12$	$2, 8$	$3, 4, 9, 10$
$A(l)$	0.99999	0.99992	0.9999	0.999
c_l (Gbps)	1	1	1	1

Table 4.2 Network profile of topology 2

Link (l)	$1,2$	$3,4$	5	$6,7$
$A(l)$	0.9999	0.9998	0.9995	0.9999
c_l (Gbps)	3	1	1	2
Link (l)	8	9	10	11
$A(l)$	0.9998	0.9992	0.999	0.998
c_l (Gbps)	2	1	1	2

Table 4.3 Traffic types in inter-domain networks

Topology	Type (s)	b_s	a_s	Load Proportion
1	1	500 Mbps	0.9998	50%
	2	500 Mbps	0.9980	50%
2	1	500 Mbps	0.9986	50%
	2	500 Mbps	0.9977	50%

4.1.2 Results

Let $\mathbb{A}_{i,s}^{\text{mth}}$ and $\mathbb{A}_{i,s}^{\text{sim}}$ be the acceptance probability of type-s call in domain i obtained from mathematical analysis and the corresponding average obtained from simulation, respectively. The percentage relative error of $\mathbb{A}_{i,s}^{\text{sim}}$ with respect to $\mathbb{A}_{i,s}^{\text{mth}}$ is defined as $\varepsilon\ (\%) = |\mathbb{A}_{i,s}^{\text{sim}} - \mathbb{A}_{i,s}^{\text{mth}}|/\mathbb{A}_{i,s}^{\text{mth}} \times 100\%$. We have examined the accuracy and the applicability of the proposed loss network model by comparing it with experimental cases (with reported examples from topology 1 in Tables 4.4 and 4.5). Table 4.4 shows the maximum percentage relative error $\varepsilon\ (\%)$ of acceptance probability for type-1 calls as approximately 0.8% and Table 4.5 shows the maximum percentage relative error $\varepsilon\ (\%)$ for the type-2 calls as approximately 0.4%. These imply that the proposed loss network model returns accurate acceptance probabilities of both type-1 and type-2 calls for all policies.

From the accuracy comparison of simulation and mathematical model based on topology 2, the mathematical analysis is also in good agreement with the simulation. Because our derivation is given by the CTMC being solved directly using the global balance equation (*exact analysis*), the comparisons turn out to be very close to the simulation results in all cases.

4.1.3 Implication of the Results

The conclusion of this section is that the accuracy of the mathematical model has been confirmed by comparing its results with the corresponding discrete-event simulations. Based on this confirmation, the results obtained from the the proposed loss network model are good enough to evaluate the system performance in the other cases. Hence, the experiments here are based on the proposed loss network model only.

Table 4.4: Accuracy comparison of simulation and mathematical model based on blocking probability of domain 1: topology 1, traffic type 1, $a_1 = 0.9998, b_1 = 500$ Mbps. Note: PC-Nash of peer service model refers to $(d_1 = 1, d_2 = 1)$ and PC-Nash of retail and wholesale service models refer to $(d_1 = 7, d_2 = 7)$

Policy	$\mathbb{A}_{i,s}(v_o, v_t)$	$\lambda_s(v_o, v_t)/\mu_s(v_o, v_t)$: Erlangs			
		1.2000	2.0000	2.8000	3.6000
ME	$\mathbb{A}_{1,1}^{\text{mth}}$	0.7534	0.6000	0.4922	0.4152
	$\mathbb{A}_{1,1}^{\text{sim}}$	0.7560	0.6011	0.4929	0.4161
	$\varepsilon(\%)$	0.3451	0.1833	0.1422	0.2168
LE	$\mathbb{A}_{1,1}^{\text{mth}}$	0.8970	0.7825	0.6726	0.5790
	$\mathbb{A}_{1,1}^{\text{sim}}$	0.8986	0.7800	0.6679	0.5818
	$\varepsilon(\%)$	0.1784	0.3195	0.6988	0.4836
ED	$\mathbb{A}_{1,1}^{\text{mth}}$	0.8840	0.7567	0.6399	0.5439
	$\mathbb{A}_{1,1}^{\text{sim}}$	0.8897	0.7614	0.6419	0.5434
	$\varepsilon(\%)$	0.6448	0.6211	0.3125	0.0919
PC-Nash	$\mathbb{A}_{1,1}^{\text{mth}}$	0.9141	0.7986	0.6843	0.5868
$d_1 = 1$	$\mathbb{A}_{1,1}^{\text{sim}}$	0.9178	0.7960	0.6844	0.5903
$d_2 = 1$	$\varepsilon(\%)$	0.4048	0.3256	0.0146	0.5965
PC-Nash	$\mathbb{A}_{1,1}^{\text{mth}}$	0.7534	0.6000	0.4922	0.4152
$d_1 = 7$	$\mathbb{A}_{1,1}^{\text{sim}}$	0.7503	0.5951	0.4949	0.4129
$d_2 = 7$	$\varepsilon(\%)$	0.4115	0.8167	0.5486	0.5539

Table 4.5: Accuracy comparison between simulation and mathematical model based on blocking probability of domain 1: topology 1, traffic type 2, $a_2 = 0.9980, b_2 =$ 500 Mbps. Note: PC-Nash of peer service model refers to $(d_1 = 1, d_2 = 1)$ and PC-Nash of retail and wholesale service models refer to $(d_1 = 7, d_2 = 7)$

Policy	$\mathbb{A}_{i,s}(v_o, v_t)$	$\lambda_s(v_o, v_t)/\mu_s(v_o, v_t)$: Erlangs			
		1.2000	2.0000	2.8000	3.6000
ME	$\mathbb{A}_{1,2}^{\text{mth}}$	0.9911	0.9608	0.9115	0.8527
	$\mathbb{A}_{1,2}^{\text{sim}}$	0.9914	0.9613	0.9094	0.8512
	$\varepsilon(\%)$	0.0303	0.0520	0.2304	0.1759
LE	$\mathbb{A}_{1,2}^{\text{mth}}$	0.9819	0.9325	0.8654	0.7955
	$\mathbb{A}_{1,2}^{\text{sim}}$	0.9805	0.9314	0.8638	0.7935
	$\varepsilon(\%)$	0.1426	0.1180	0.1849	0.2514
ED	$\mathbb{A}_{1,2}^{\text{mth}}$	0.9827	0.9362	0.8733	0.8070
	$\mathbb{A}_{1,2}^{\text{sim}}$	0.9834	0.9384	0.8723	0.8064
	$\varepsilon(\%)$	0.0712	0.2350	0.1145	0.0743
PC-Nash	$\mathbb{A}_{1,2}^{\text{mth}}$	0.9809	0.9303	0.8628	0.7930
$d_1 = 1$	$\mathbb{A}_{1,2}^{\text{sim}}$	0.9824	0.9297	0.8645	0.7892
$d_2 = 1$	$\varepsilon(\%)$	0.1529	0.0645	0.1970	0.4792
PC-Nash	$\mathbb{A}_{1,2}^{\text{mth}}$	0.9911	0.9608	0.9115	0.8527
$d_1 = 7$	$\mathbb{A}_{1,2}^{\text{sim}}$	0.9895	0.9613	0.9094	0.8492
$d_2 = 7$	$\varepsilon(\%)$	0.1614	0.0520	0.2304	0.4105

4.2 Performance Evaluation: Two Domains without an Interconnection Link

This section studies the performance of ME, LE, ED and PC-Nash when these policies are applied to inter-domain networks with two concatenated domains without an interconnection link. This topology setting refers to the sharing of an edge router between two connected domains. Alternatively, this case represents a scenario where the interconnection link between two edge routers of two domains has a larger capacity than the total bandwidth required by the traffic across the domain boundaries. This study concentrates only on the investigation of the effectiveness of the considered policies implemented in the inter-domain network, regardless of the effect of a bottleneck by the interconnection link.

4.2.1 Experimental Setting

The experimental setting in this section is the same as the setting in the experiments in Section 4.1. The network topologies for testing are illustrated in Figure 6.11. The profiles of topologies are presented in Tables 4.1 and 4.2. The experiments have been conducted on the topologies shown in Figure 6.11. In the experiments, let every call route from one origin-destination pair with independent Poisson call arrivals and exponentially distributed call holding times. The investigation take into consideration multiple call types and their constraints and load proportion are listed in Table 4.3. The analytical results have been obtained by using a program developed in MATLAB® and run on the computer cluster consisting of three computing nodes each with core-2-quad 2.0-GHz Xeon™processors and a 4-GByte memory.

4.2.2 Results

This section presents the results obtained from the mathematical analysis with using the loss network model. The investigation of the four policies is based on the inter-domain networks shown in Figure 6.11 to study the effect of the path quality (in terms of availability value and path capacity) in the two concatenated domains with a common point of interconnection. The multiple traffic types with their constraints listed in Table 4.3 are taken into consideration. To see the effect of loading in each topology, the experiments have been carried out with total offered load ranging from light to oversaturated conditions. For the Path-Classification scheme, $D_i = 7$ and $D_i = 3$ for all the domains in topologies 1 and 2, respectively. Consequently, there are 49 and 9 possible cases, which take a long time to simulate, and therefore there is a need for analytical computation. The assigned number D_i is based on the distribution of the availability of the paths and is herein set so that ME, LE and ED are at least distinguishable when being expressed in the Path-Classification parameter. The results have been evaluated under three business models, peer, retail and wholesale.

Table 4.6 Optimal QoS level of PC-Nash for offered load (0.4–4 Erlangs)

Utility function	Optimal QoS level	
	Topology 1 ($D_i = 7$)	Topology 2 ($D_i = 3$)
Peer	$(d_1 = 7, d_2 = 7)$	$(d_1 = 1, d_2 = 3)$
Retail	$(d_1 = 1, d_2 = 1)$	$(d_1 = 3, d_2 = 1)$
Wholesale	$(d_1 = 1, d_2 = 1)$	$(d_1 = 3, d_2 = 1)$

Table 4.6 presents the optimal QoS levels of PC-Nash in accordance with the three utility functions, peer, retail and wholesale. The optimal results referring to PC-Nash suggest that, in inter-domain networks with the same path quality like that in topology 1, the maximum level of QoS apportionment, i.e., PC-Nash at a setting of $d_1 = 7$ and $d_2 = 7$, leads to the system performing well for the peer service model. In contrast to the retail and wholesale service models, the minimum level of QoS apportionment, i.e., PC-Nash using policy $d_1 = 1$ and $d_2 = 1$, leads to the system achieving the highest utility. The reason for this is that when $d_i = 7$ is applied, the highest availability route is shared between the lowest and highest availability requests, but the two types of requests are separated by using the other QoS level setting. This leads to $d_i = 7$ performing the lowest in bandwidth usage and the lowest in the mean number of accepted calls. Thus, ISPs should apply the same policy, but they do not need to try their best using $d_i = 7$ to obtain the most optimal profits.

When the network qualities are different (referring to topology 2), setting $d_1 = 1$ and $d_2 = 3$ is suitable for the peer service model while setting $d_1 = 3$ and $d_2 = 1$ is suitable for the retail and wholesale service models. The optimal operating point suggests that, for the retail/wholesale service models, an upstream domain (referring to the higher quality network or Domain 1 in Figure 4.1(b)) should implement a high QoS level apportionment, while a downstream domain (referring to the lower quality network or Domain 2 in Figure 4.1(b)) should implement a low QoS level apportionment, and vice versa for the peer service model. This is because a small domain has a very limited resource of high availability links. The high availability request will be blocked if the upstream domain does not support the path with the highest availability.

PC-Nash yields the highest utilities for all the tested cases because of its inherent optimal QoS level setting. Thus, the effectiveness of these three conventional policies have been quantified here in terms of the utility-difference ratio

$$\frac{\text{utility of PC-Nash} - \text{utility of policy}}{|\text{utility of PC-Nash}|} \times 100\%. \tag{4.1}$$

The effectiveness of these path-provisioning policies depends on the network topology and the utility function. For the inter-domain networks with the same path quality (Figures 4.2–4.4), ME performs the best with respect to the peer service model while it performs the worst with respect to the retail and wholesale service models. In contrast, LE performs well with respect to the retail and wholesale service models, but worst with respect to the peer service model. The reason is the same as that for the setting $d_i = 7$ and $d_i = 1$ for PC-Nash, respectively.

For inter-domain networks with different path qualities (see Figures 4.5–4.7), ED performs the best with respect to the peer service model, while it performs worst with respect to the retail service model. Unlike the case of the same-path-quality network, ME is the best for the retail service model while it is the worst for the wholesale service model. On the other hand, LE is the best for a wholesale service model. The reason is that when ME is used, more calls with high availability request can be accepted than when using LE or ED, while LE and ED maximise the total accepted calls regardless of the call type. With ME, the ISPs can gain their utility from the high acceptance rate of the calls with a high-availability request instead of from calls with a low-availability request. Consequently, ME is the worst with respect to the wholesale service model because of less overall call acceptance.

It should be noted that, in the case of inter-domain networks with the same path quality, the performance of conventional policies is quite close to that of PC-Nash. Therefore, the conventional policies can be efficiently used for this case. However, the performance of the conventional policies is significantly less than that of PC-Nash in inter-domain networks with different path qualities.

4.2.3 Implication of the Results

Based on the accuracy of the mathematical model that has been confirmed by comparing its results with the corresponding discrete-event simulations in Section 4.1, in Section 4.2 the effectiveness of the proposed policy has been investigated by comparing it with the conventional policies, i.e., ME, LE and ED, when two domain networks without interconnection link between domain. With the utility functions of practical service models, ME and LE are found to provide comparable utilities to PC-Nash with respect to the peer and retail/wholesale service models, respectively, for a network with the same path quality. However, for networks with different path qualities, PC-Nash significantly outperforms all the conventional policies. From this evidence, the PC-Nash is thus expected to be useful

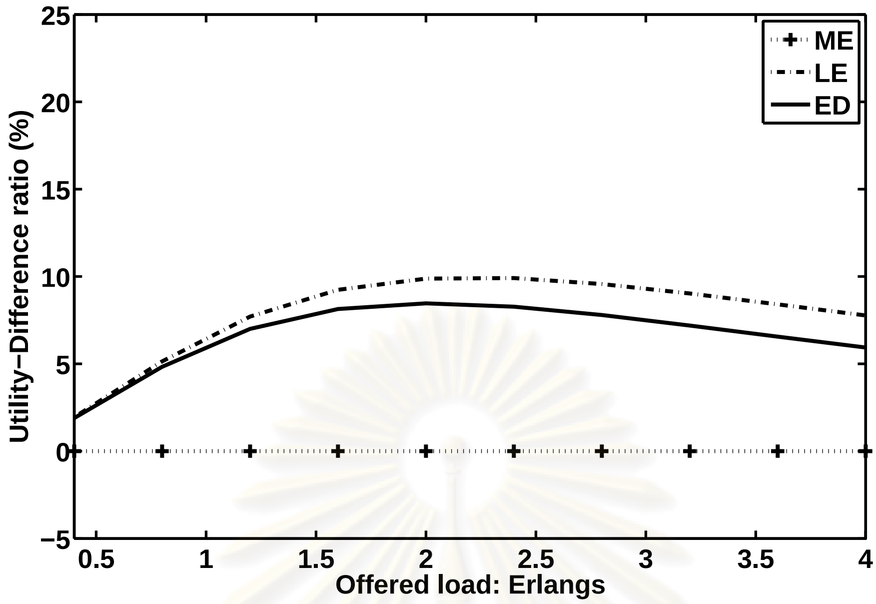


Figure 4.2: Results for inter-domain networks with same path quality (topology 1): Utility-Difference ratio for peer service model based on utility of domain 1 ($u_1 = u_2$): $D_i = 7$ for $i = 1, 2$, and $u_i = -\beta_i w_i$, where $\beta_i = 0.35$ units per Mbps.

in QoS provisioning of practical inter-domain networks.

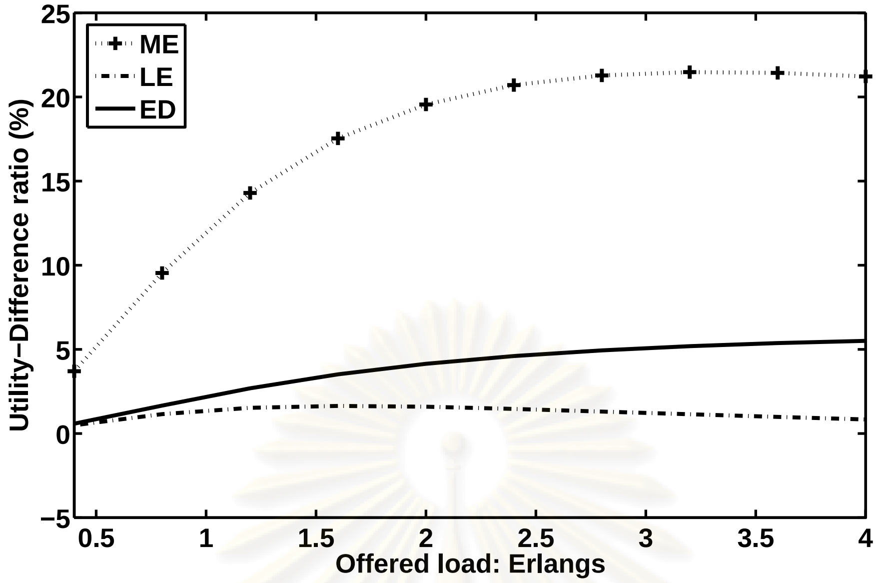


Figure 4.3: Results for inter-domain networks with same path quality (topology 1): Utility-Difference ratio for retail service model based on utility of domain 1 ($u_1 = u_2$): $D_i = 7$ for $i = 1, 2$, and $u_i = \sum_{s=1}^{S} g_i(a_s)\sigma_{i,s} - \beta_i w_i$ where $\beta_i = 0.35$ units per Mbps, $g_i(a_1) = 1000$ and $g_i(a_2) = 1500$ units per connection.

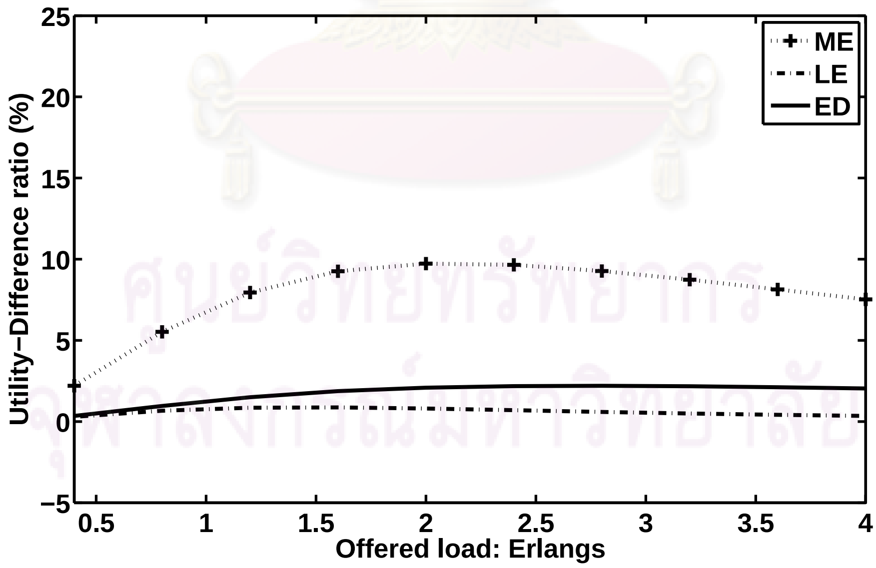


Figure 4.4: Results for inter-domain networks with same path quality (topology 1): Utility-Difference ratio for wholesale service model based on utility of domain 1 ($u_1 = u_2$): $D_i = 7$ for $i = 1, 2$, and $u_i = \sum_{s=1}^{S} g_i(a_s)\sigma_{i,s} - \beta_i w_i$, where $\beta_i = 0.35$ units per Mbps and $g_i(a_1) = g_i(a_2) = 1000$ units per connection.

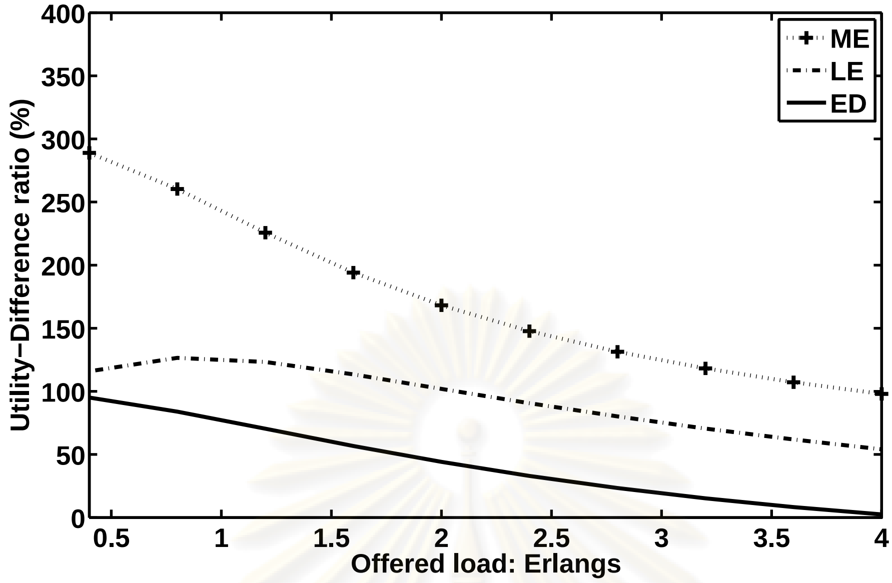


Figure 4.5: Results for inter-domain networks with different path qualities (topology 2): Utility-Difference ratio for peer service model based on utility of domain 1 ($u_1 = u_2$): $D_i = 3$ for $i = 1, 2$, and $u_i = -\beta_i w_i$, where $\beta_i = 0.35$ units per Mbps.

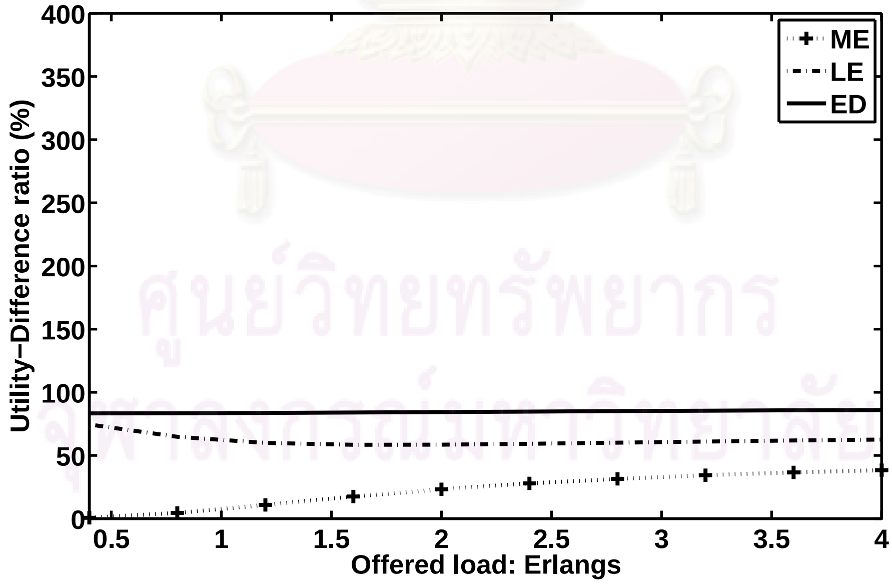


Figure 4.6: Results for inter-domain networks with different path qualities (topology 2): Utility-Difference ratio for retail service model based on utility of domain 1 ($u_1 = u_2$): $D_i = 3$ for $i = 1, 2$, and $u_i = \sum_{s=1}^{S} g_i(a_s)\sigma_{i,s} - \beta_i w_i$ where $\beta_i = 0.35$ units per Mbps, $g_i(a_1) = 1000$ and $g_i(a_2) = 1500$ units per connection.

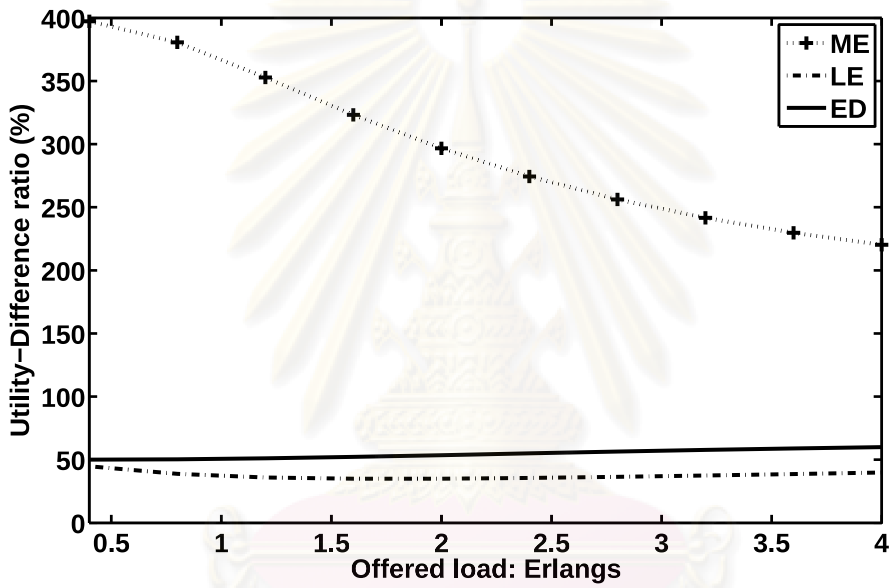


Figure 4.7: Results for inter-domain networks with different path qualities (topology 2): Utility-Difference ratio for wholesale service model based on utility of domain 1 ($u_1 = u_2$): $D_i = 3$ for $i = 1, 2$, and $u_i = \sum_{s=1}^{S} g_i(a_s)\sigma_{i,s} - \beta_i w_i$, where $\beta_i = 0.35$ units per Mbps and $g_i(a_1) = g_i(a_2) = 1000$ units per connection.

4.3 Performance Evaluation: Two Domains with an Interconnection Link

Typical inter-domain networks interconnect by joining their edge routers using interconnection links. Due to the increasing amount of traffic across multiple domains, the capacity of the interconnection link might be less than the amount of the maximum bandwidth simultaneously requested by the traffic across a domain boundary. Once this occurs in the inter-domain networks, the limited capacity of the inter-connection link might affect the effectiveness of the implemented policy. The previous study in Section 4.2, nevertheless, does not consider the issue of bottleneck by an interconnection link. Therefore, in this section, the effectiveness of the four policies is investigated on when the capacity of the interconnection link is limited.

4.3.1 Effect of Interconnection Link Bottleneck

The analytical approach in this subsection is proposed for studying the effect of an interconnection bottleneck in the inter-domain networks. The analysis is done based on the network with multiple concatenated domains. A network model with multiple domains connected by interconnection links is taken into consideration. Let $\acute{\mathcal{L}}(v_o, v_t)$ denote the set of interconnection links connecting a sequence of domain pairs from origin v_o to destination v_t. Given that each domain pair is connected by a single interconnection link, the number of links in $\acute{\mathcal{L}}(v_o, v_t)$ is equal to $h-1$, where h is the number of domains from v_o to v_t. Interconnection link $l_{i,j} \in \acute{\mathcal{L}}(v_o, v_t)$ connects the edge routers of domains i and j. Assume link availability $A(l_{i,j})$ is equal to 1, so that the effect of the unavailability of link $l_{i,j}$ is omitted.

Define $f_{l_{i,j}}(s)$ as a flow value of the type-s calls from the edge router to another edge router in domain i which is offered to link $l_{i,j}$. The value of the flow can be obtained by using the max-flow/min-cut theorem [56] with respect to the set of paths that can be provisioned to the type-s call arriving at domain i, $\tilde{\mathcal{K}}_i(s, \mathbf{n})|_{\mathbf{n}=\mathbf{0}}$. Note that $f_{l_{i,j}}(s) = 0$ if no path in domain i satisfies the availability or bandwidth constraints of a type-s call. In the other words, $f_{l_{i,j}}(s) = 0$ when $\tilde{\mathcal{K}}_i(s, \mathbf{n})|_{\mathbf{n}=\mathbf{0}} = \emptyset$. Let $c_{l_{i,j}}$ be the capacity of interconnection link $l_{i,j}$. Link $l_{i,j}$ can carry some traffic flows in which the total amount does not exceed the link capacity $c_{l_{i,j}}$.

Observe that interconnection link $l_{i,j}$ is considered a bottleneck, if

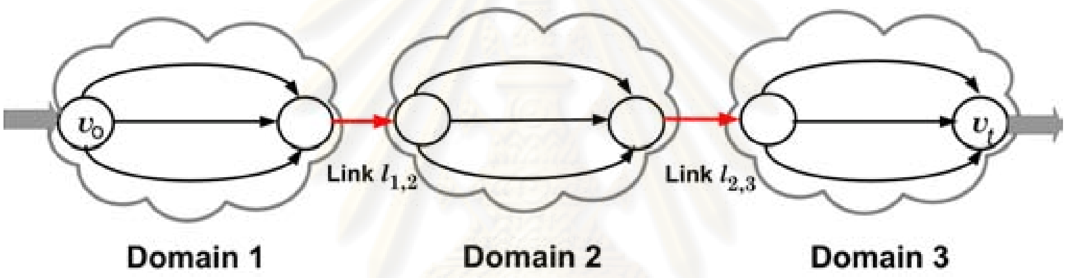
$$c_{l_{i,j}} \leq \min_{\acute{l} \in \acute{\mathcal{L}}(v_o, v_t)} \left\{ c_{\acute{l}} \right\}, \tag{4.2}$$

and

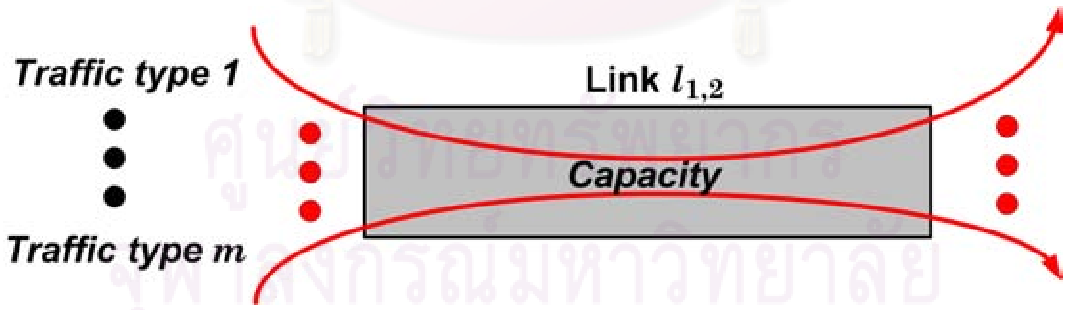
$$c_{l_{i,j}} \leq \left\{ \min_{s \in S} \left\{ f_{l_{i,j}}(s) : f_{l_{i,j}}(s) > 0 \right\} \right\}. \tag{4.3}$$

A call, which requests to route from an edge router of domain i and terminates outside the domain i, is blocked and lost on interconnection link $l_{i,j}$ if the remaining capacity of link $l_{i,j}$ is less than its bandwidth request, or if no a single path from edge-to-edge router meets its availability request. An accepted call, therefore, depends on the remaining capacity of the interconnection link or the path availability instead of the remaining capacity of any link inside the domain. With that regard, the network model in this case can simply be analysed by using a single link model as proposed in [57].

Figure 4.8(a) illustrates an example of an inter-domain network with the interconnection bottleneck. To analyse the performance of the network, the inter-domain network model is mapped to a single link model as shown in Figure 4.8(b). Then, the traffic flows passing through link $l_{1,2}$ must be the allowable traffic according to the implemented policy in every domain along the end-to-end routes.



(a) Example of the inter-domain networks with interconnection links: let $h = 3$, $\acute{\mathcal{L}}(v_o, v_t) = \{l_{1,2}, l_{2,3}\}$, and suppose $l_{1,2}$ is a bottleneck.



(b) Single link model with m traffic types sharing link $l_{1,2}$, where $m \leq |S|$.

Figure 4.8: Example of mapping inter-domain network with the interconnection bottleneck to a single link model.

Based on the same assumption of the call arrival discussed in Chapter 3, calls requesting from origin node v_o to destination node v_t are Poisson streams at rate λ_s for all $s \in S$. The call holding times are distributed exponentially at a certain mean $1/\mu_s$. The mean call arrivals and the mean call holding times are independently and identically distributed and do not depend on the system state. Since the network model is mapped to a single link model, the dimensions of route r in the defined state $\mathbf{n} = [n_{r,s} : r \in \mathcal{R}, s \in S]$ can be omitted. Thus, let $\mathbf{n}(l_{i,j}) = [n_s(l_{i,j}) : s \in S]$ be the state of link $l_{i,j}$, where $n_s(l_{i,j})$ is the number of ongoing type-s calls in link $l_{i,j}$. The state space in (3.1) is rewritten as

$$\Omega = \left\{ \mathbf{n}(l_{i,j}) : \mathbf{n}(l_{i,j})\mathbf{b} \leq c_{l_{ij}} \right\}, \tag{4.4}$$

where column vector $\mathbf{b} = [b_s : s \in S]$. Thus, the set of blocking states for type-s calls between the origin-destination pair (v_o, v_t) in (3.7) is redefined as

$$\Omega_B(s, v_o, v_t) = \{ \mathbf{n}(l_{i,j}) \in \Omega : \mathbf{n}(l_{i,j}) + \mathbf{e}_s \notin \Omega \}, \tag{4.5}$$

where $\mathbf{e}_s$ is the unit vector with a 1 in the sth column. To obtain the steady-state probability $\pi(\mathbf{n}(l_{i,j}))$, one can directly solve the normalisation condition and global-balance equations of the resultant Markov chain. Alternatively, the steady-state probability $\pi(\mathbf{n}(l_{i,j}))$ in this network system can be simply calculated by using the product form solution (e.g. [57–59]);

$$\pi(\mathbf{n}(l_{i,j})) = G^{-1} \prod_{s \in S} \left[\frac{[\lambda_s/\mu_s]^{n_s(l_{i,j})}}{n_s(l_{i,j})!} \right], \tag{4.6}$$

where the normalisation constant is

$$G = \sum_{\mathbf{n}(l_{i,j}) \in \Omega} \prod_{s \in S} \left[\frac{[\lambda_s/\mu_s]^{n_s(l_{i,j})}}{n_s(l_{i,j})!} \right]. \tag{4.7}$$

Based on the obtained stead-state probability from (4.6), the performance of ME, LE, ED and PC-Nash can be evaluated from (3.8)–(3.10).

According to this network model, a call is blocked because of an inadequate remaining capacity of the interconnection link or no satisfied path ($\tilde{\mathcal{K}}_i(s, \mathbf{n})|_{\mathbf{n}=\mathbf{0}} = \emptyset$) with respect to the employed policy. This leads to an interesting question for such a network model; that is, how many traffic streams will be allowed to share the bottleneck link $l_{i,j}$. This number of streams depends on the policy used in each domain and the characteristics of the call types and the network topologies. Define $S_p \subseteq S$ as the set of call types which can be allowed to access link $l_{i,j}$ when policy p is employed in the network, where $p \in \{ME, LE, ED, PC{-}Nash\}$ denotes the policy used in the inter-domain networks. Hence, the number of traffic types allowed to access link $l_{i,j}$ is equal to $|S_p|$. According to an end-to-end path provisioning process, the set of call types accessing link $l_{i,j}$ with respect to policy p can be expressed as

$$S_p = \{ s \in S : \tilde{\mathcal{K}}_i(s, \mathbf{n})|_{\mathbf{n}=\mathbf{0}} \neq \emptyset, \text{for } i = 1, \ldots, h \}. \tag{4.8}$$

On the basis of updating the constraint targets ($a^t_{i,s}$ and $b^t_{i,s}$) from upstream domain 1 to downstream domain h, (4.8) can be shortened to

$$S_p = \{s \in S : \tilde{\mathcal{K}}_h(s, \mathbf{n})|_{\mathbf{n}=\mathbf{0}} \neq \emptyset\}. \tag{4.9}$$

For convenience, we assume every link in $\mathcal{L} - \acute{\mathcal{L}}(v_o, v_t)$ has a capacity greater than $c_{l_{i,j}}$, so that $|S_p|$ depends on only the path availability. From (4.9), $|S_p|$ depends on the possibility that $\tilde{\mathcal{K}}_h(s, \mathbf{n})|_{\mathbf{n}=\mathbf{0}} \neq \emptyset$. That is, s is in S_p if there is a path in domain h with an availability that is at least equal to $a^t_{h,s}$. Then, ME, LE and ED must be taken into account. For LE, the assigned paths of the upstream domains push the burden of responsibility in an availability target to the downstream domains, but this is not true for ME. For ED, the upper bound of availability target $a^{ED}_{i,s}$ is shifted up from $a^t_{i,s}$ to $\min\left\{\sqrt[h]{a_s}, \left(\frac{a_s}{\prod_{j=1}^{i-1} A(k_j)}\right)^{1/(h-i+1)}\right\}$ (see (2.14)). In particular, $a^{ED}_{i,s}$ is always $\geq a^t_{i,s}$. Therefore, the downstream domains suffer less from their availability target. In comparison to ME, LE and ED, the number of accessible call types of LE, ED and ME is ranked as $|S_{LE}| \leq |S_{ED}| \leq |S_{ME}|$ when every domain along the end-to-end route has the same path quality. On the other hand, the number of accessible call types for ED might be less than that of LE when some of the domains in the middle of the end-to-end route have poor path qualities; that is $|S_{ED}| \leq |S_{LE}| \leq |S_{ME}|$. The reasoning behind this is since availability target $a^{ED}_{i,s} > a^t_{i,s}$ for $1 < i < h$, domain i might suffer from the necessary responsibility in the availability target of ED rather than relax due to the availability target of LE. Although the upstream domains share a high level of responsibility for the availability target, the middle domain still faces the difficulty of attaining its updated target. However, PC-Nash always provides the highest performance associated with the considered utility function. When every domain employs the highest QoS-level (set $d_i = D_i$ for $i, ..., h$), $|S_{PC\text{–}Nash}|$ approaches to $|S_{ME}|$. Also, when every domain employs the lowest QoS-level (set $d_i = 1$ for $i, ..., h$) for every domain, $|S_{PC\text{–}Nash}|$ approaches to $|S_{LE}|$. Therefore, the results of PC-Nash correspond to those of ME for the retail and wholesale service models, and its results are close to those of LE for the peer service model.

4.3.2 Experimental Setting

The objective of these experiments is to give some examples of the performance evaluation based on the mapped single link model and to show the obtained results corresponding to the analysis. The experiments are set similarly to the experiments described in Section 4.1, but an interconnection link between the two domains is added into the topology. The network topologies for testing are illustrated in Figure 4.9. The profiles of topologies are presented in Tables 4.7 and 4.8. For all the experiments, let every call route from one origin-destination pair with independent Poisson call arrivals and exponentially distributed call holding times. From the analysis, the performance of this single link model can be divided into two cases. The first case is that all call types are allowed to access the bottleneck link, and the other is that some call types cannot be allowed to access the bottleneck link. The investigation considers multiple call types of which the constraints and load proportion are listed in Tables 4.3 and 4.9 for the first and the second cases, respectively. The analytical results have been obtained by using the program developed in MATLAB® and run on the computer cluster consisting of three computing nodes each with core-2-quad 2.0-GHz Xeon™processors and 4-GByte memory.

Table 4.7 Network profile of topology 1

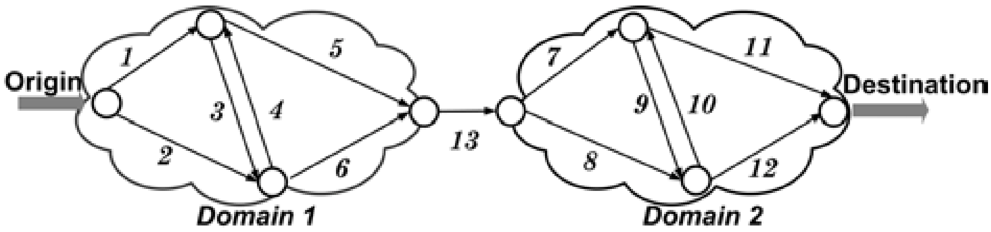
Link (l)	$1, 5, 7, 11$	$6, 12$	$2, 8$	$3, 4, 9, 10$	13
$A(l)$	0.99999	0.99992	0.9999	0.999	1
c_l (Gbps)	2	2	2	2	1

Table 4.8 Network profile of topology 2

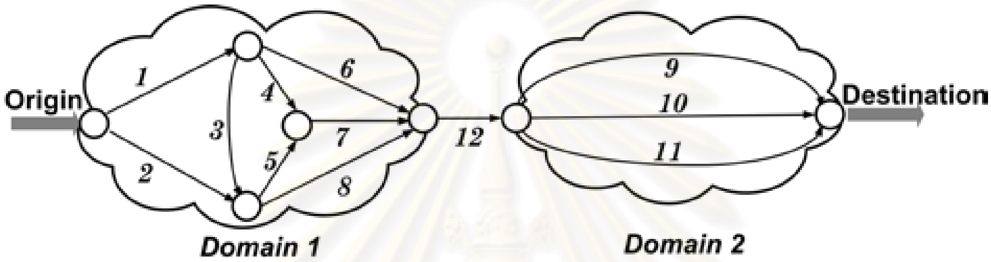
Link (l)	$1, 2$	$3, 4$	5	$6, 7$	
$A(l)$	0.9999	0.9998	0.9993	0.9999	
c_l (Gbps)	4	2	2	3	
Link (l)	8	9	10	11	12
$A(l)$	0.9998	0.9992	0.999	0.998	1
c_l (Gbps)	3	2	2	3	1

Table 4.9 Traffic types in inter-domain networks

Topology	Type (s)	b_s	a_s	Load Proportion
1	1	500 Mbps	0.99982	50%
	2	500 Mbps	0.99800	50%
2	1	500 Mbps	0.9986	50%
	2	500 Mbps	0.9977	50%



(a) Topology 1: concatenation of two identical network topologies, where label of link $l \in \{1, \ldots, 13\}$.



(b) Topology 2: concatenation of two different network topologies, where label of link $l \in \{1, \ldots, 12\}$.

Figure 4.9 Network topologies for two concatenated domains with interconnection bottleneck link.

4.3.3 Results

Figure 4.10 presents the results from an experiment done on topology 1 (see Figure 4.9(a)) under the traffic characteristic listed in Table 4.3. As one expected, the performance of all the policies, i.e. ME, LE, ED and PC-Nash is the same. This is due to the topology setting and the availability requests. The availability of paths from the edge-to-edge routers are 0.99998, 0.99982, 0.99891 and 0.99889, while for the availability requests $a_1 = 0.9998$ and $a_2 = 0.998$. For ME, the route with the highest availability value is assigned to every call. Hence, $S_{ME} = \{1, 2\}$. For LE, in domain 1 the paths with availabilities of 0.99982 and 0.99891 are assigned to call types 1 and 2, respectively. Then, the updated availability targets $a^t_{2,1} \approx 0.99998$ and $a^t_{2,2} \approx 0.9991$. Note that there are paths in domain 2 that satisfy the availability targets of both call types. For ED, the availability targets for call types 1 and 2 are $a^{ED}_{i,1} \approx 0.9999$ and $a^{ED}_{i,2} \approx 0.999$. With the same results as with ME and LE, there are some paths in domains 1 and 2 which satisfy both call types. With this experimental setting, the performance of PC-Nash for the peer, retail and wholesale service models are also equal to the results of ME, LE and ED. Consequently, $|S_{ME}| = |S_{LE}| = |S_{ED}| = |S_{PC-Nash}|$ for this example.

The other example has been tested on the same topology as that in Figure 4.10, but the call characteristic has been changed. Based on the call characteristic in Table 4.9, the results of ME, ED and PC-Nash are the same as shown in Figure 4.11, whereas the results of LE change as shown in Figure 4.12. The reason is that when LE policy is deployed in the inter-domain networks, domain 1 always assigns path with availability 0.99982 for a call which requests $a_1 = 0.99982$. This assigned path of domain 1 causes domain 2 cannot find any path to support that call request. Nevertheless, this situation dose not happen in ME and ED cases. Consequently, $|S_{LE}| < |S_{ED}| = |S_{ME}|$ for this example.

Observe the results from topology 2 in Figure 4.9(b) when the call characteristic is set following that listed in Table 4.9. In this example, the path quality in domain 1 is different from of that in domain 2. The results of ME and ED are similar to the results in Figure 4.11, and the results of LE are similar to the results in Figure 4.12. These experimental results draw the conclusion that $|S_{LE}| < |S_{ED}| = |S_{ME}|$. Note that, the analysis that $|S_{ED}|$ might be less than $|S_{LE}|$, but it cannot be seen in the two-concatenated-domain cases. Further investigation will therefore be needed to study cases in which the concatenated domains are greater than 2 domains ($h > 2$). In order to complete the analysis results, let us provide the results of the three-domain cases in the next section.

Consider the effectiveness of all the path provisioning policies in terms of the utility-difference ratio. Figures 4.13–4.15 represent the percentage of difference in the utilities of ME, LE and ED compared to that of PC-Nash based on the three business models, namely the peer, retail and wholesale service models, respectively. Here the results of the first experiment are omitted because there is no difference between all of the policies. Hence, these three figures are for the second and third experiments, which show that the performance of LE is different from that in the other policies (i.e., ME, ED and PC-Nash). Figures 4.13–4.15 show the same trend in the difference of utility, which decreases by increasing the offered load. Not surprisingly, LE is similar to PC-Nash for the peer service model, while ME and ED are close to PC-Nash for the retail and wholesale service models.

4.3.4 Implication of the Results

In this section, the effect of the interconnection bottleneck in the inter-domain is studied by the analytical approach. The analysis is based on the concatenation of multiple domains in order to perform a generalized analysis. This analysis is confirmed by the experimental examples for two-domain cases. This finding shows that using ME ensures that the performance is always well associated with the resultant of the highest allowable call types ($|S_{ME}|$) compared to the results of LE and ED. The examples have shown that in some settings the results from LE and ED are equal to that of ME. The

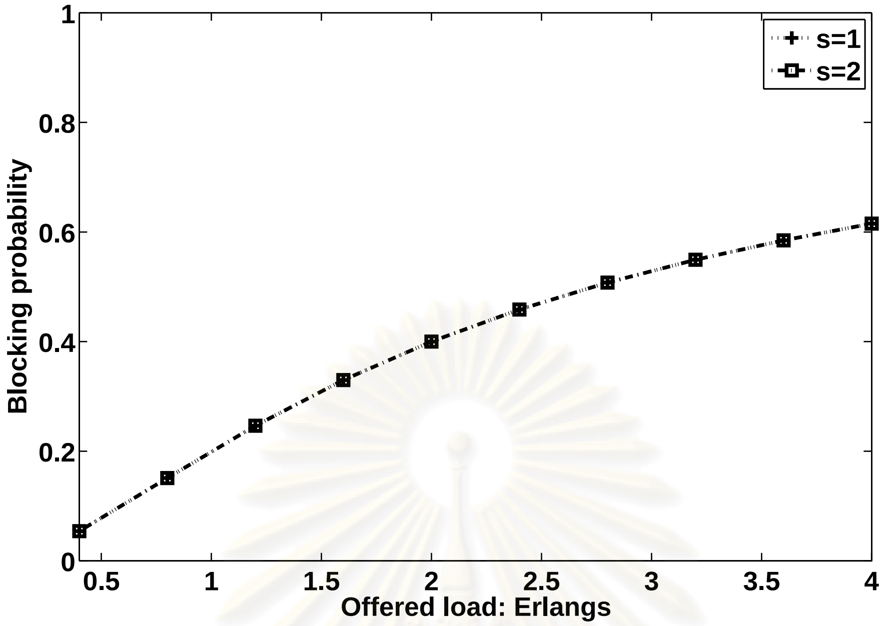


Figure 4.10: Call blocking probability of call types $s = \{1, 2\}$ for policies ME, LE, ED and PC-Nash (for retail and wholesale service models) based on topology 1 in Figure 4.9(a) and load traffic setting in Table 4.3.

performance of this policy is the highest, which is the same level as ME, because of the inherit optimization by PC-Nash. Since the examples given in this section are limited based on the two-domain network, the experimental results cannot perform perfectly due to the conclusion that sometimes $|S_{ED}| < |S_{LE}|$. To fulfill the confirmation of the analysis, the multiple concatenated domains will be investigated in the next Chapter.

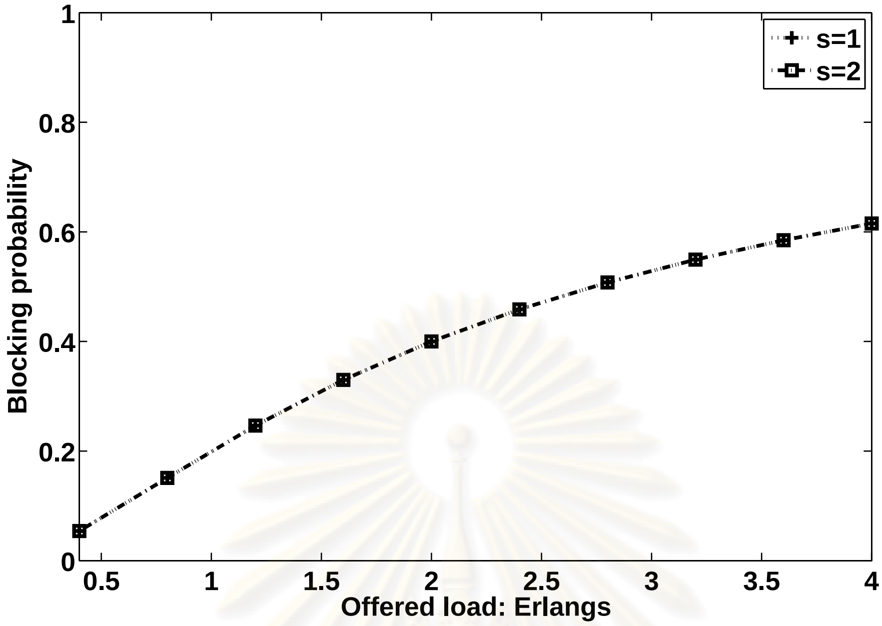


Figure 4.11: Call blocking probability of call types $s = \{1, 2\}$ for policies ME, ED and PC-Nash (for retail and wholesale service models) based on topology 1 in Figure 4.9(a) and load traffic setting in Table 4.9.

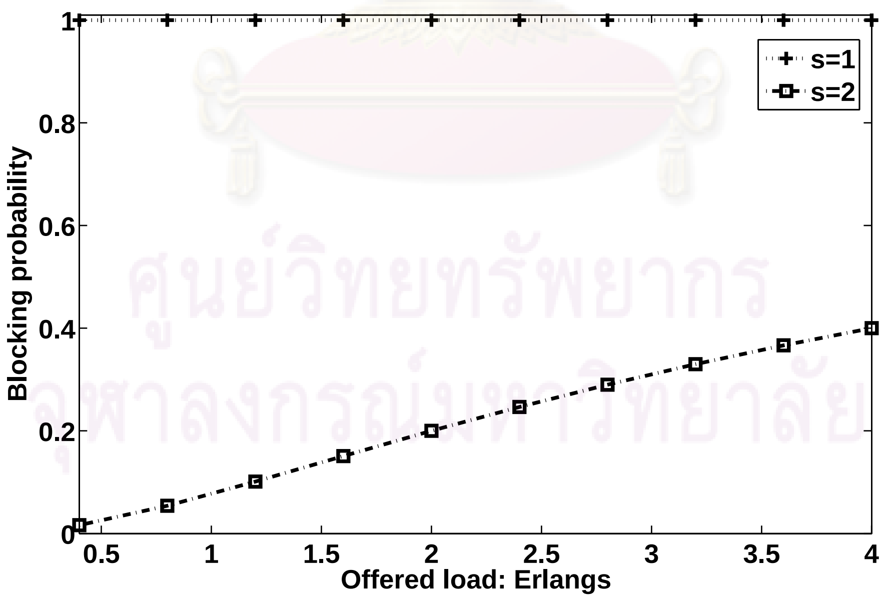


Figure 4.12: Call blocking probability of call types $s = \{1, 2\}$ for policies LE, ED and PC-Nash (for retail and wholesale service models) based on topology 1 in Figure 4.9(a) and load traffic setting in Table 4.9.

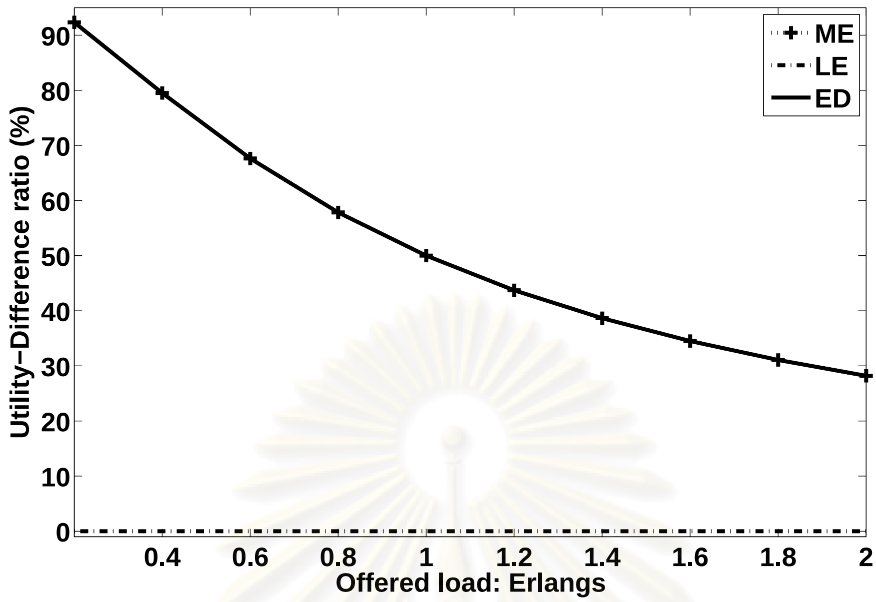


Figure 4.13: Results for inter-domain networks with same path quality (topology 1) and load traffic setting in Table 4.9: Utility-Difference ratio for peer service model based on utility of domain 1 ($u_1 = u_2$): $D_i = 7$ for $i = 1, 2$, and $u_i = -\beta_i w_i$, where $\beta_i = 0.35$ units per Mbps.

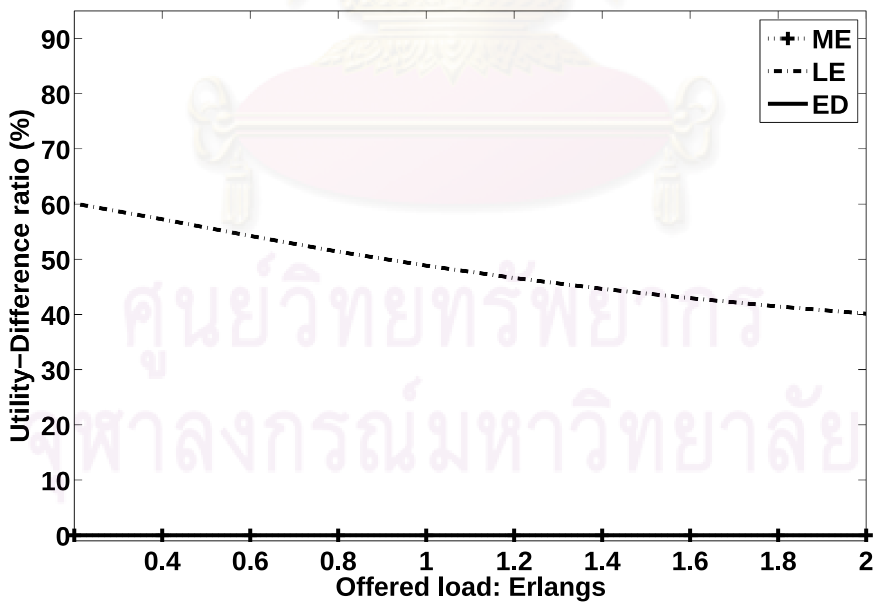


Figure 4.14: Results for inter-domain networks with same path quality (topology 1) and load traffic setting in Table 4.9: Utility-Difference ratio for retail service model based on utility of domain 1 ($u_1 = u_2$): $D_i = 7$ for $i = 1, 2$, and $u_i = \sum_{s=1}^{S} g_i(a_s)\sigma_{i,s} - \beta_i w_i$ where $\beta_i = 0.35$ units per Mbps, $g_i(a_1) = 1000$ and $g_i(a_2) = 1500$ units per connection.

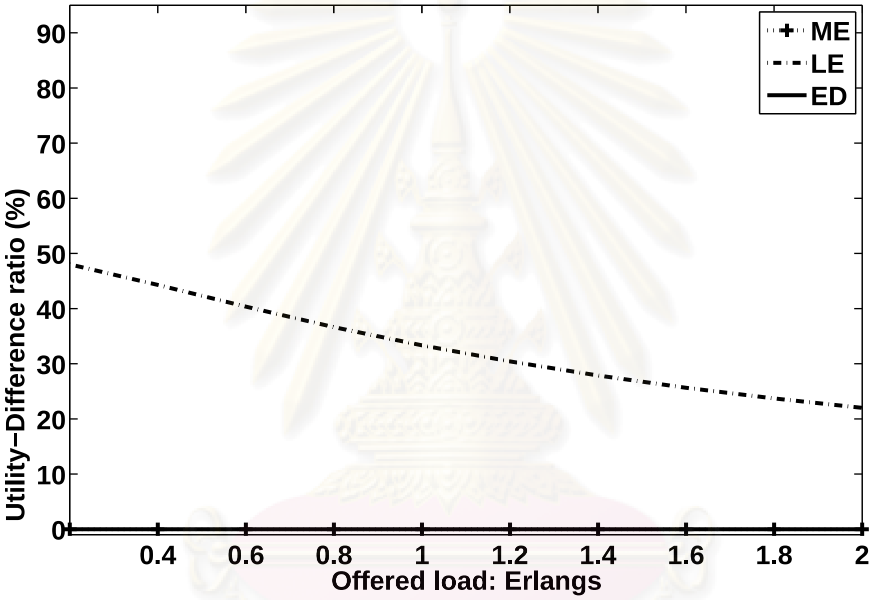


Figure 4.15: Results for inter-domain networks with same path quality (topology 1) and load traffic setting in Table 4.9: Utility-Difference ratio for wholesale service model based on utility of domain 1 ($u_1 = u_2$): $D_i = 7$ for $i = 1, 2$, and $u_i = \sum_{s=1}^{S} g_i(a_s)\sigma_{i,s} - \beta_i w_i$, where $\beta_i = 0.35$ units per Mbps and $g_i(a_1) = g_i(a_2) = 1000$ units per connection.

CHAPTER V

HIERARCHICAL NETWORKS

Today's Internet structure composes many complex interactions between thousands of domains. An individual domain administratively controled by a single ISP uses its own routing policy to select a route for supporting an end-to-end QoS connection request. In practice, the routing policy depends on the business relationships between the neighboring domains, which can be categorised as customer-provider or peer relationships according to the hierarchical structure of the Internet [60]. The inter-domain levels based on the hierarchical structure refer to the network tiers of which the top to bottom levels represent tier-1, tier-2 and tier-3, respectively [61]. The hierarchical structure of inter-domain networks can basically be drawn like that shown in Figure 5.2. The hierarchical structure is composed of three tiers of which definitions are given as follows [61]:

- Tier 1: ISPs which access to the global Internet routing table and have a huge network capacity. As a result, Tier-1 ISPs do not borrow or buy network capacity from other ISPs.

- Tier 2: ISPs which have a smaller presence in telecommunication markets than Tier-1 ISPs and may lease part or all of their network from a Tier-1 ISP.

- Tier 3: ISPs which purchase their transit from other ISPs (typically Tier-2 ISPs) to reach the Internet.

The business relationships between two inter-domain networks on the same inter-domain level and on the different inter-domain levels are classified as peer and customer-provider models, respectively [62]. The top-level networks are considered as the providers who own large networks, while smaller networks in the lower-level belong to their customers. A relationship between the same tier level is peer-to-peer. In the peer relationship, most domains have a comparable network size as well as a comparable amount of exchanged traffic demand. In a provider-customer relationship, the customer is typically a smaller domain that pays a larger domain for access to the rest of the Internet.

Observe the numerical results shown in the previous sections (Sections 4.2 and 4.3), an optimal operating point (corresponding to PC-Nash) depends on the relationship of the two connected domains. An undeniable fact is that the relationship between the two domains has influence on how much traffic is exchanged at the POI (point of interconnection) in the inter-domain networks, and also

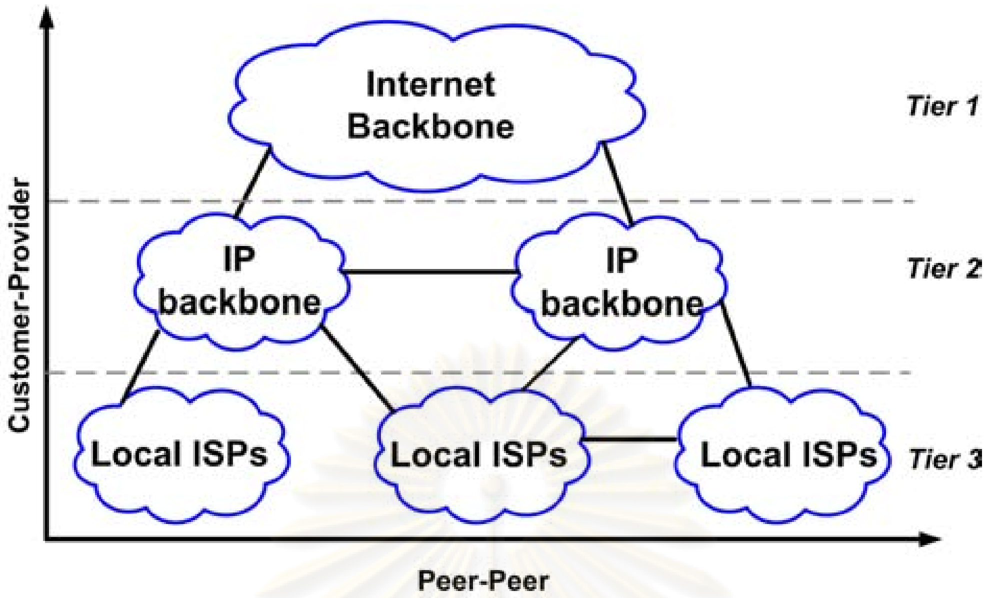


Figure 5.1 Internet hierarchy

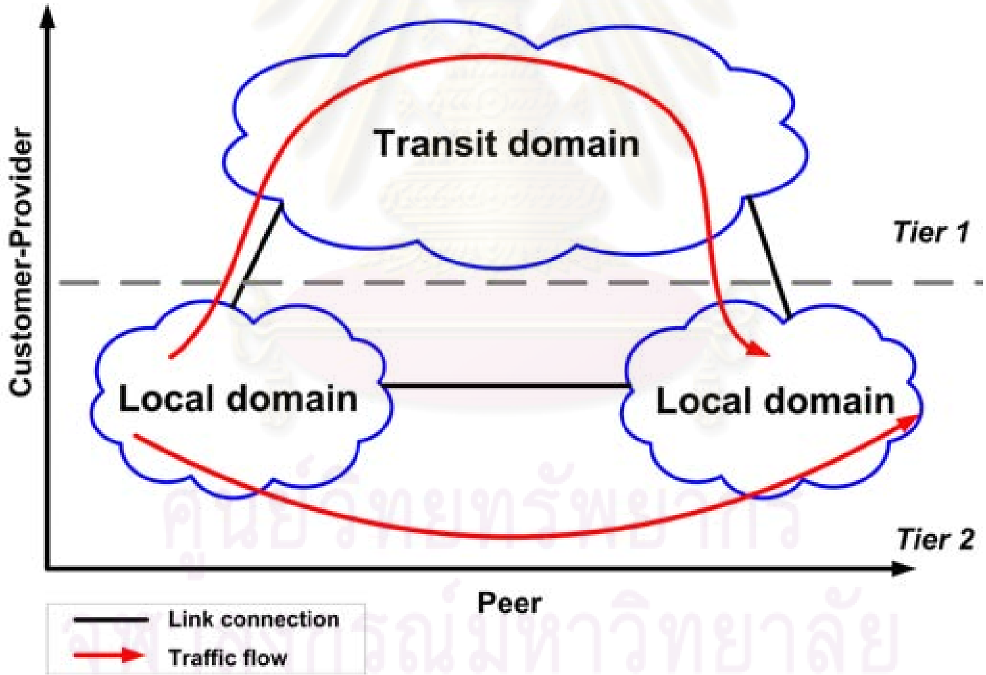


Figure 5.2 Inter-domain hierarchical structure

depicts which QoS-level should be implemented in each domain. This section therefore investigates the effectiveness of the path provisioning policies based on the business relationships with respect to the hierarchical inter-domain networks. In order to observe the basic concept of a hierarchical structure, the study here focuses on the interaction between two adjacent tiers as shown in Figure 5.2.

According to the Internet hierarchy (Figure 5.1), some ISPs use a single homed network of which the traffic can be routed to the neighbouring domain via only one exterior gateway. Multihomed networks have recently replaced single homed networks in order for the ISPs to improve their network reliability. In doing so, their traffic can route to at least two exterior gateways. Since two kinds of networks may render a different performance of path provisioning policies, this section provides fundamental studies for both single homed and multihomed networks.

5.1 Single Homed Network

Small customer domains may home their network to a single ISP to connect to the Internet. They assign one of their routers to be an exterior gateway which connects it with a router in their neighbour domain. Thus, this is the simplest case of an inter-domain routing policy setting when the inter-domain traffic has to pass through only one gateway. Recommendation RFC 2270 [63] has suggested the solution of a BGP configuration for a single homed network regarding the issue of how to manage the routing table and its scalability. Although such a customer domain can easily make a routing decision in order to communicate across domains, a pragmatic problem with a single homed network is which policy provides the most effective end-to-end QoS routing. Consequently, this section discusses on the effectiveness of the path provisioning policies in a single homed network environment.

5.1.1 Experimental Setting

In a single homed network, the customer homes the network to an ISP. The experiment for this study is based on the three-concatenated domains shown in Figure 5.3, where domains 1 and 3 singly home to domain 2. In this study, the observation has been done on the interconnection bottleneck, where the links jointing between the exterior gateways are considered a bottleneck. The performance of the path provisioning policies has been evaluated. The performance comparison has been made with respect to the resultant performance of the four policies, i.e., ME, LE, ED, and PC-Nash. The experiments have been done in MATLAB® by using the proposed analytical method. The independent Poisson call arrivals and exponentially distributed call-holding times are assumed for every call type. The topology profile is presented in Table 5.1. Multiple call types are also considered; the calls originated from node v_1 and terminated at node v_{12}, which is denoted as an OD-pair (v_1, v_{12}). The characteristics of each call type are listed in Table 5.2. The total offered load is varied to clarify the effect of the loading. The PC-Nash equilibria are obtained by setting

$D_1 = D_3 = 3$ and $D_2 = 2$ for the PC schemes. Thus, the performance of 18 cases $(3 \times 2 \times 3 = 18)$ must be tested to obtain a PC-Nash.

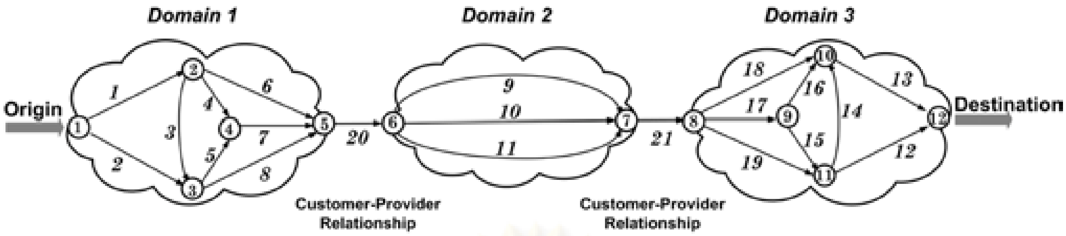


Figure 5.3: Network topology: concatenation of three identical network topologies with 21 links. Note: the number on each link represents a link label.

Table 5.1 Network profile of topology for single homed network

Link (l)	$1, 2, 12, 13$	$3, 4, 14, 16$	$5, 15$	$6, 7, 17, 18$	
$A(l)$	0.9999	0.9999	0.9999	0.9998	
c_l (Gbps)	4	2	2	3	
Link (l)	8,19	9	10	11	$20, 21$
$A(l)$	0.9998	0.9992	0.9991	0.999	1
c_l (Gbps)	3	2	2	3	1

Table 5.2 Traffic types in inter-domain networks

Topology	Type (s)	b_s	a_s	Load proportion
2	1	500 Mbps	0.9986	50%
	2	500 Mbps	0.9977	50%

5.1.2 Results of Single Homed Network

The experiment is tested under a scenario in which domains 1 and 3 have significantly higher quality paths than domain 2. Figures 5.4 and 5.5 illustrate the call blocking probability of ME, LE, ED and PC-Nash based on the single homed network environment, where domain 2 has poor path qualities. These results show that the number of allowable call types of ME, LE and PC-Nash are equal to 2 ($|S_{ME}| = |S_{LE}| = |S_{PC-Nash}| = 2$), while the number of allowable call types of ED is equal to 1 ($|S_{ED}| = 1$). The resultant performance of the implemented policies shows the confirmation of the following statement as described in Section 4.3; $|S_{ED}| \leq |S_{LE}| \leq |S_{ME}|$ when some domains in the middle of the end-to-end route have poor path qualities. The reason is that when the inter-domain networks deploy the ED policy, the availability target $a_{i,s}^{ED}$ of the first domains might suffer from the high level of responsibility in their availability targets. In contrast to ED, firstly domains deploying LE relax with the lower level of responsibility in their availability targets than the last domains do. For call type 1 in this experiment, $a_{1,1}^{ED} \approx 0.9995$ and $a_{2,1}^{ED} \approx 0.9994$ for ED, whereas $a_{1,1}^{t} \approx 0.9986$ and $a_{2,1}^{t} \approx 0.9988$ for LE. Therefore, the call type 1 cannot be accepted by ED, but it can be accepted by LE.

Figures 5.6 and 5.7 present the utility-difference ratio of the retail and wholesale service models. As shown in these two figures, ME and LE provide their utilities on the same level as PC-Nash, while ED provides a lower utility than ME, LE and PC-Nash. Note that the utility-difference ratio of ED for the retail service model is higher than that for the wholesale service model.

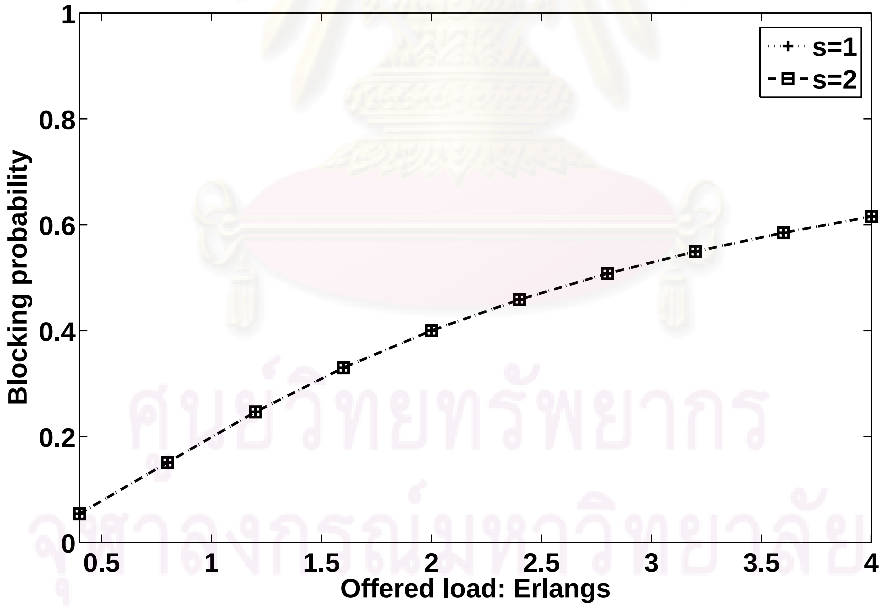


Figure 5.4: Results for inter-domain network with single homed environment: Call blocking probability of call types $s = 1, 2$ from ME, LE and PC-Nash $(d_1 = 3, d_2 = 2, d_3 = 3)$.

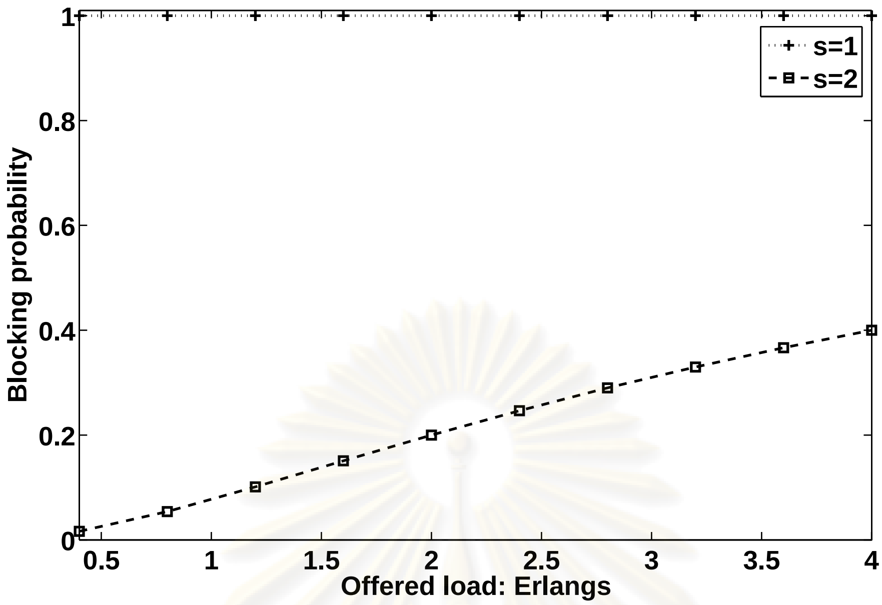


Figure 5.5: Results for inter-domain network with single homed environment: Call blocking probability of call types $s = 1, 2$ from ED.

5.1.3 Implication of the Results

In this section, the effectiveness of the path provisioning policies has been investigated on a single homed network environment. In order to fulfill the analytical conclusion in Section 4.3, the experiment has been run for the case of three-concatenated domains with a interconnection bottleneck link. As expected, the results show the confirmation of the analysis in Section 4.3 that $|S_{ED}| \leq |S_{LE}| \leq |S_{ME}|$ when some domains in the middle of the end-to-end route have poor path qualities. Compared to PC-Nash in terms of the utility-difference ratio, of course, the utility based on the retail service model provides a more significant difference than that based on the wholesale service model.

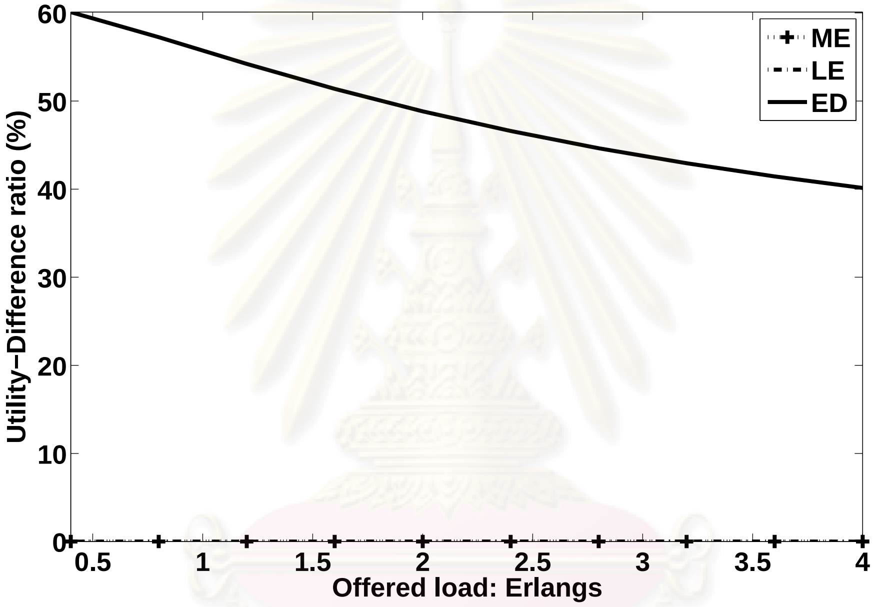


Figure 5.6: Results for inter-domain network with single homed environment: Utility-Difference ratio for retail service model based on utility of domain 1 ($u_1 = u_2$): $D_1 = D_3 = 3$, $D_2 = 2$, and $u_i = \sum_{s=1}^{S} g_i(a_s)\sigma_{i,s} - \beta_i w_i$ where $\beta_i = 0.35$ units per Mbps, $g_i(a_1) = 1000$ and $g_i(a_2) = 1500$ units per connection.

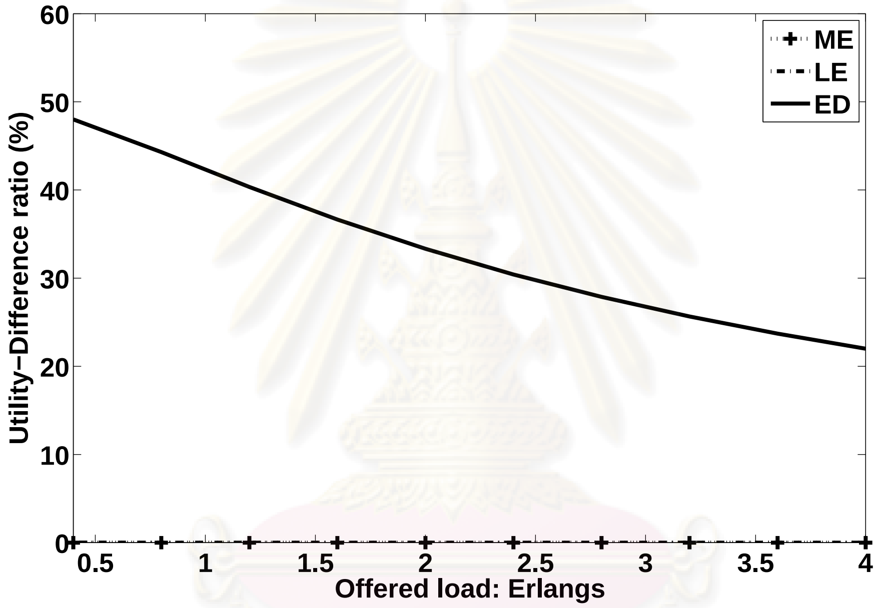


Figure 5.7: Results for inter-domain network with single homed environment: Utility-Difference ratio for wholesale service model based on utility of domain 1 ($u_1 = u_2$): $D_1 = D_3 = 3$,$D_2 = 2$ and $u_i = \sum_{s=1}^{S} g_i(a_s)\sigma_{i,s} - \beta_i w_i$, where $\beta_i = 0.35$ units per Mbps and $g_i(a_1) = g_i(a_2) = 1000$ units per connection.

5.2 Multihoming to a Single Domain

Typically, multihoming techniques are used by many autonomous systems, such as Tier-3 ISPs, and small networks for businesses to connect to the Internet in order to increase their network reliability [64]. A network is said to be multihomed if it has multiple external links (either to an ISP, or to different ISPs). This section focuses on a multihomed network to a single ISP. There are several techniques to control traffic across a domain boundary via multiple gateways. Basically, the administrator might set their traffic route to every gateway router in order to balance load. The other common technique is for the traffic to be assigned to one gateway router and let the other gateway be a backup. Recently, some studies have worked on evaluating and realising the benefits of multihoming [65]. The most remarkable conclusion in this literature is that selecting the right gateways yields a performance improvement. However, this work did not consider the provisioning path under the QoS constraints. In this section, the study focuses on the effectiveness of the path provisioning policies (i.e., ME, LE, ED and PC-Nash) in a multihomed environment to a single domain.

5.2.1 Experimental Setting

The investigation focuses on the effect of a multihomed network to a single domain. The experiment for this case study is based on the three-concatenated domains with two exterior gateways between the connected domains, as shown in Figure 5.8. The performance of the path provisioning policies has been evaluated. The comparison have been made with respect to the resultant performances of four policies, namely, ME, LE, ED, and PC-Nash. The experiments have been done in MATLAB® by employing the proposed analytical method. The independent Poisson call arrivals and exponentially distributed call-holding times are assumed for every call type. The topology profile is presented in Table 5.3. Multiple call types are considered; the calls originated from node v_1 and terminated at node v_{12}, which is denoted as an OD-pair (v_1, v_{12}). The characteristics of each call type are listed in Table 5.4. The total offered load is varied to clarify the effect of the loading. The PC-Nash equilibria are obtained by setting $D_1 = D_3 = 5$ and $D_2 = 2$ for the PC schemes. Thus, the performance of 50 cases $(5 \times 2 \times 5 = 50)$ must be tested to obtain a PC-Nash.

5.2.2 Results of Multihoming to a Single Domain

Figures 5.9 and 5.10 illustrate the utility-difference ratio of ME, LE, and ED compared with PC-Nash based on the retail and wholesale service models. The results of multihoming to a single

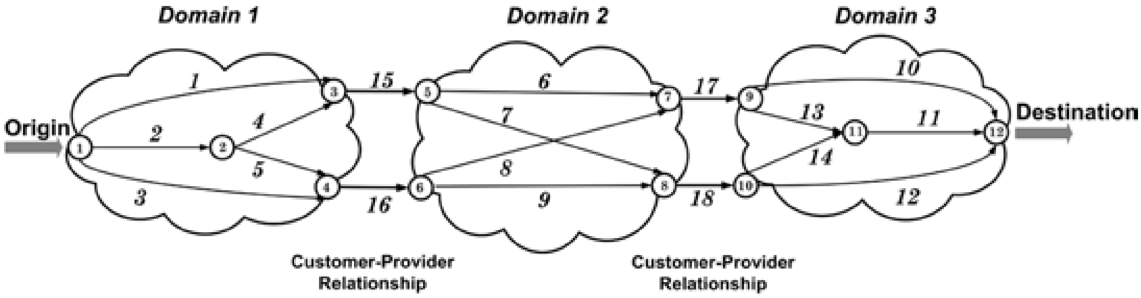


Figure 5.8: Network topology: concatenation of three identical network topologies with 18 links. Note: number on each link represents the link label.

Table 5.3 Network topology profile for network topologies in Figure 5.8

Link (l)	$1, 2, 10, 11$	$3, 12$	$4, 13$	$5, 14$
$A(l)$	0.9999	0.9995	0.9997	0.9998
c_l (Gbps)	2	2	2	2
Link (l)	6	7	8	9
$A(l)$	0.9999	0.9998	0.9997	0.9995
c_l (Gbps)	2	2	2	2

Table 5.4 Call type characteristics

Call type (s)	a_s	b_s	Load proportion
1	0.9990	500 Mbps	40%
2	0.9990	300 Mbps	40%
3	0.9993	500 Mbps	10%
4	0.9993	300 Mbps	10%

domain network are different from that from a single homed network. That is, the performance of ED is the best compared to ME and LE. Specifically, the utilities of ED are the closest to PC-Nash, while the utilities of ME are slightly lower than that in ED and PC-Nash. This finding contradicts the conclusion in the case of a single homed network because, in this case, ED can separate the different call types to the different gateways. In contrast, ME allows every call type to share the same exterior gateway. Therefore, ED can better balance the traffic between two exterior gateways than ME.

The utility-different ratio of LE is 100% because there is no accepted call. The reason behind

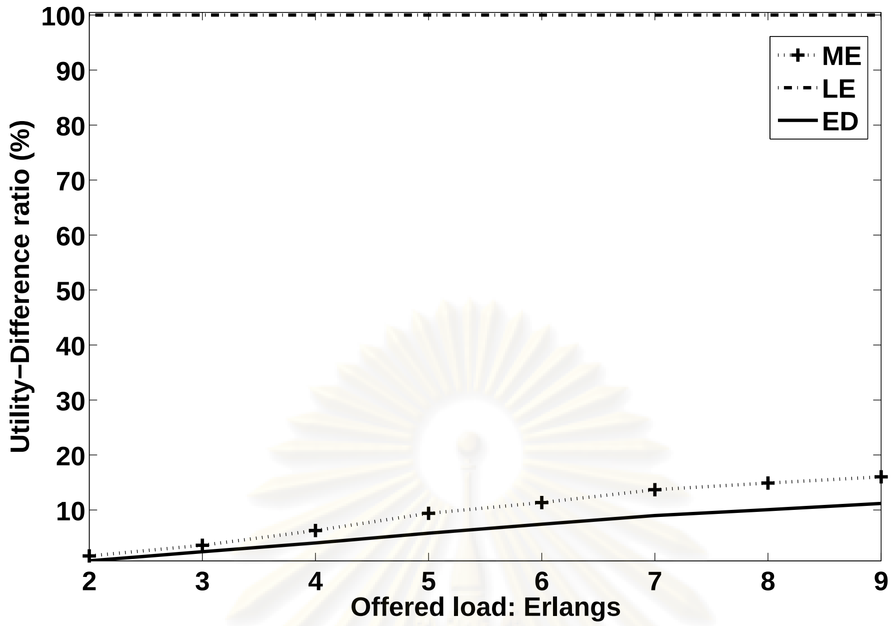


Figure 5.9: Results of single homed network for concatenation of three identical networks: Utility-Difference ratio for retail service model based on utility of domain 1 ($u_1 = u_2$): $D_1 = D_3 = 5, D_2 = 2$ for $i = 1, 2$, and $u_i = -\beta_i w_i$, where $\beta_i = 0.35$ units per Mbps.

this call rejection is that LE cannot provision the right set of paths with respect to this topological setting. When deploying LE, domain 1 always selects the path with the availability $A(l_3) = 0.9995$ for all requests $(a_1 = a_2 = 0.999$ and $a_3 = a_4 = 0.9993)$. This selection lifts the burden of path selection to domain 2. Domain 2 must select one in the set of paths which connects the exterior gateway (node v_4). There are two paths (l_8 and l_9) for call types 1 and 2. When using LE, domain 2 must select link l_9, where availability $A(l_9) = 0.9995$, for call types 1 and 2, while it cannot find any path for call types 3 and 4. However, the path provisioning of domain 2 for call type 1 creates a difficulty for domain 3, since it cannot find any path matching the availability request. Note that PC-Nash can provide the highest utilities with respect to the retail and wholesale service models because PC-Nash can match the right set of path selections for those gateways corresponding to the request constraints.

5.2.3 Implication of the Results

This section discusses the investigation of the effectiveness of the path provisioning policies (i.e., ME, LE, ED and PC-Nash) based on being multihomed to a single domain environment. Each domain may face the difficulty of how to efficiently select the gateway router rather than select the

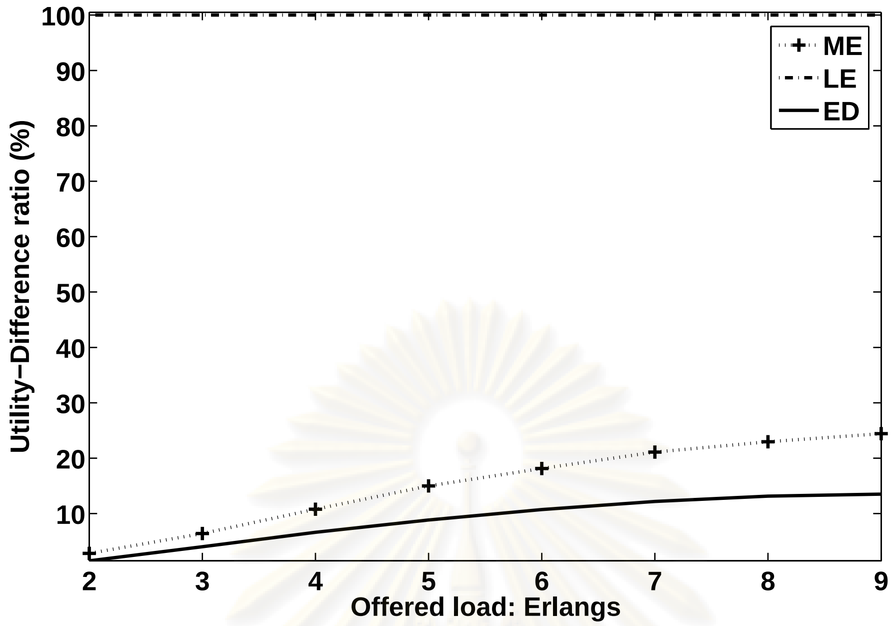


Figure 5.10: Results of single homed network for concatenation of three identical networks: Utility-Difference ratio for wholesale service model based on utility of domain 1 ($u_1 = u_2$): $D_1 = D_3 = 5, D_2 = 2$ for $i = 1, 2$, and $u_i = -\beta_i w_i$, where $\beta_i = 0.35$ units per Mbps.

best path to support a call request. The right set of paths selected corresponding to the requests can help to more efficiently provide the appropriate network. The reported results based on the topological setting in this experiment show that employing ED and ME can drive the system close to the optimum operating point. On the other hand, LE pushes the burden to the latter domains suffering from the availability target. Therefore, LE is not recommended for implementation to this kind of network environment. In fact, the remark conclusion of this finding depends on the topological setting. Nevertheless, PC-Nash is found by learning algorithm MSA which provides the optimal set of path selections for all the requests.

5.3 Multihoming to Multiple Domains

A multihomed network is a currently used technique for connecting a network domain to multiple ISPs in order to improve the network reliability, redundancy and supplier diversity [64], while this technique challenges researchers to consider the practical issues, such as the scalability and routing policy capability. To support the multihoming concept, some researches [65–68] have proposed several solutions to make multihoming practical in the Internet protocol. For example, IPv4 multihoming practices have been added to the Classless Inter Domain Routing (CIDR) architecture [66], which assumes that the routing table entries can be aggregated upon a hierarchy of customers and service providers. Many different schemes, e.g., [65, 69, 70], have been proposed for leveraging traffic under the multihomed network environment, so that these schemes improve the efficiency in terms of the network performance and revenue. Akella et al. [65] have quantified the benefits of multihoming and shown that selecting the right set of providers yields the performance improvement. This work motivated Liu and Xiao [70] to propose a load balancing mechanism that dynamically balances the inbound traffic in multihomed networks. Focusing on the least cost routing, Wang [69] has proposed an optimal algorithm for multihomed networks to achieve an optimal set of ISPs based on the ISPs' charging models. These studies are the motivation for this dissertation on whether or not to consider that the focused path provisioning policies (i.e., ME, LE, ED and PC-Nash) can efficiently leverage traffic to multiple accesses when taking into account the business relationship models for hierarchical networks. To fulfill the investigation, the effectiveness of the path provisioning policies for an end-to-end QoS support in multihomed to multiple domains is discussed in this section.

5.3.1 Experimental Setting

This section provides the results from our investigation on the most effective policies for use in the multihoming environment. In the multihoming environment, each domain connects to two domains in order to increase its network reliability. The experiment on the multihomed network is based on the triangle network model as shown in Figure 5.11. The topology profile is presented in Table 5.5. The business relationship of the two connected domains is denoted as in Figure 5.11; customer-provider relationships are for domain 1 to domain 2 and domain 2 to domain 3, and a peer relationship is for domain 1 to domain 3. Multiple call types are also considered; the calls originated from node v_1 and terminated at node v_{10}, which is denoted as an OD-pair (v_1, v_{10}). The characteristics of each call type are listed in Table 5.6. The independent Poisson call arrivals and exponentially distributed call-holding times are assumed for every call type. The effect of loading has been investigated by varying the total offered load. The performance of the path provisioning policies have been evaluated and compared against the four policies, namely, ME, LE, ED, and PC-Nash. Similar to that in the first case, we set $D_1 = D_3 = 5$ and $D_2 = 2$ for the PC schemes. Consequently, there are 50 $(5 \times 2 \times 5 = 50)$ testing cases in order to obtain a PC-Nash.

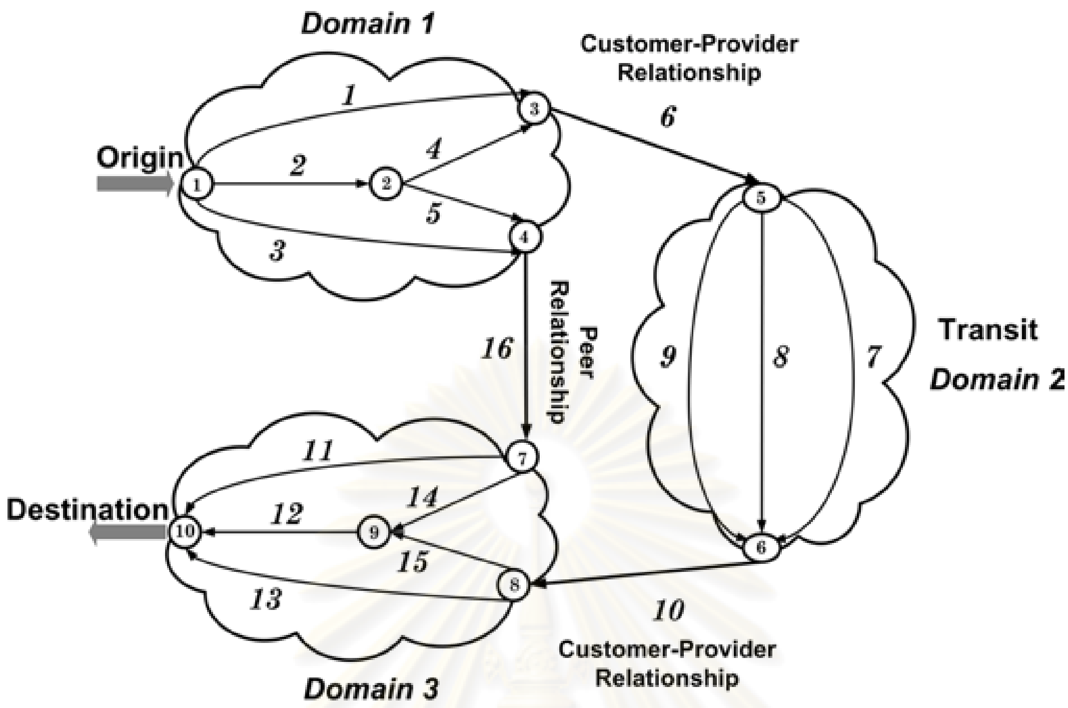


Figure 5.11: Network topology: triangular identical network topologies with 16 links. Note: the link number represents the link label.

Table 5.5 Network topology profile for network topologies in Figure 5.11

Link (l)	$1, 2, 7, 11, 12$	$3, 13$	$4, 14$	$5, 8, 15$	9	$6, 16, 10$
$A(l)$	0.9999	0.9995	0.9997	0.9998	0.9996	1
c_l (Gbps)	4	4	4	4	4	2

Table 5.6 Call type characteristics

Call type (s)	a_s	b_s	Load proportion
1	0.9990	500 Mbps	40%
2	0.9990	300 Mbps	40%
3	0.9996	500 Mbps	10%
4	0.9996	300 Mbps	10%

5.3.2 Results of Multihomed to Multiple Domains

Taking into consideration the topological structure with a multihomed to a single domain in Section 5.2, the routing policy does not concern the difference in charge whereby the traffic passes to different gateways. Therefore, the optimal solution of the path provisioning policy only suggests how to match the exterior gateways among domains. Unlike the aforementioned investigation in Section 5.2, the routing to multiple gateways, which connect different domains, must take into consideration the different charging models in order to optimise both the network performance and the revenue.

The end-to-end QoS path provisioning based on an inter-domain network in Figure 5.11 can be classified into two groups. The first group represents the paths which route from the origin to the destination by passing through the transit domain (Figure 5.12). The second group represents the paths which route from the origin to the destination without passing through the transit domain (Figure 5.13). In this investigation, it is assumed that the interconnection links are the bottleneck links. Based on this separation with respect to the interconnection link model, these two routing groups can be mapped to two single link models as shown in Figures 5.12 and 5.13.

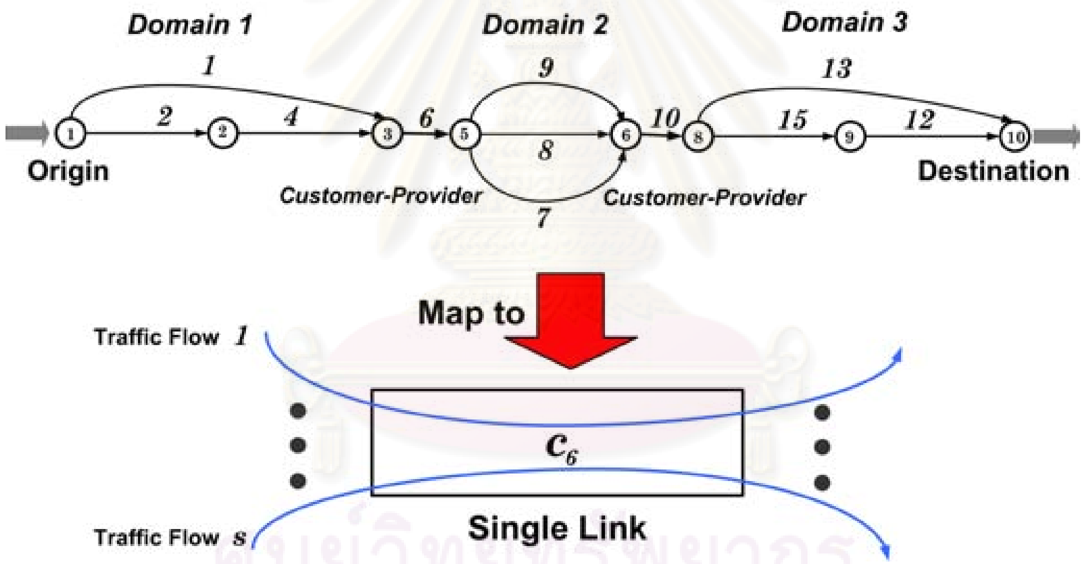


Figure 5.12 Topology mapping to a single link model for the routes passing through three domains.

Figure 5.14 presents the results of the call blocking probability for ME, LE, ED and PC-Nash: $(d_1 = 5, d_2 = 2, d_3 = 1), \ldots, (d_1 = 5, d_2 = 2, d_3 = 5)$, while Figure 5.15 illustrates the results of the call blocking probability for the path-classification scheme with the following QoS-levels: $(d_1 = 2, d_2 = 2, d_3 = 1), \ldots, (d_1 = 2, d_2 = 2, d_3 = 5)$. Note that the QoS-level of domain 1 affects how a call is routed. For example, when domain 1 deploys QoS-level $d = 5$, every call type is routed to domain 2, but call types 3 and 4 are blocked by domain 3. When domain 1 deploys QoS-level $d = 2$, call types 1 and 2 are routed to domain 2, whereas the call types 3 and 4 are directly routed to domain 3. In these cases, the performance of this topology does not depend on the QoS-level of domain 3.

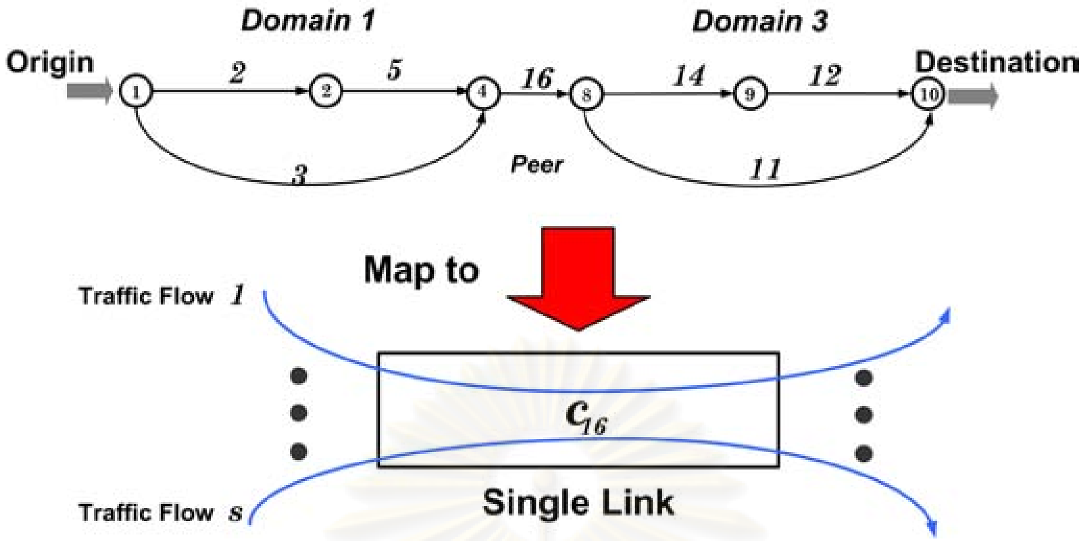


Figure 5.13 Topology mapping to a single model for the routes passing through two domains.

Therefore, these different policies, i.e., $(d_1 = 2, d_2 = 2, d_3 = 1), \ldots, (d_1 = 2, d_2 = 2, d_3 = 5)$, provide the same performance as shown in Figure 5.16. Likewise, deploying these policies, i.e., $(d_1 = 2, d_2 = 2, d_3 = 1), \ldots, (d_1 = 2, d_2 = 2, d_3 = 5)$, also provide the same performance as shown in Figure 5.17.

When the inter-domain networks deploy ME and PC-Nash, there are two call types (i.e., $s = 1$ and $s = 2$) which are allowed to access the interconnection links l_6 and l_{10} (see Figure 5.16). Based on the customer-provider relationship model, the utility function of domains 1, 2 and 3 for ME and PC-Nash is calculated by using

$$u_i = \sum_{s=1,2} g_i(a_s)\sigma_{i,s} - \beta_i w_i, \tag{5.1}$$

where w_i is obtained by using (3.10). That is

$$w_i = \sum_{s=1,2,v_o,v_t} \mathbb{A}_{i,s}(v_o, v_t) b_s \lambda_s(v_o, v_t)/\mu_s(v_o, v_t). \tag{5.2}$$

For LE and ED, there are two call types (i.e., $s = 1$ and $s = 2$) which are allowed to access the interconnection link l_{16} (see Figure 5.18). Based on the peer relationship model, the utility function of domain 1 and 2 is calculated by

$$u_i = -\beta_i w_i, \tag{5.3}$$

where w_i can be calculated as (5.2). There are some QoS-levels, i.e., $(d_1 = 2, d_2 = 2, d_3 = 1), (d_1 = 2, d_2 = 2, d_3 = 2), \ldots, (d_1 = 2, d_2 = 2, d_3 = 5)$, which provide different performance from ME, LE, ED and PC-Nash as shown in Figure 5.17. Call types 1 and 2 are assigned to pass the transit domain (domain 2) with respect to the customer-provider relationship, whereas the call types 3 and 4 are assigned to access domain 3 directly with respect to the peer relationship. Thus, the utility function of domain 1 can be calculated by

$$u_i = \sum_{s=1,2} g_i(a_s)\sigma_{i,s} - \beta_i w_i, \tag{5.4}$$

where w_i is calculated by using

$$w_i = \sum_{s=1,2,3,4,v_o,v_t} \mathbb{A}_{i,s}(v_o,v_t) b_s \lambda_s(v_o,v_t)/\mu_s(v_o,v_t). \tag{5.5}$$

The results of the utility-difference ratio for domain 1 are shown in Figures 5.19 and 5.20. Note that following (5.1) and (5.5), the difference between two utilities is only in the cost function, i.e., $-\beta_i w_i$. Consequently, the utility-difference ratio of ME and path-classification scheme with QoS-levels $(d_1 = 2, d_2 = 2, d_3 = 2)$ comparing with PC-Nash with respect to the retail service model is the same as that with respect to the wholesale service model .

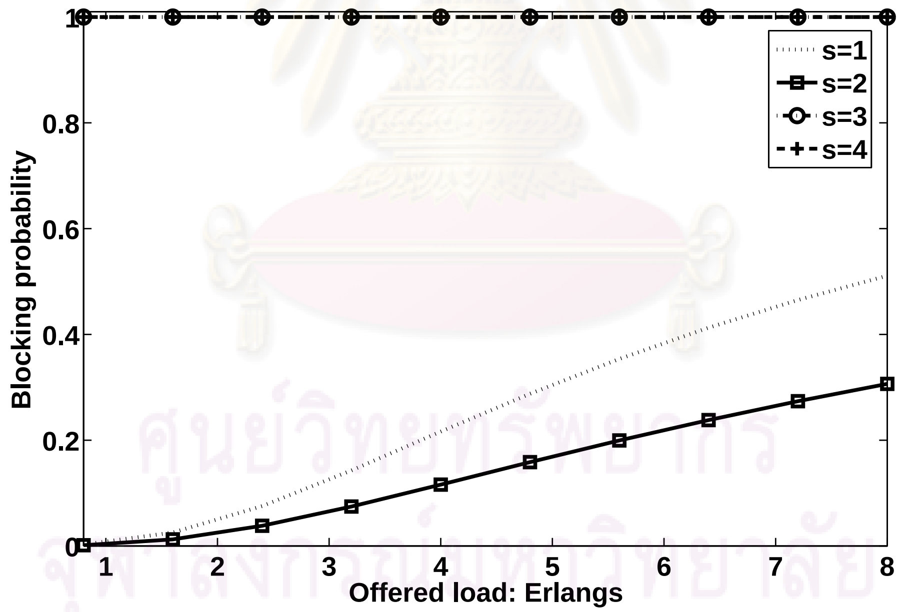


Figure 5.14: Result of the call blocking probability for ME, LE, ED and PC-Nash: $(d_1 = 5, d_2 = 2, d_3 = 1), \ldots, (d_1 = 5, d_2 = 2, d_3 = 5)$, where $D_1 = D_3 = 5$ and $D_2 = 2$.

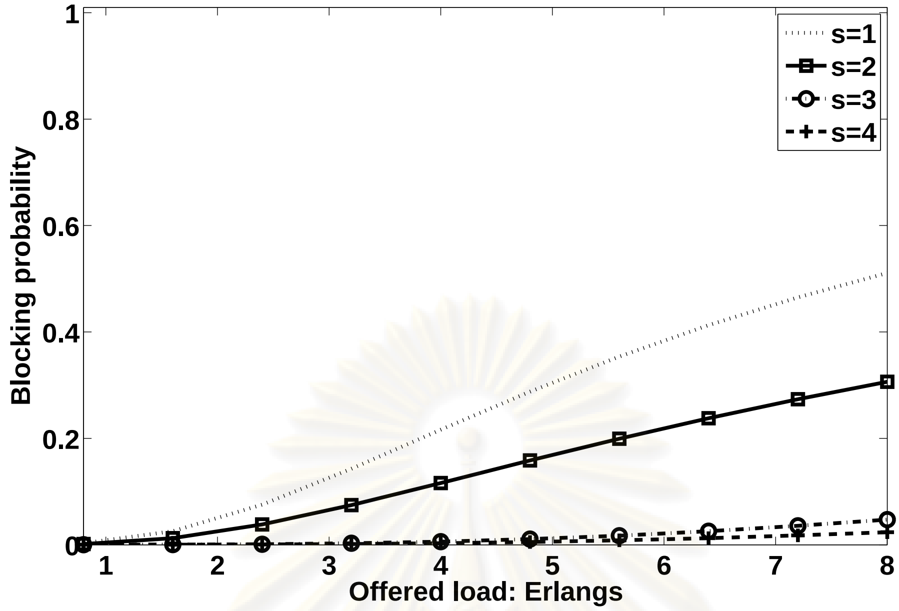


Figure 5.15: Result of call blocking probability for path-classification scheme with QoS-levels: $(d_1 = 2, d_2 = 2, d_3 = 1), \ldots, (d_1 = 2, d_2 = 2, d_3 = 5)$, where $D_1 = D_3 = 5$ and $D_2 = 2$.

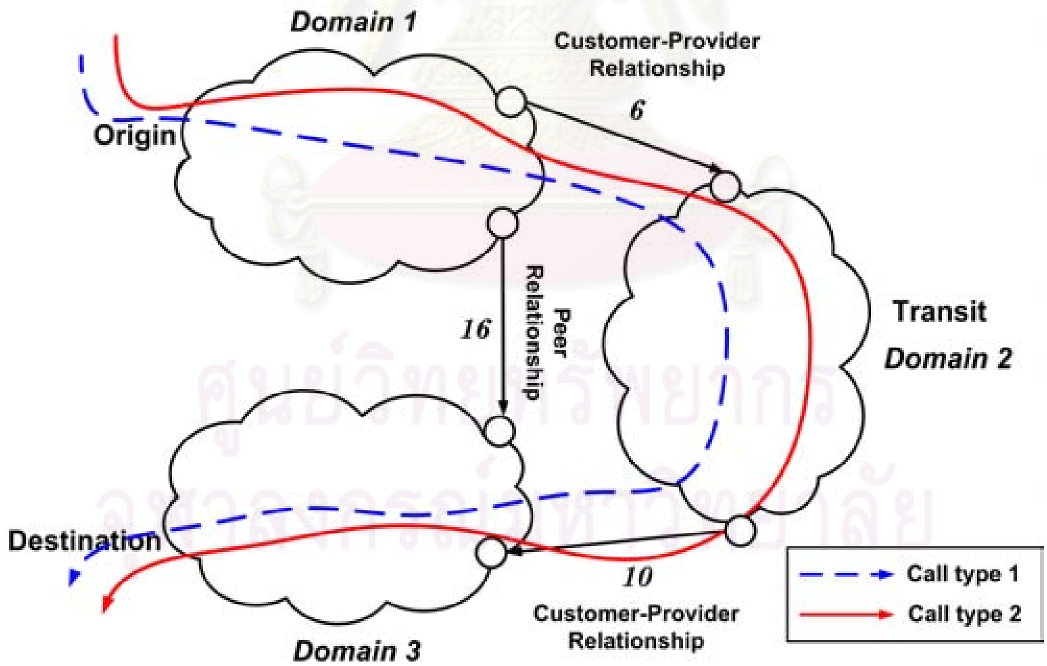


Figure 5.16: Call types 1 and 2 are routed in interconnection link l_6 and l_{10} when every domain deploys ME and PC-Nash: $(d_1 = 5, d_2 = 2, d_3 = 1), \ldots, (d_1 = 5, d_2 = 2, d_3 = 5)$, where $D_1 = D_3 = 5$ and $D_2 = 2$.

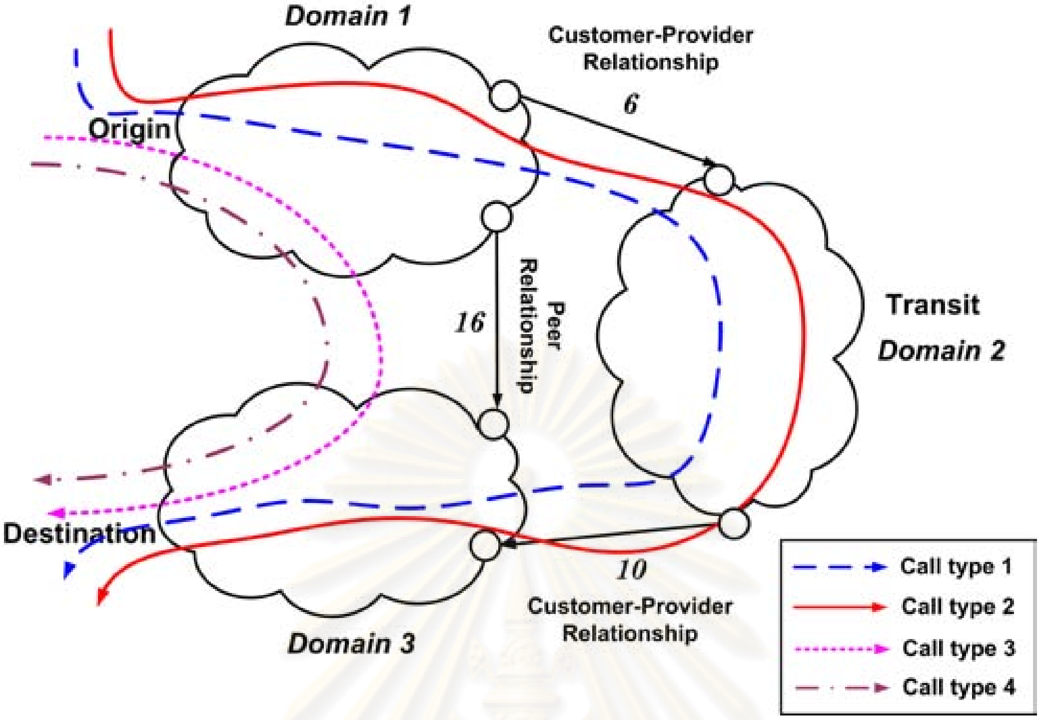


Figure 5.17: Result for path-classification scheme with QoS-levels: $(d_1 = 2, d_2 = 2, d_3 = 1), \ldots, (d_1 = 2, d_2 = 2, d_3 = 5)$, where $D_1 = D_3 = 5$ and $D_2 = 2$.

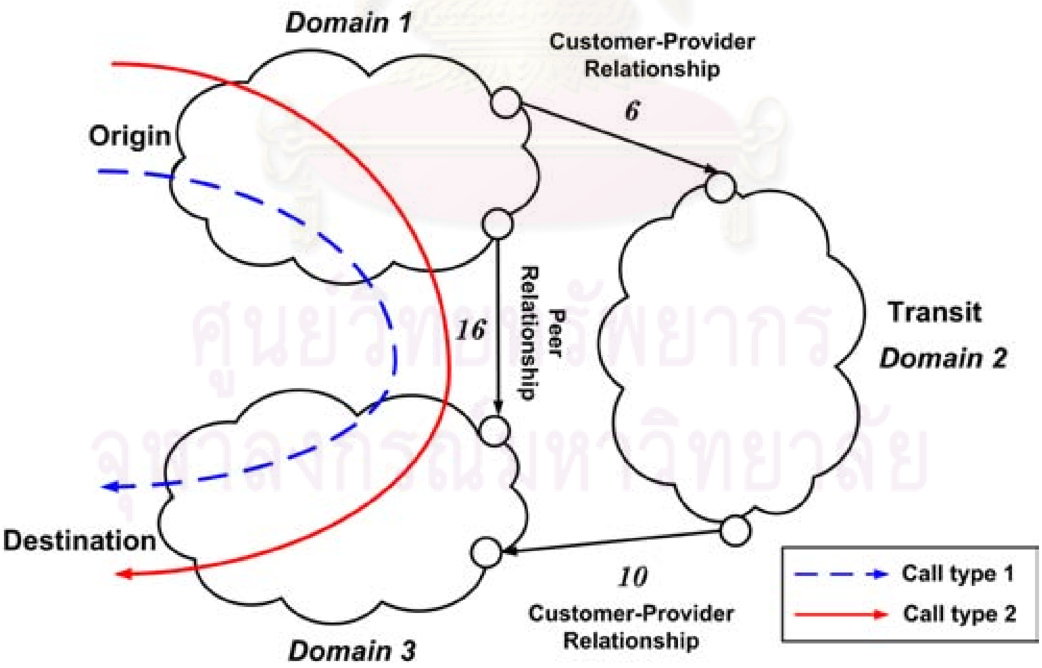


Figure 5.18: Call types 1 and 2 are routed in interconnection link l_{16} when every domain deploys LE and ED.

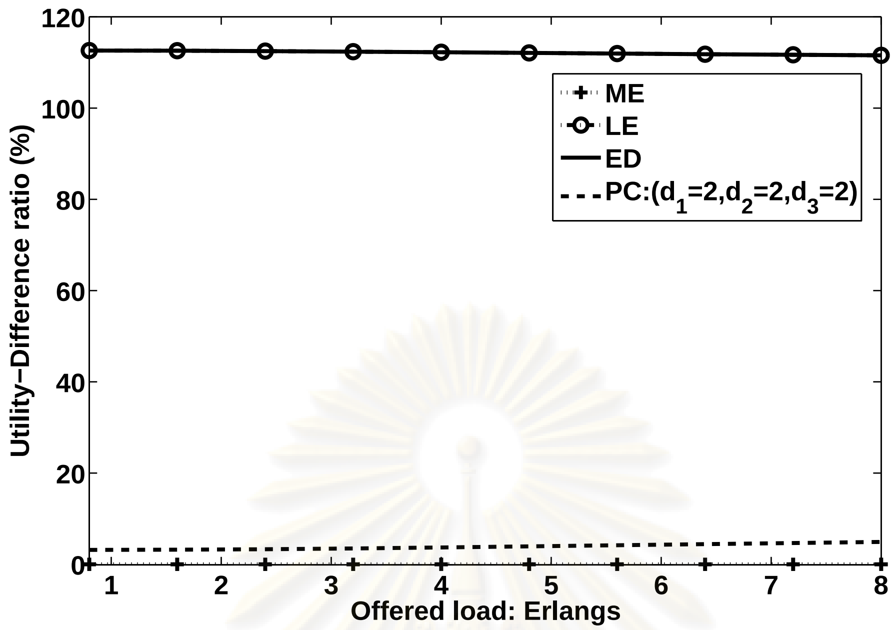


Figure 5.19: Results for inter-domain network with single homed environment: Utility-Difference ratio for retail service model based on utility of domain 1 (u_1): $D_1 = D_3 = 3$, $D_2 = 2$, and $u_i = \sum_{s=1}^{S} g_i(a_s)\sigma_{i,s} - \beta_i w_i$ where $\beta_i = 0.35$ units per Mbps, $g_i(a_1) = g_i(a_2) = 1000$ and $g_i(a_3) = g_i(a_4) = 1500$ units per connection.

5.3.3 Implication of the Results

This section focused on the multihomed to multiple domains environment. The effectiveness of the considered policies, namely ME, LE, ED and PC-Nash have been tested on the three connected domains with multihomed networks. The business relationship between two connected domains is given following the Internet hierarchy: the customer-provider for the transit domain and a peer for the non-transit domain. The reported results show that PC-Nash can provide the most benefit in terms of utility value. In addition, ME can also provide the same performance as that of PC-Nash. On the other hand, LE and ED provide the worst performance. The remarkable thing about the results is that some of the QoS-level sets of the path-classification scheme provide the least call blocking probability because these policies make the different call types route separately to the different exterior gateways. Therefore, some call types do not share the capacity in the same route. If the network goal is to achieve a high performance level, these policies are recommended for implementation in the multihomed network environment. However, the utility of this setting is still less than that of ME and PC-Nash because of the charging according to the business model amongst the three domains. The conclusion

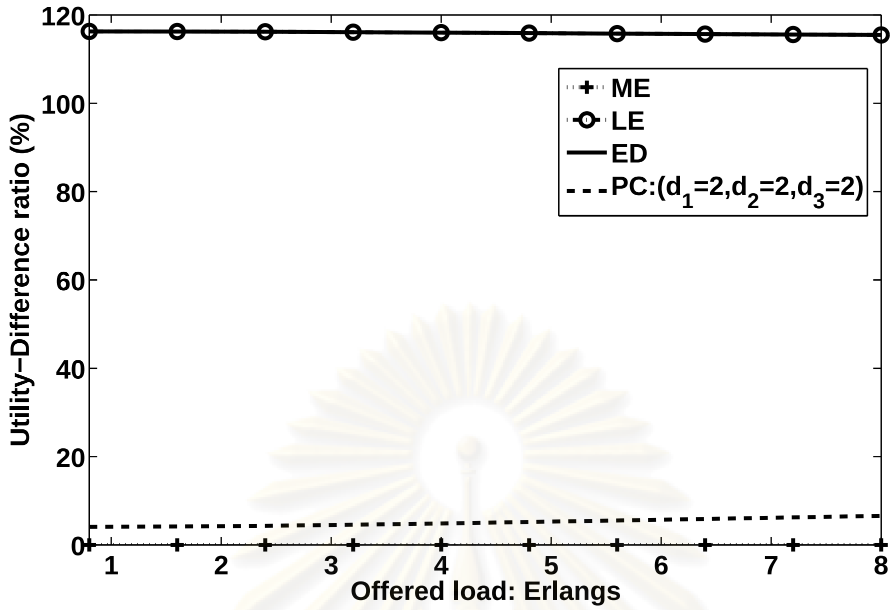


Figure 5.20: Results for inter-domain network with single homed environment: Utility-Difference ratio for retail service model based on utility of domain 1 (u_1): $D_1 = D_3 = 3$, $D_2 = 2$, and $u_i = \sum_{s=1}^{S} g_i(a_s)\sigma_{i,s} - \beta_i w_i$ where $\beta_i = 0.35$ units per Mbps, $g_i(a_1) = g_i(a_2) = g_i(a_3) = g_i(a_4) = 1000$ units per connection.

based on these results is that PC-Nash or ME are a good possible routing policy for multihomed networks, while LE and ED do not leverage traffic in this environment. Apart from this topology setting, PC-Nash will also perform at a higher level performance and have a good revenue because of its inherent optimisation.

CHAPTER VI

PC-NASH EXTENSION

While providing an end-to-end QoS service in inter-domain networks is considered throughout this dissertation, one concern is the flexibility to adjust the proposed PC-Nash to several objectives. This chapter outlines some of the issues that need to be considered in the real practice. One interesting issues is that rational ISPs tend to behave selfish path provisioning. Although PC-Nash can provide the necessary optimal path provisioning in terms of achieving the business model objectives (e.g. peer, wholesale and retail), it cannot guarantee the optimality that can be obtained from cooperative unselfish operating point. The other issue is that, in PC-Nash, classifying the path according to only path availabilities may lead some paths to over utilisation, while this leaves other paths to under utilisation. To improve the network utilisation, the traffic on the paths should be balanced. This chapter, therefore, focuses on the investigation of PC-Nash extension to twofold problem: to cope with the selfish ISP problem (see in Section 6.1) and to improve the network performance by using load balancing (see in Section 6.2).

6.1 Selfish Behaviour Prevention

Focusing on the connection-oriented services based on MPLS/GMPLS in the inter-domain network, the ISPs are facing with challenges of a twofold problem. First, the major problem is how to provide an end-to-end QoS guarantee according to the subscribers' requests in the inter-domain network. Second, the end-to-end QoS cannot be done without coordination from multiple network domains. Several previous researches have proposed schemes to deal with this need. For example, adopting BGP at the edge routers is a typically useful technique to construct an end-to-end connection across the multiple domains [71], [72]. The key idea of these works is to achieve the end-to-end QoS services by extending BGP to include Traffic Engineering (TE) information across domain boundaries.

Besides the modified BGP approaches, several researches have investigated the path provisioning policies to overcome the problem of end-to-end QoS during a path establishment (e.g. [13–15]). Three policies, i.e. least-effort, most-effort and equal-distribution policies, have been proposed in [13] with the concept of minimum, maximum and equal responsibility in terms of path availability effort.

With these policies, the ISPs do not necessarily require internal TE extension across domains. However, the freedom of policy selection is not held. Instead of forcing all domains to execute the same path selection policy, the proposed idea of letting ISPs freely select a path according to their own "path-classification" scheme has been proposed in Chapter 3. In practice, game-theoretical approach drives the system to achieve the equilibrium point of which one drawback leads to selfishness by using the utility function of three business models (i.e. peer, wholesale, retail models).

Observe that the selfish behavior cannot drive the system to satisfy the subscribers as well as the other operators in the same inter-domain network [32], [73]. Therefore, another challenge to ISPs is to prevent the impact of the other ISPs' selfishness. There are several researches (e.g. [32], [73]) which adopt the concept of penalty to punish selfish operators. Consequently, a penalty function is taken into account in this section.

The study here focuses on how to overcome the end-to-end QoS path provisioning problem in a competitive network environment and to prevent selfish path provisioning. The path-classification scheme is adopted to broaden the policy selection for the end-to-end QoS path provisioning. Moreover, the utility function is newly adjusted by adding a penalty term to prevent the selfishness. The investigation relies on an equilibrium point of mixed strategies in the game theory. The optimal policy regarding three business models, i.e. peer, wholesale and retail, is evaluated. The comparison of system performance among different policies have been investigated.

6.1.1 Proposed Penalty Function

Regarding the path-classification scheme, ISPs can use this scheme to help them provision their traffic routes. The ISPs just select the preferred policy $d_i \in \{1, \ldots, D_i\}$ for routing management. However, this scheme does not provide any mechanism to prevent occurrences of extremely selfish policy selection. Consider the utility function proposed in Section 3.3, i.e., (3.17),

$$u_i = \sum_{s \in S} g_i(a_s)\sigma_{i,s} - \beta_i w_i, \tag{6.1}$$

where $g_i(a_s) = 0$ for peer service model, $g_i(a_s)$ is equal to positive revenue rate for wholesale service model, and $g_i(a_s)$ depends on call types for retail service model. As realised from the results in [14], setting the utility function according to only maximum network profit (referred to wholesale and retail service models) and minimum network cost (referred to peer service model) cannot prevent the selfish path provisioning. In other words, these results show that all operators prefer a path that minimises its own bandwidth consumption and offers the least possible availability as its promised QoS during

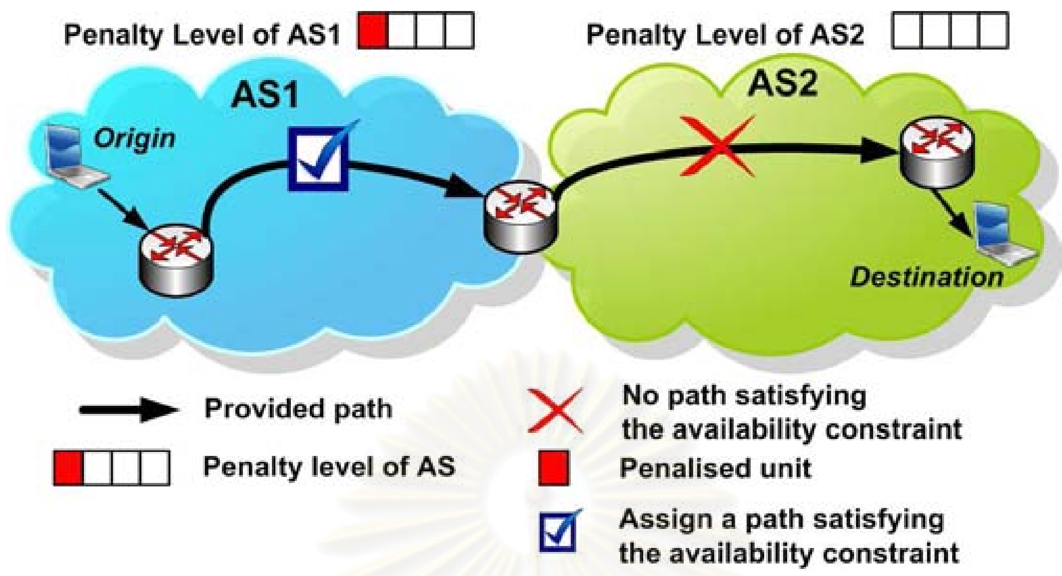


Figure 6.1 Penalty concept

a connection establishment at a burden of other ISPs that have not yet specified their promised QoS constraints. Therefore, the idea of penalty function is introduced to prevent the selfishness.

End-to-end path establishment is generally constructed as a sequence of provided paths from the origin to the destination. End-to-end path establishment may not succeed with its requested QoS constraints if any previous domain provides very low availability path. If so, the remaining downstream domains cannot find any path satisfying their availability targets. This behavior of the upstream domain is clarified here as a *selfish path provisioning*. Hence, the penalty function is defined in terms of how much the regulator punishes the ISPs who selfishly provision their paths. The concept of penalty is summarised in Figure 6.1. With this definition, the penalty function is mathematically formulated as

$$\Upsilon_i = \sum_{s \in S} f_i(s)\gamma_i(s) \tag{6.2}$$

where penalty factor $f_i(s)$ represents penalised value per a type-s call of domain i and $\gamma_i(s)$ be the mean number of rejected type-s calls. Therefore, utility function in (6.1) is redefined as

$$u_i = \sum_{s \in S} g_i(a_s)\sigma_{i,s} - \beta_i w_i - \sum_{s \in S} f_i(s)\gamma_i(s). \tag{6.3}$$

The performance of the network by using this utility function is reported in [74]. The effectiveness of selfishness prevention is evaluated in terms of how much total call blocking probability of the system can be reduced. The reported results in [74] show that including the penalty term in the utility function can force the system players (ISPs) to become less selfishness. However in practice, the penalty term should be carefully chosen as to motivate all participants to act as the regulatory authority's approval. The question left behind the defined *selfish path provisioning* is how to trace back who behaves a selfish ISP in the inter-domain network. In the real telecommunication business markets, the right of the regulator is quite limited, and it is impossible to ask for the log files of all ISPs to trace one should be punished. The best that the regulator can do is to motivate all ISPs in the inter-domain network trying to cooperate with each other. In doing so, the new penalty function of selfishness punishment is redefined. Define the mean number of rejected type-s calls of domain i as

$$\gamma_i(s) = \sum_{\mathbf{n} \in \Omega_B(s,v_o,v_t)} \pi(\mathbf{n}) \lambda_s(v_o, v_t) / \mu_s(v_o, v_t). \tag{6.4}$$

All domains found oneself a no-win situation when any domain behaves selfishness. This number reflects the loss-loss situation. Thus, this penalty function will drive the optimum operating point into unselfish behavior corresponding to their network environment.

6.1.2 Experimental Setting

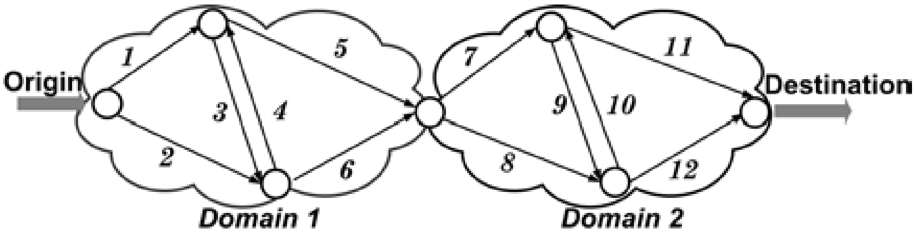
A preliminary investigation of newly proposed utility function to prevent selfish path provisioning in inter-domain networks has been done with two concatenated domains. In order to illustrate the effectiveness of the proposed utility function, the results of PC-Nash are compared with those of ME, LE and ED policies. The investigation includes the cases of peer, wholesale and retail service models.

The experimental setting for this investigation is the same as the setting in the experiments of Section 4.1. The network topologies for testing are re-illustrated in Figure 6.2. The topologies' profiles are presented in Tables 6.1 and 6.2. For all experiments, let every call route from one origin-destination pair with independent Poisson call arrivals and exponentially distributed call holding times. The investigation considers multiple call types of which the constraints and load proportion are listed in Table 6.3. The analytical results have been obtained by the program developed in MATLAB® and run on the computer cluster consisting of 3 computing nodes each with core-2-quad 2.0 GHz Xeon™processors and 4-GByte memory.

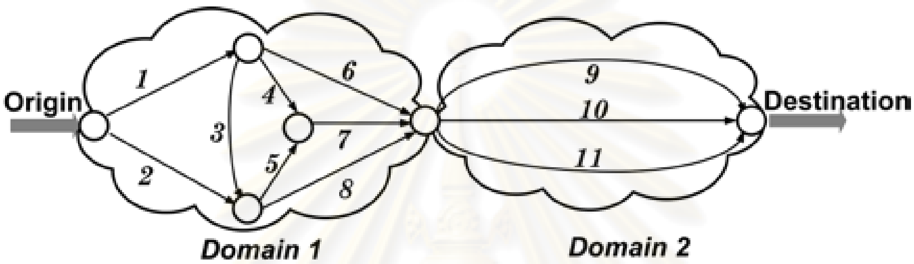
6.1.3 Results

This subsection presents the examples of preventing selfish path provisioning. The examples have been tested via adopting the new utility function in (6.3). For quantification, the evaluation is done via the rejected-call-difference ratio,

$$\frac{1}{|S|} \sum_{s \in S} \frac{\gamma_i(s) - \acute{\gamma}_i(s)}{\acute{\gamma}_i(s)} \times 100\%, \tag{6.5}$$



(a) Topology 1 (concatenation of two identical network topologies), where label of link $l \in \{1, \dots, 12\}$.



(b) Topology 2 (concatenation of two different network topologies), where label of link $l \in \{1, \dots, 11\}$.

Figure 6.2 Network topologies

Table 6.1 Network profile of topology 1

Link (l)	$1, 5, 7, 11$	$6, 12$	$2, 8$	$3, 4, 9, 10$
$A(l)$	0.99999	0.99992	0.9999	0.999
c_l (Gbps)	1	1	1	1

where $|S|$ is a number of call types, and $\gamma_i(s)$ and $\acute{\gamma}_i(s)$ are the mean numbers of rejected type-s calls from PC-Nash without the penalty function and PC-Nash with the penalty function, respectively.

Figure 6.3 illustrates the rejected-call-difference ratio for peer, wholesale and retail service models in the case of the inter-domain networks with the same path quality. The comparison between PC-Nash without the penalty function and PC-Nash with the penalty function shows that the penalty function can reduce the mean rejected calls in the case of peer service model, but not in the case of retail and wholesale service models. The reason is that, for peer service model, PC-Nash without the penalty function minimises the network cost by minimising accepted calls, while PC-Nash with the

Table 6.2 Network profile of topology 2

Link (l)	$1, 2$	$3, 4$	5	$6, 7$
$A(l)$	0.9999	0.9998	0.9995	0.9999
c_l (Gbps)	3	1	1	2
Link (l)	8	9	10	11
$A(l)$	0.9998	0.9992	0.999	0.998
c_l (Gbps)	2	1	1	2

Table 6.3 Traffic types in inter-domain networks

Topology	Type (s)	b_s	a_s	load proportion
1	1	500 Mbps	0.9998	50%
	2	500 Mbps	0.9980	50%
2	1	500 Mbps	0.9986	50%
	2	500 Mbps	0.9977	50%

penalty function optimises between the penalty cost by reducing rejected calls and the network cost by reducing accepted calls. Therefore, these two policies approach to the different optimal operating points, where PC-Nash with the penalty function can reduce rejected call from PC-Nash without the penalty function. In contrast, based on wholesale and retial service models, PC-Nash with and without the penalty function maximise the revenue by increasing accepted calls. Thus, adding the penalty term for these two business models does not affect the optimal operating point.

Additionally, the highest difference is found in light load and the difference declines by more load of peer service model. This is because, in the light load, there are some policies setting that let network accept more calls to minimise the penalty term. However, no policy setting can increase the accepted calls in heavy load. Observe that including the penalty term in the utility function of peer service model can force the system to reach unselfishness.

Figures 6.4–6.5 show the effectiveness of the path-provisioning policies compared with PC-Nash with penalty function. For the inter-domain networks with the same path quality, LE performs best, while ME performs worse with respect to peer, retail and wholesale service models. The worse

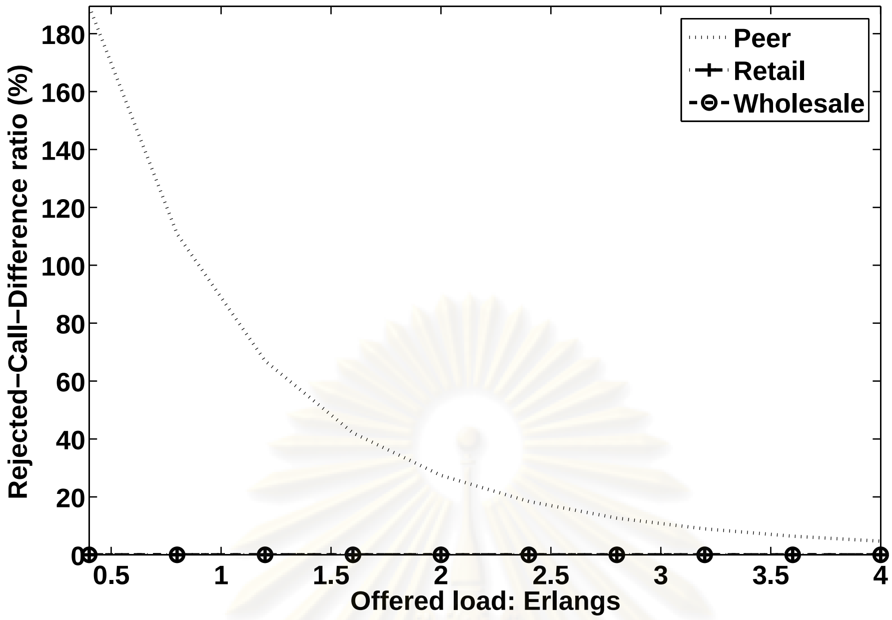


Figure 6.3: Results for inter-domain network with the same path quality (topology 1): the rejected-call-difference ratio for peer, wholesale and retail service models, where $D_i = 7$ for $i = 1, 2$, $u_i = \sum_{s \in S} g_i(a_s)\sigma_{i,s} - \beta_i w_i - \sum_{s \in S} f_i(s)\gamma_i(s)$, $\beta_i = 0.35$ unit per Mbps, $f_i(s) = 1000$ unit per call for $i = 1, 2$, $g_i(a_1) = g_i(a_2) = 0$ for peer service model, $g_i(a_1) = 1000, g_i(a_2) = 1500$ for retail service model, and $g_i(a_1) = 1000, g_i(a_2) = 1000$ for wholesale service model.

performance is resulted in the middle-light load (1.6 Erlangs) of the case of wholesale and in the middle-heavy load (3.2 Erlangs) of the case of retail service models.

When the penalty function has been applied for the inter-domain networks with different path qualities, the comparison of peer, wholesale and retial service models in terms of the rejected-call-difference ratio in Figure 6.7 shows the same trend as in Figure 6.3. However, the effectiveness of the path-provisioning policies compared with PC-Nash with penalty function as shown in Figures 6.8–6.10 is different from the case of the inter-domain networks with the same path quality. ME performs the best, whereas ED perform worse for peer, wholesale and retail service models.

6.1.4 Implication of Results

In this section, the problem of selfish path provisioning in the inter-domain network has been studied. Many works of literature have adopted the idea of penalty to control selfish behaviour in network systems. Similarly, the penalty term which punishes according to the number of rejected calls has been added in the utility function to prevent the selfish path provisioning. Under non-

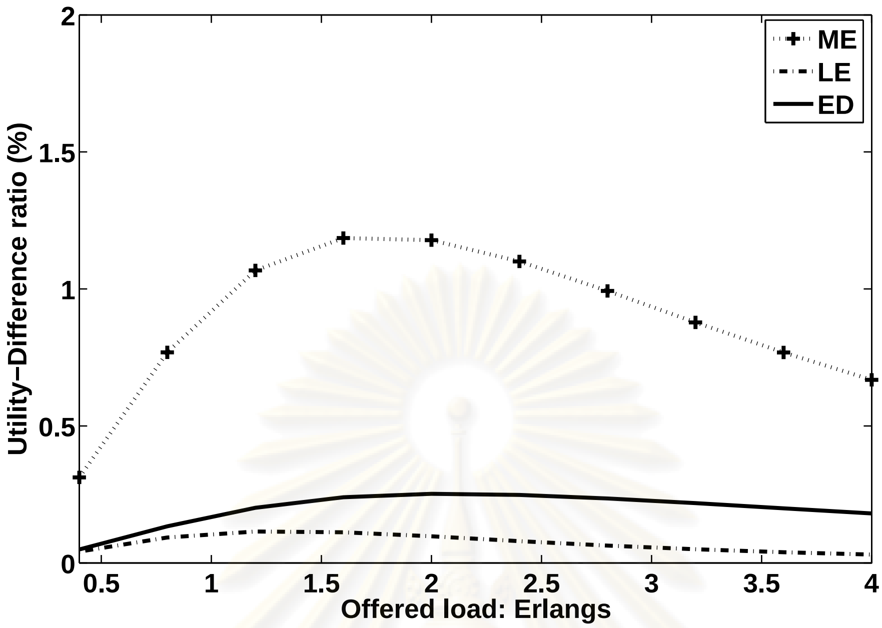


Figure 6.4: Results for inter-domain network with the same path quality (topology 1): The utility-difference ratio for peer service model based on the utility coefficient setting as in Figure 6.3.

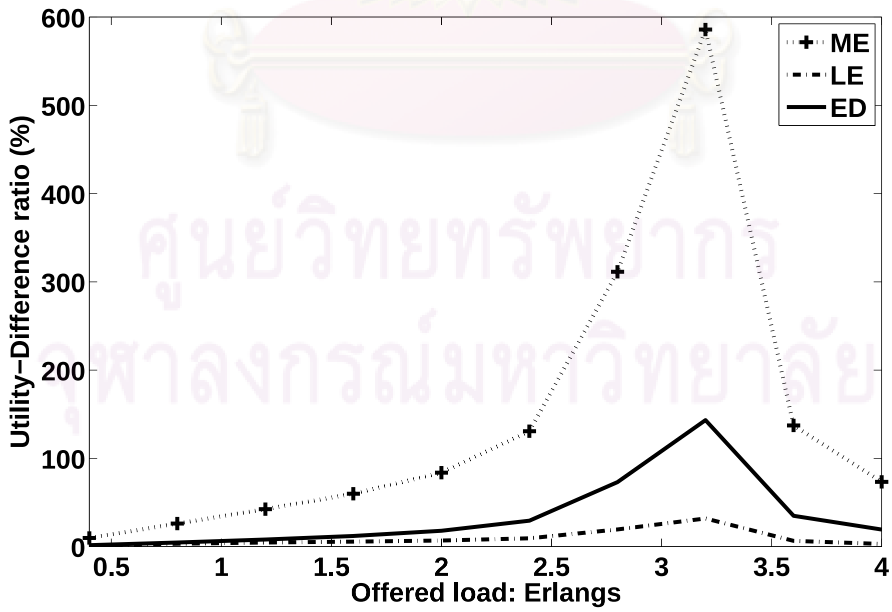


Figure 6.5: Results for inter-domain network with the same path quality (topology 1): The utility-difference ratio for wholesale model based on the utility coefficient setting as in Figure 6.3.

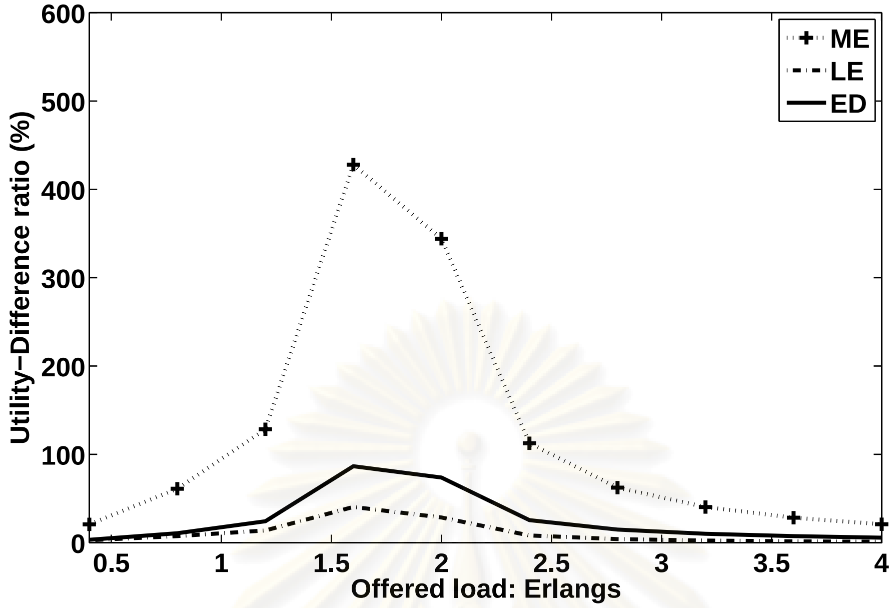


Figure 6.6: Results for inter-domain network with the same path quality (topology 1): The utility-difference ratio for retail service model based on the utility coefficient setting as in Figure 6.3.

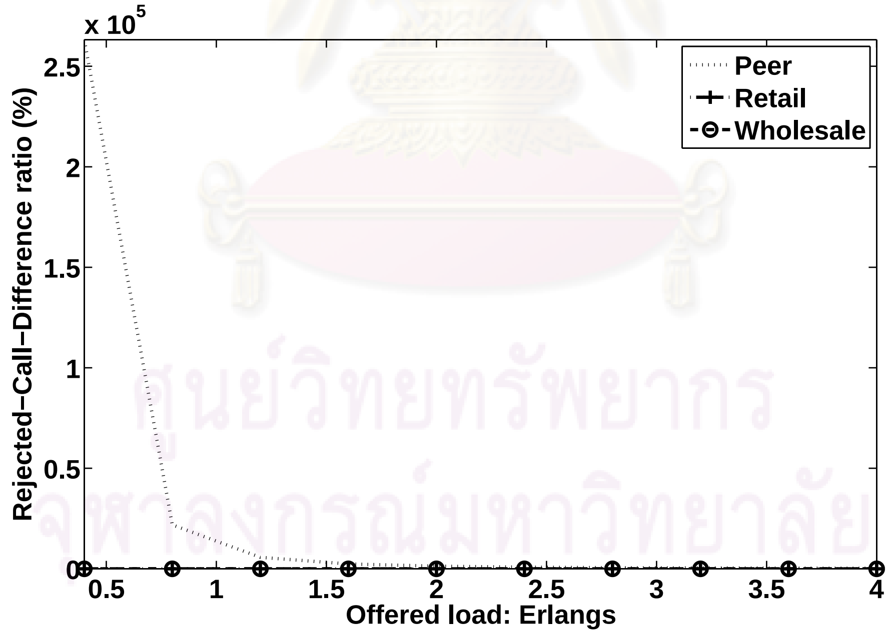


Figure 6.7: Results for inter-domain network with the different path qualities (topology 2): the rejected-call-difference ratio for peer, wholesale and retail service models, where $D_i = 3$ for $i = 1, 2$, $u_i = \sum_{s \in S} g_i(a_s)\sigma_{i,s} - \beta_i w_i - \sum_{s \in S} f_i(s)\gamma_i(s)$, $\beta_i = 0.35$ unit per Mbps, $f_i(s) = 1000$ unit per call for $i = 1, 2$, $g_i(a_1) = g_i(a_2) = 0$ for peer service model, $g_i(a_1) = 1000, g_i(a_2) = 1500$ for retail service model, and $g_i(a_1) = 1000, g_i(a_2) = 1000$ for wholesale service model.

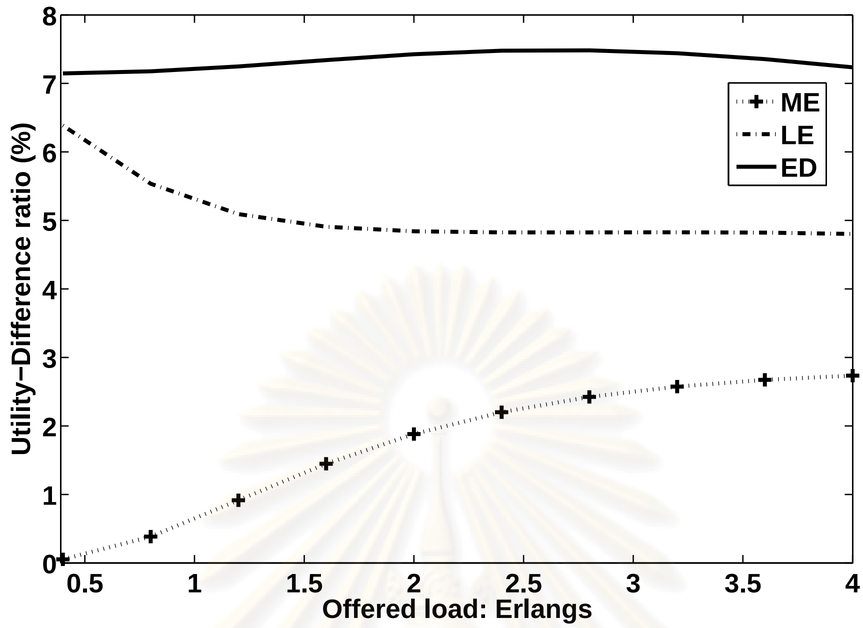


Figure 6.8: Results for inter-domain network with the different path qualities (topology 2): The utility-difference ratio for peer service model based on the utility coefficient setting as in Figure 6.7.

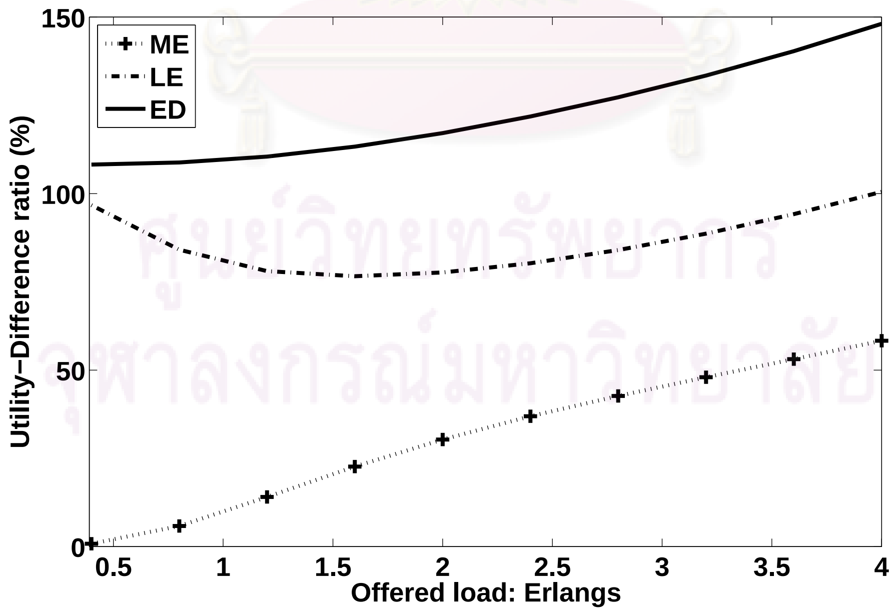


Figure 6.9: Results for inter-domain network with the different path qualities (topology 2): The utility-difference ratio for wholesale model based on the utility coefficient setting as in Figure 6.3.

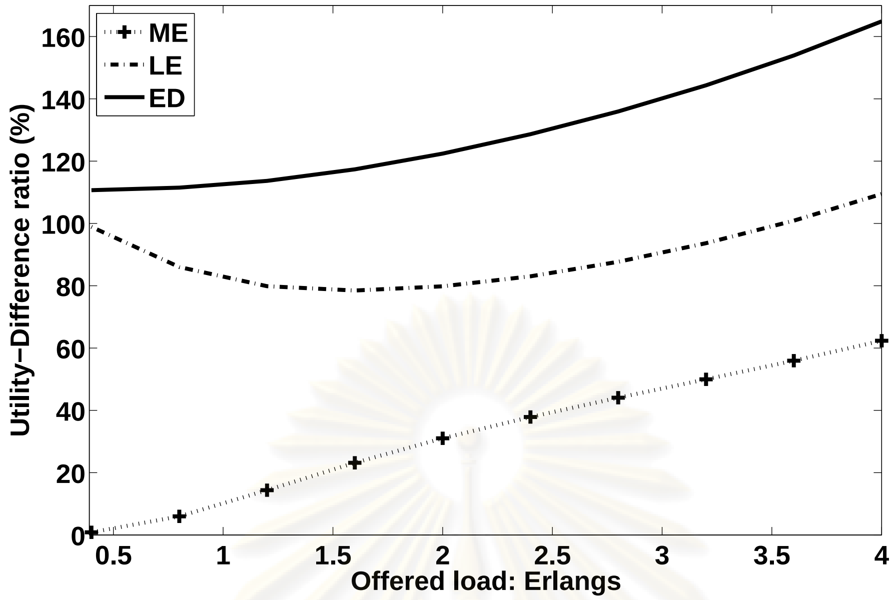


Figure 6.10: Results for inter-domain network with the different path qualities (topology 2): The utility-difference ratio for retail service model based on the utility coefficient setting as in Figure 6.3.

cooperative situation as the individual autonomous system, the concept of game theory for searching the equilibrium point has been adopted. With MSA, the new optimal operating point of the system can be achieved with respect to the new utility function. This operating point is called PC-Nash with the penalty function. The performance evaluation has been tested with two topologies: the inter-domain with the same path quality and the inter-domain networks with different path qualities. The selfishness is measured in terms of the rejected-call-difference ratio. Based on the results, adding the penalty term in the utility function can force ISPs to become unselfish, especially for peer service model. Based on the observation of policy effectiveness, LE performs the best in the case of inter-domain with the same path quality, while ME perform the best in the case of inter-domain with the different path qualities. On the other hand, ME performs worse in the case of inter-domain with the same path quality, whereas ED performs worse in the case of inter-domain with the different path qualities.

6.2 Load Balancing

Path-classification scheme that offers ISPs the freedom of choices in assigning the level of responsibility in QoS constraints. This scheme does not force the ISPs to assign the paths in the same level of QoS or disclose their network topologies and does not require TE signals to be forwarded across domains. It requires only that the ISPs classify paths on the basis of their availabilities regardless of the amount of capacity remaining on each path. The optimal PC based on the framework of non-cooperative game theory, PC-Nash, can improve resource efficiency over ME, LE, and ED because PC-Nash allows ISPs small choices of path selection. Efficiency resource usage of PC-Nash implies that balancing routing among paths in the same QoS level can improve resource efficiency. However, PC-Nash only balances the load in the sense of random path selection. There has been no explicit investigation of load balancing on the basis of remaining capacity of each path.

One way to improve resource efficiency and to guarantee end-to-end QoS in inter-domain networks is to use load-balancing routing policy. The load-balanced path-classification (LBPC) scheme presented here provides end-to-end QoS guarantees and dynamically balances the loads among the paths in the network. It is based on the least load routing concept, which is used by Lee and Tiento [75] and Wang et.al [76], for example, to solve the call congestion problem in a core network. The LBPC scheme extends the PC scheme of Suksomboon et al. [14] by not only classifying paths in accordance with their availabilities but also by taking into account the least busy path in the path classification process. Non-cooperative game theory is well suited for solving the call congestion problem because each domain is independently controlled. Therefore, the optimal group of classified paths under the LBPC scheme is depicted at the point of Nash equilibrium on the basis of the non-cooperative game theoretical framework. The effectiveness of the scheme is evaluated by comparing with conventional policies (ME, LE, ED [13], and PC-Nash [14]) in terms of call blocking probability and utility for practical business models. While previous work [14] use the framework of a two-person game, a non-cooperative game theoretical framework for three players is introduced here.

6.2.1 Proposed Load-Balanced Path-Classification Scheme

The responsibility in availability constraint is the key to controlling call rejection, and assigning paths on the basis of load balancing is the key to using network resources efficiently. ISPs may concern about achieving high network utilisation, which means utilising network resources efficiently and reducing the number of call rejections. The proposed ***Load-Balanced Path-Classification (LBPC)***

scheme helps ISPs balance the trade-off between responsibility in availability constraint and load balancing.

The proposed LBPC scheme is extended from the PC scheme to improve resource efficiency. The difference between PC and LBPC schemes is how paths are ranked. The LBPC scheme takes both availability and the remaining bandwidth of paths into account in the ranking process. This new ranking process is proposed to distribute different call types to the appropriate paths which have different qualities based on a network state. Doing so help balance the traffic in the network, so that high resource efficiency is achieved.

Let all paths in $\tilde{\mathcal{K}}_i(s, \mathbf{n})$ be ranked based on two values. The first value is path availability, $A(k_i)$. Let the second value be corresponding to the proportion of the remaining capacity which is given by

$$\left[\frac{C(k_i, \mathbf{n})}{\max\limits_{\tilde{k}_i \in \tilde{\mathcal{K}}_i(s,\mathbf{n})} C(\tilde{k}_i, \mathbf{n})} \right], \tag{6.6}$$

where $k_i \in \tilde{\mathcal{K}}_i(s, \mathbf{n})$. The idea behind using the proportion of remaining capacity is to give the maximum positive value to the least congested path based on the state of the network. Therefore, the least busy path has the highest value, while the busiest path has the lowest value. Note that this term is always positive because

$$\min_{\tilde{k} \in \tilde{\mathcal{K}}_i(s,\mathbf{n})} C(\tilde{k}_i, \mathbf{n}) = b_s, \tag{6.7}$$

and

$$\frac{b_s}{\max\limits_{\tilde{k} \in \tilde{\mathcal{K}}_i(s,\mathbf{n})} C(\tilde{k}_i, \mathbf{n})} \leq \left[\frac{C(k_i, \mathbf{n})}{\max\limits_{\tilde{k}_i \in \tilde{\mathcal{K}}_i(s,\mathbf{n})} C(\tilde{k}_i, \mathbf{n})} \right] \leq 1. \tag{6.8}$$

To avoid every call type sharing the same path with respect to an employed QoS-level, the proportion of remaining capacity is weighted by the difference between the highest availability request for every call type and the availability request of type-s call, $[\max_{\tilde{s} \in S} a_{\tilde{s}} - a_s]$. Hence, the path value based on the remaining capacity is given by

$$\left[\max_{\tilde{s} \in S} a_{\tilde{s}} - a_s \right] \times \left[\frac{C(k_i, \mathbf{n})}{\max\limits_{\tilde{k}_i \in \tilde{\mathcal{K}}_i(s,\mathbf{n})} C(\tilde{k}_i, \mathbf{n})} \right]. \tag{6.9}$$

For the highest and the lowest availability requests of calls, the bound value of this weighted term is given by

$$0 \leq \left[\max_{\tilde{s} \in S} a_{\tilde{s}} - a_s \right] < \max_{\tilde{s} \in S} a_{\tilde{s}}, \tag{6.10}$$

where $\min_{\tilde{s}\in S} a_{\tilde{s}} > 0$. Therefore, from (6.8) and (6.10), the bound value of (6.9) is given by

$$0 \leq \left[\max_{\tilde{s}\in S} a_{\tilde{s}} - a_s\right] \times \left[\frac{C(k_i, \mathbf{n})}{\max\limits_{\tilde{k}_i\in\tilde{\mathcal{K}}_i(s,\mathbf{n})} C(\tilde{k}_i, \mathbf{n})}\right] < \max_{\tilde{s}\in S} a_{\tilde{s}}. \tag{6.11}$$

This weighted term $[\max_{\tilde{s}\in S} a_{\tilde{s}} - a_s]$ is multiplied to the proportion of the remaining capacity term because of to allow the highest availability request to access all paths in $\tilde{\mathcal{K}}_i(s, \mathbf{n})$, regardless of their remaining capacity. Therefore, ranking paths for a call requesting the highest availability depends on only availability value of each path. In contrast, a lower availability request is allowed to access the paths by taking into account the path availability and the remaining capacity of these paths. Consequently, all paths in $\tilde{\mathcal{K}}_i(s, \mathbf{n})$ are ranked differently based on the network state and the availability request of a call.

To combine the two QoS parameters, i.e., availability and the remaining bandwidth of paths, into a unique value, the availability of path and the proportion of remaining path capacity are linearly weighted. Let $\tau(k_i, s, \mathbf{n})$ denote a unique value of path k_i when a call types s arrives in domain i being at network state **n**, which is given by

$$\tau(k_i, s, \mathbf{n}) = \nu_\delta \tau_\delta(k_i) + \nu_\zeta \tau_\zeta(k_i, s, \mathbf{n}), \tag{6.12}$$

where

$$\tau_\delta(k_i) = \log(A(k_i)), \tag{6.13}$$

$$\tau_\zeta(k_i, s, \mathbf{n}) = \left[\max_{\tilde{s}\in S} a_{\tilde{s}} - a_s\right] \times \left[\frac{C(k_i, \mathbf{n})}{\max\limits_{\tilde{k}_i\in\tilde{\mathcal{K}}_i(s,\mathbf{n})} C(\tilde{k}_i, \mathbf{n})}\right], \tag{6.14}$$

and ν_δ and ν_ζ are the coefficient parameters of $\tau_\delta(k_i)$ and $\tau_\zeta(k_i, s, \mathbf{n})$, respectively. Note that $\tau_\delta(k_i)$ dominates $\tau_\zeta(k_i, s, \mathbf{n})$ if $a_s = \max_{\tilde{s}\in S} a_{\tilde{s}}$ or $C(k_i, \mathbf{n})$ for all $k_i \in \tilde{\mathcal{K}}_i$ is equal to $\max_{\tilde{k}_i\in\tilde{\mathcal{K}}_i} C(\tilde{k}_i, \mathbf{n})$. That is, the least load routing is not affected the ranking process when either an incoming call requests for the highest availability or the traffic load is balanced in the network. By (6.12), every call type can share the same path if every path in a network achieves a balance, while the different call types must be distributed to the different paths whenever every path is under an imbalance in the remaining capacity.

The proposed LBPC scheme comprises four steps.

Step 1: Ranking: Given domain i, the paths satisfing both constraints (bandwidth $b^t_{i,s}$ and availability $a^t_{i,s}$) are ranked with (6.12). The paths in $\tilde{\mathcal{K}}_i(s, \mathbf{n})$ are ranked on a linear scale based on their value $\tau(k_i, s, \mathbf{n})$ from minimum to maximum.

Step 2: Categorisation: The paths are classified with equal interval into small groups.

Step 3: Group selection: Each domain independently selects a group of paths, which represents the level of QoS apportionment.

Step 4: Path selection: The paths in a selected group are randomly chosen.

Note that ranking on a linear scale in Step 1 can be applied to many QoS parameters, e.g., jitter and delay by adding in the term τ_δ.

Let d_i be the index of QoS-level of paths of domain i and D_i be the number of levels for domain i. Note that, with the LBPC scheme, whichever category is selected, the allocated paths always satisfy both the bandwidth and availability requests. For the sake of simplicity, the selection of QoS-level d_i in the LBPC scheme is called ”LBPC-level d_i” hereafter.

The LBPC scheme has two significant differences from the ME, LE, and ED policies proposed by Pongpaibool and Kim [13]. First, the LBPC scheme classifies the paths into small groups by ranking them on the basis of their quantified values, which takes into account availability and remaining path capacity. This enables the network to achieve tunable resource usage efficiency. Second, the LBPC scheme randomly chooses the paths in a selected group, which means that all paths are treated fairly under the equity principle at the same quality level.

The LBPC scheme can be independently implemented in any domain. With this scheme, despite the many choices in path provisioning, ISPs can select their preferred LBPC-level of paths from D_i options for call admission control. The LBPC scheme can therefore be considered as a general representation of the PC scheme of Suksomboon et al. [14] with ν_ζ set to 0. In practice, ISPs adjust their selections to achieve their own objectives, such as maximum chance of call success or lowest bandwidth consumption. Therefore, ISPs can independently select solutions that enhance their network performance as well as minimise their network resources.

6.2.2 Experimental Setting

The performance of the proposed LBPC scheme is evaluated by applying it to three concatenated network domains (see Figure 6.11) and comparing the results against four benchmark policies, namely, ME, LE, ED, and PC-Nash. The scheme has been implemented in MATLAB®, and the simulation results have been obtained with 95% confidence intervals from ten independent runs per point. The time for each simulation run is 720 time units. Independent Poisson call arrivals and exponentially distributed call-holding times are assumed for every call type. The topology profile is presented in Table 6.4.

Multiple call types are considered; the calls originated from node v_1 and terminated at node v_8, which is denoted as an OD-pair (v_1, v_8). The characteristics of each call type are listed in Table 6.5. To clarify the effect of loading, we varied the total offered load. The weighting coefficients (τ_δ and τ_ζ) in LBPC scheme are set to 1 because the effect of weighting coefficients is omitted. The PC-Nash and LBPC-Nash equilibria are obtained by setting $D_1 = D_3 = 5$ and $D_2 = 2$ for the PC and LBPC schemes. Consequently, there are 50 $(5 \times 2 \times 5 = 50)$ combinations of test cases for the two schemes. The number of path categories depends on the distribution of path availability. This number should provide results covering all possible performance levels. The evaluations are based on three business models: peer, retail and wholesale services.

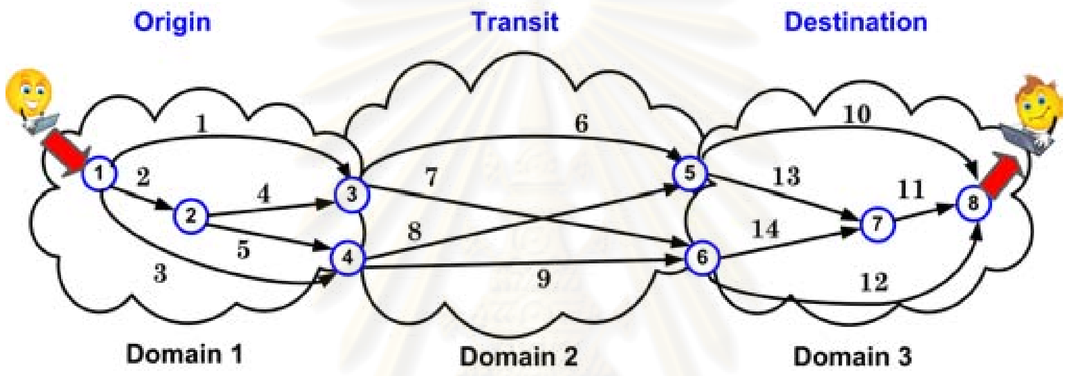


Figure 6.11: Network topology: concatenation of three identical network topologies with 14 links. Note: the numbers on the links represent the link labels.

Table 6.4 Network topology profile

Link (l)	$1, 2, 10, 11$	$3, 12$	$4, 13$	$5, 14$
$A(l)$	0.9999	0.9995	0.9997	0.9998
c_l (Gbps)	2	2	2	2
Link (l)	6	7	8	9
$A(l)$	0.9999	0.9998	0.9997	0.9995
c_l (Gbps)	2	2	2	2

6.2.3 Results

Figure 6.12 shows the call blocking probabilities against the offered load for the ME, LE, and ED policies for the peer, retail, and wholesale service models. The call blocking probability (1.0)

Table 6.5 Call type characteristics

Call type (s)	a_s	b_s	Load proportion
1	0.9990	500 Mbps	40%
2	0.9990	300 Mbps	40%
3	0.9993	500 Mbps	10%
4	0.9993	300 Mbps	10%

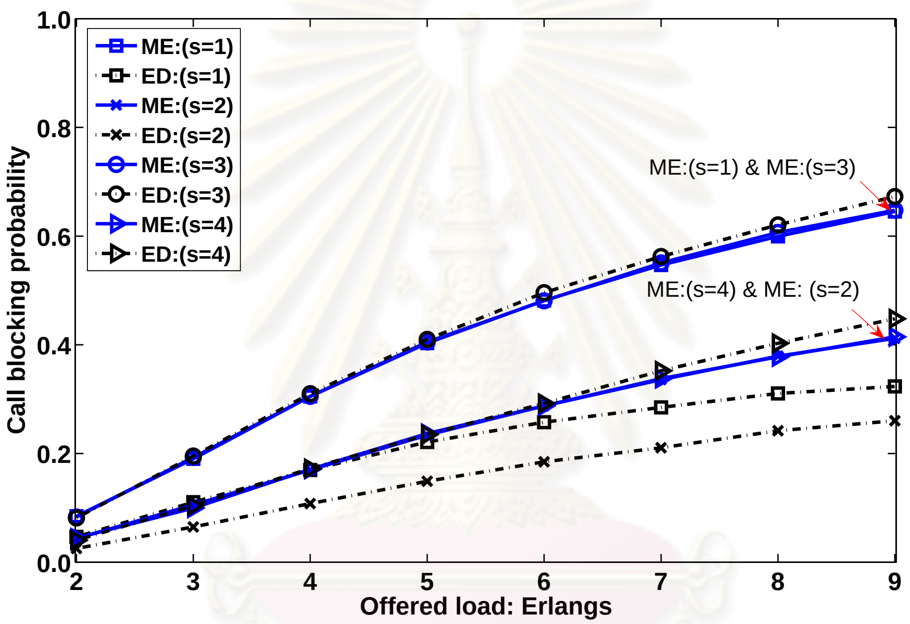


Figure 6.12: Call blocking probabilities of OD-pair (v_1, v_2) with ME and ED policies for peer, retail, and wholesale service models (call blocking probability of LE is equal to 1 for all call types.)

is the highest for the LE policy. This is because the LE policy lets all domains select the lowest availability paths for each request. For example, for $a_1 = 0.9990$, domain 1 assigns path $k_1 = l_3$ and domain 2 assigns path $k_2 = l_9$, for which the availabilities are 0.9995. Then, domain 3 cannot find a path that satisfies all availability request types (e.g., for call type $s = 1$, $a^t_{3,1} = 0.9990/(0.9995 * 0.9995) = 1$). The probability is the lowest for the ED policy. This is because, with the ED policy, the lower bound of responsibility in availability is greater than that with the LE for all domains with respect to equally responsibility in availability (e.g., for $a_1 = 0.9990, a^t_{1,1} = \sqrt[3]{0.9990} \approx 0.9997$, and for $a_2 = 0.9993, a^t_{1,2} = \sqrt[3]{0.9993} \approx 0.9998$). Thus, every domain can find at least one path satisfying this availability request. With the ME policy, the highest availability path is always assigned to the

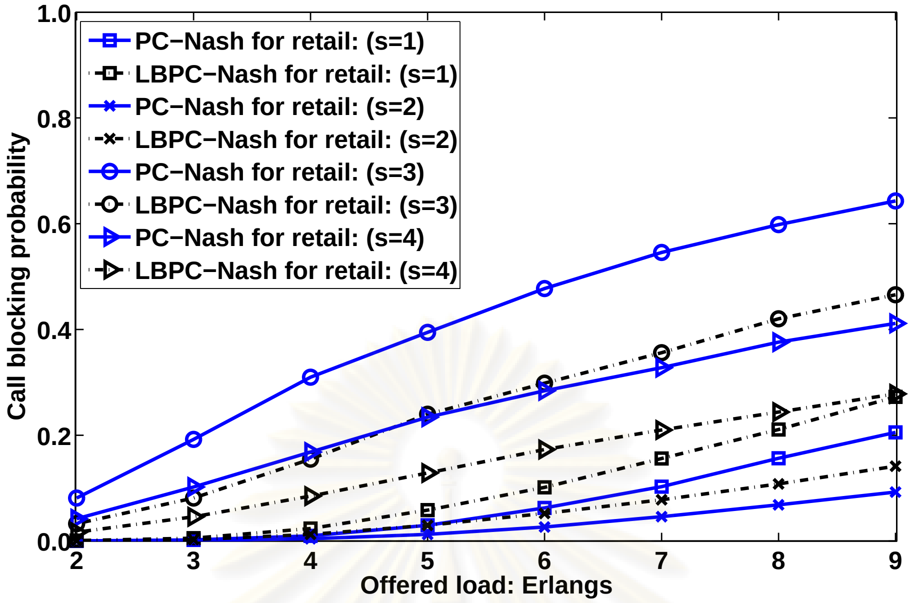


Figure 6.13: Call blocking probabilities of OD-pair (v_1, v_2) with PC-Nash and LBPC-Nash policies for retail service and wholesale service models (call blocking probabilities with PC-Nash and LBPC-Nash for retail service model were similar to those for wholesale service model.)

request. The call blocking probability with ED is less than that with ME for call types 1 and 2 while the probabilities with ED and ME are comparable for call types 3 and 4.

Figure 6.13 shows the call blocking probabilities for the PC-Nash and LBPC-Nash policies for the retail and wholesale service models. Those for LBPC-Nash are significantly lower than for PC-Nash for call types 3 and 4, while they are slightly higher for types 1 and 2. These results indicate that performance can be improved by taking load balancing into account. In addition, both PC-Nash and LBPC-Nash outperform ME, LE, and ED polices in terms of call blocking probability.

LBPC-Nash yields the highest utilities because of its inherent optimal QoS level setting and optimally balanced load. For a peer service model, let the effectiveness of ME, LE, ED and PC-Nash be quantified in terms of the utility-difference from the utility of LBPC-Nash

$$\text{utility of LBPC-Nash} - \text{utility of policy} \tag{6.15}$$

because the utilities of LBPC-Nash is the highest with zero value, while others are less than zero. Figure 6.14 indicates the difference in utility between the conventional policies and LBPC-Nash. For retail and wholesale service models, the effectiveness of ME, LE, ED and PC-Nash are quantified in terms of the utility-difference ratio

$$\frac{\text{utility of LBPC-Nash} - \text{utility of policy}}{|\text{utility of LBPC-Nash}|} \times 100\%. \tag{6.16}$$

Figures 6.15 and 6.16 show the utility-difference ratio against the offered load for ME, LE, ED and PC-Nash policies for the retail and wholesale service models, respectively. LBPC-Nash consistently has the highest utility while ED has the lowest utility for the peer service model and LE has the lowest utility for the retail and wholesale service models. As aforementioned reason, ED provides lower call blocking probability for every call type than ME and LE. Therefore, based on the peer service model, ED provide the lowest utility. With LBPC-Nash policy, the traffic is dynamically balanced based on the current network state and well matches the utility functions. Consequently, LBPC scheme can improve system performance from PC-Nash and also provide guaranteed end-to-end QoS in an inter-domain network.

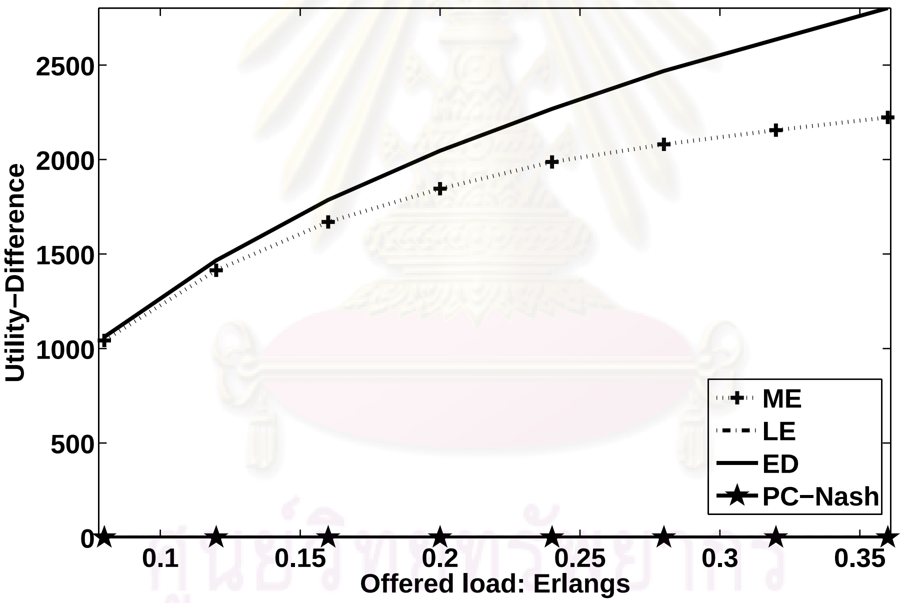


Figure 6.14: Results for inter-domain network of three-cascading domains: The utility-difference from the utility of LBPC-Nash for peer service model of domain 1 ($u_1 = u_2 = u_3$): $D_1 = D_3 = 5, D_2 = 2$, and $u_i = -\beta_i w_i$, where $\beta_i = 0.35$ units per Mbps for $i = 1, 2, 3$.

6.2.4 Implication of the Results

This section considers the problem of how to utilise resource efficiency under the condition of guaranteeing end-to-end QoS in inter-domain network. Provisioning path based on load balancing on the basis of QoS guarantees is a solution. The proposed load-balanced path-classification

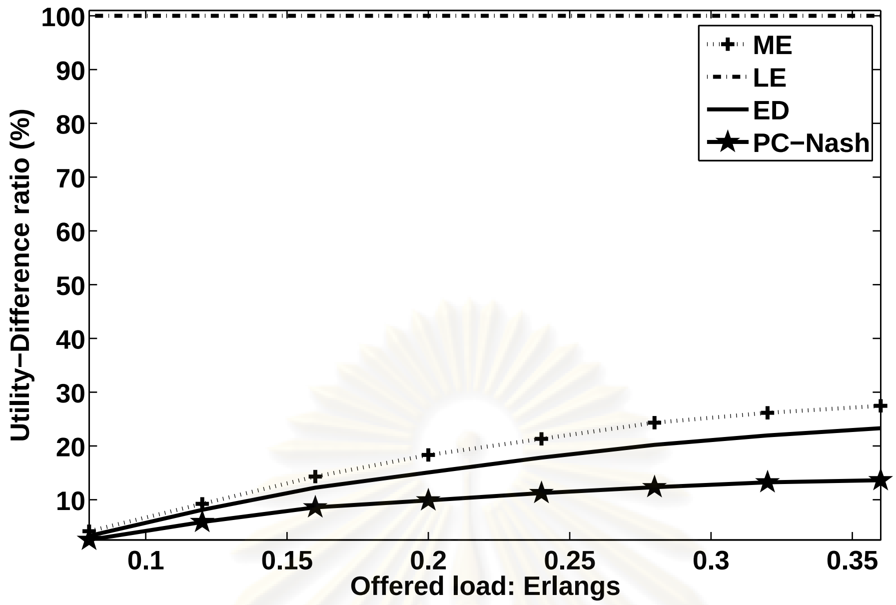


Figure 6.15: Results for inter-domain network of three-cascading domains: The utility-difference ratio for retail service model of domain 1 $(u_1 = u_2 = u_3)$: $D_1 = D_3 = 5, D_2 = 2$, and $u_i = \sum_{s=1}^{S} g_i(a_s)\sigma_{i,s} - \beta_i w_i$, where $\beta_i = 0.35$ units per Mbps, $g_i(a_1) = g_i(a_2) = 1000$ units per connection, and $g_i(a_3) = g_i(a_4) = 1500$ units per connection for $i = 1, 2, 3$.

(LBPC) scheme helps balance the trade-off between responsibility in availability constraint and load balancing. Given that ISPs prefer to retain domain control and that they have an inherent conflict of interests, non-cooperative game theory is used to identify the optimal operating point of the LBPC scheme. Experimental evaluation by simulation using three concatenated network domains showed that the optimal LBPC, LBPC with Nash equilibrium, provides the best performance in terms of call blocking probability and utility compared with the most-effort, least-effort, equal-distribution, and PC-Nash policies. Consequently, optimal load balancing along with optimal responsibility in availability constraint can improve system performance based on end-to-end QoS guarantees.

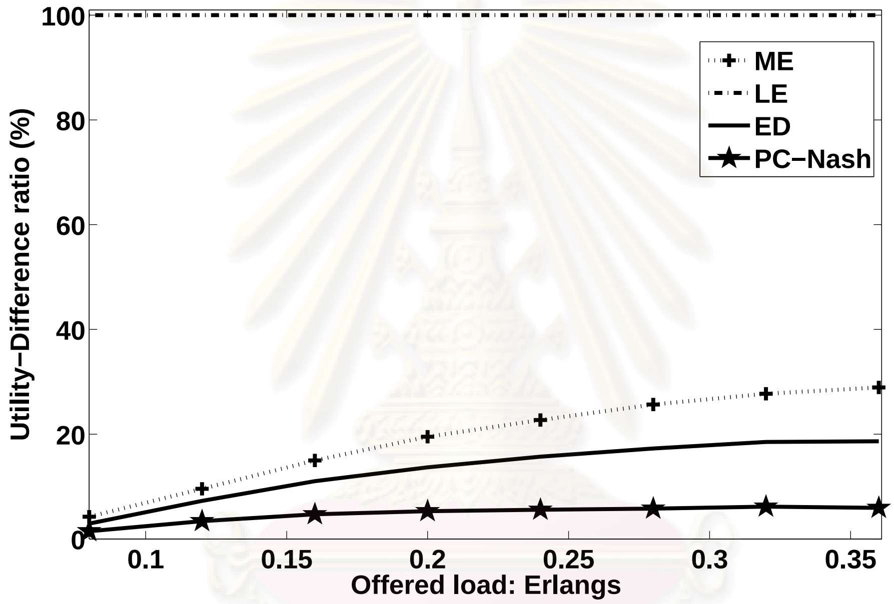


Figure 6.16: Results for inter-domain network of three-cascading domains: The utility-difference ratio for wholesale service model of domain 1 ($u_1 = u_2 = u_3$): $D_1 = D_3 = 5$, $D_2 = 2$, and $u_i = \sum_{s=1}^{S} g_i(a_s)\sigma_{i,s} - \beta_i w_i$, where $\beta_i = 0.35$ units per Mbps, and $g_i(a_s) = 1000$ units per connection for all $s \in S$ for $i = 1, 2, 3$.

CHAPTER VII

CONCLUSION AND FUTURE WORK

This section provides the conclusions of this dissertation in which the contributions are sequentially described. The conclusions have been drawn as a summary of what the dissertation has proposed and the important findings based on the reported results. To complete the dissertation, some unresolved research challenges in the research area of inter-domain QoS routing have been addressed for the future work.

7.1 Conclusion

This dissertation has proposed a new framework to solve the end-to-end QoS path provisioning problem in inter-domain networks. A framework has been proposed to improve the manageability of QoS apportionment and to find the optimal operating point in non-cooperative domain environments. The optimal operating point referring to optimal QoS level apportionment is obtained by using the proposed QoS provisioning framework with PC-Nash. Based on the utility functions reflecting the practical business models, the game value has been found to capture the resultant level of competition amongst the considered domains. In addition, an accurate loss network model based on the CTMC has been derived for evaluating the QoS-level selection in PC-Nash. This network model has also been extended to evaluate the conventional policies, i.e., ME, LE and ED, being used as the comparison basis.

The accuracy of the mathematical models has been confirmed by comparison with the discrete-event simulations. From the reported numerical results comparing ME, LE and ED with PC-Nash, it has been found that, for the two domains with the same path quality, the highest QoS-level apportionment is suitable for the peer service model, while the lowest QoS-level apportionment performs well for the retail and wholesale service models. In addition, mixed policies between the high QoS-level apportionment for a domain of high quality paths (an upstream domain) and low QoS-level apportionment for a domain of the low quality paths (a downstream domain) are suitable for domains containing different path qualities.

PC-Nash as an effective QoS routing policy using in inter-domain networks has been rigorously investigated in the cases that two domains connect to each other without a bottleneck through an interconnection link. Further investigation has been focused on the effect of the interconnection bottleneck in the inter-domain network. The performance of this kind of network can be analysed by the well-known product-form solution. The analysis is based on the concatenation of multiple domains in order to perform a generalised analysis. This analysis is confirmed by the experimental examples of cases of two- and three-domains. The reported results depict that ME always performs better than or equally well to LE and ED. The examples have shown that in some settings the results of LE and ED are equal to that of ME. Underlining the analysis, ED may provide lower performance than LE in some topological characteristics of a network consisting of more than two domains. The reported results confirm the analysis that the performance of ED is less than that of LE and ME when some domains in the middle of an end-to-end route have poor path qualities. Due to the inherit optimization by PC-Nash, the performance of this policy is the same as that of ME. Using the highest QoS-level apportionment is thus recommended in inter-domain networks with the interconnection bottleneck link.

This dissertation has also explored beyond a single homed network. In a multihomed network environment, each domain may face more difficulties in efficiently selecting gateway routers than in selecting the best path to support a call request. The problem becomes how to select the right set of paths corresponding to the requests that provides the network efficiency. The reported results based on the topological setting in this experiment show that using ED and ME can drive the system close to the optimal operating point. On the other hand, LE pushes the burden to the later domains suffering from the availability target. Therefore, LE is not recommended for implementation to this kind of network environment. PC-Nash, however, operates based on the optimal set of path selections for the overall requests. In doing so, PC-Nash always achieves the highest performance for a multiomed network environment.

To extend PC-Nash to prevent selfish path provisioning in an inter-domain network, the idea of a penalty has been adopted in the utility function. Under a non-cooperative situation for an individual domain the game theory concept for searching for the equilibrium point has been adopted. With MSA, the new optimal operating point of the system can be achieved with respect to the new utility function. This operating point is called PC-Nash with the penalty function. The performance evaluation has been conducted on two topologies: an inter-domain with the same path quality and the inter-domain networks with different path qualities. The selfishness has been measured in terms of the rejected-call-difference ratio. Based on the results, adding the penalty term in the utility function can force the ISPs to become unselfish, especially for the peer service model. Based on the observation of the policy effectiveness, LE performs the best in the case of an inter-domain with the same path quality, while ME performs the best in the case of an inter-domain with the different path qualities.

A provisioning path based on load balancing has been seen as a solution to improve the resource utilisation and concurrently guarantee an end-to-end QoS in inter-domain networks. The proposed load-balanced path-classification (LBPC) scheme helps balance the trade-off between the responsibility in the availability constraint, which is important for establishing an end-to-end QoS call, and the load balancing, which is important for achieving an efficient network resource management. Given that ISPs prefer to retain domain control and that they have an inherent conflict of interests, non-cooperative game theory is used to identify the optimal operating point of the LBPC scheme. Experimental evaluation using three concatenated network domains showed that the optimal LBPC, which is an LBPC with Nash equilibrium, provides the best performance in terms of the call blocking probability and utility compared with the most-effort, least-effort, equal-distribution, and PC-Nash policies. Consequently, an optimal load balancing along with an optimal responsibility in the availability constraint can improve the system performance.

7.2 Future Work

The challenge of end-to-end QoS path provisioning in inter-domain networks not only lines in the responsibility of every ISP in order to accomplish their customers' requests; the inherent complexity in the Internet's today requires the optimal QoS path-provisioning to effectively operate from dynamic aspects. To undertake the necessary improvements for supporting the sustainable requirements of users on the Future Internet, this section introduces some opening questions and directions that are worth taking into consideration to make the PC-Nash concept work in future practices.

The tuneable parameters such as the maximum number of QoS-levels for the path-classification scheme and the co-efficient parameters of the utility function have been pre-assigned in the dissertation in order to narrow the investigation to the major purpose of this dissertation. Although some guideline has been provided in this dissertation, the different settings of these parameters can affect the optimal QoS-level apportionment. One of the possible directions of how to select the maximum number of QoS-levels for the path-classification scheme might depend upon the distribution of the path qualities in each domain. This reflects the new paradigm of future exploration.

Sometimes a path provisioning process of an ISP under unknown the other ISPs' capabilities may cause the system to worsen. To improve the network performance, crankback signalling [77] with a path-classification scheme can be suggested to renegotiate of the QoS apportionment. Doing so leads the research area of the negotiation problem.

In a multihomed network environment, PC-Nash is a successful solution to selecting the right set of paths connecting an exterior gateway. Trading traffic between neighbouring domains on a practical Internet not only depends on the end-to-end QoS apportionment, but also depends on their charging prices. Additionally, what makes a proper solution for setting an optimal cost function for the interconnection links is crucial in an inter-domain network problem. A possible thread for load balancing and optimal pricing opens a challenge research problem. A useful guideline is a combination of an optimal pricing scheme in a cooperative manner for inter-domain routing [78] and LBPC-Nash, so that it helps balance the traffic and increase the revenue in the multihomed networks.

Last but not least, incorporating to a few statistical traffic patterns and the pricing negotiation in the inter-domain networks for seeking for an optimal routing policy for QoS path provisioning opens interesting research areas and welcomes novel contributions and improvements in the routing technique for the future.

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Appendix

Appendix

List of Publications

Suksomboon, K., Pongpaibool, P., and Aswakul, C., "An Equilibrium Policy for Providing End-to-End Service Level Agreements in Interdomain Network," in Proceedings of IEEE Wireless Communications and Networking Conference, 2008. (WCNC 2008), Las Vegas, NV, IEEE, 31 March 2008-3 April 2008 2008. Content taken from Chapter III.

Suksomboon, K., Pongpaibool, P., Ji, Y., and Aswakul, C., "PC-Nash: QoS Provisioning Framework with Path-Classification Scheme under Nash Equilibrium," The Computer Journal, (First published online: December 7, 2010), doi: 10.1093/comjnl/bxq084. Content taken from Chapter III and Chapter IV.

Suksomboon, K., Pongpaibool, P., and Aswakul, C., "Game-Theoretic Approach to Prevent Selfish Path Provisioning in Interdomain Networks," in Proceedings of 5th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology, 2008. (ECTI-CON 2008), Krabi, Thailand, 14–17 May 2008 2008. Content taken from Chapter VI.

Suksomboon, K., Ji, Y., Pongpaibool, P., and Aswakul, C., "Load-Balanced Path Provisioning for Guaranteeing End-to-End QoS in Inter-Domain Networks," in Proceedings of 10th International Symposium on Communications and Information Technologies (ISCIT 2010), Tokyo, Japan, 26-29 Oct. 2010. Content taken from Chapter VI.

Biography

Kalika Suksomboon was born in 1980 in Phuket, Thailand. She received her B.Eng. degree with 2nd class honors in Telecommunication Engineering from King Mongkut's Institute of Technology Ladkrabang, Thailand in 2001 and received her M.Eng. in Electrical Engineering from Chulalongkorn University, Thailand in 2004. She has been pursuing the Doctoral degree in Electrical Engineering at Chulalongkorn University, Bangkok, Thailand, since 2006. In 2009, she has joined Yusheng Ji laboratory as an internship student at the National Institute of Informatics (NII), Tokyo. Her recent research interests include routing in inter-domain networks and application of game theory.