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CONTROL ARCHITECTURE OF SURVIVABLE MULTI-DOMAIN OPTICAL NETWORKS

By

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fulfillment of the requirements for the degree of

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ABSTRACT

Optical networks have been widely adopted as the transport network in research industry for years. To better utilize the high speed benefit of optical transport networks, control architecture have become the focus of research in recent years.

In this thesis, I have developed a control plane architecture integrated with a set of algorithms, schemes and protocols. Based on the two-level inter-domain and intra-domain hierarchical control architecture, I proposed an inter-domain routing algorithm, ring-based topology aggregation scheme and modified RSVP-TE signalling protocol. This thesis aims to provide an efficient control plane architecture in terms of inter-domain routing, intra-domain routing, topology aggregation and signalling.

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Last, but not least, it has been my pleasure to study with my friends. I acknowledge their contributions to my studies.

ACRONYMS

AS	Autonomous System
BGP	Border Gateway Protocol
CC	Connect/Confirmation
CR-LDP	Constraint-based Routing Label Distribution Protocol
ENAW	Effective Number of Available Wavelengths
EPSP	Extend-Path-Shared Protection
IDRA	Inter-Domain Routing Agency
IDC	Inter-Domain Communications
IGP	Interior Gateway Protocol
IP	Internet Protocol
ISP	Internet Service Provider
LSSP	Local Segment-Shared Protection
MPLS	Multi-Protocol Label Switching
NGN	Next Generation Network
NH	Next Hop
NRI	Network Reachability Information
NSF	National Science Foundation
OBGP	Optical Border Gateway Protocol
OBGP+	Optical Border Gateway Protocol+

OSPF	Open Shortest Path First
OXC	Optical Switches
P-Cycle	Pre-Configured Protection Cycle
PCE	Path Computation Element
PIN	Photonic Inter-domain Negotiator
POBS	Polymorphous Optical Burst Switching
PSI	Path State Information
RIT	Reservation/scheduling with Just-in-Time Switching
RSVP-TE	Resource Reservation Protocol-Traffic Engineering
TA	Topology Aggregation
TAG	Tell-And-Go
TE	Traffic Engineering
WAV	Wavelength Availability Vector

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LIST OF NOTATIONS

$L_{i,j}$	Transmission delay between domain i and domain j
P_i	Processing delay in domain i
R_i	Reservation delay in domain i
$D_{i,j}$	Total signalling delay between domain i and domain j

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Chapter 1 INTRODUCTION

1.1: Background

With the development of Next Generation Network (NGN), network customers require faster establishment of connection and robust services. To meet these demands the control plane concept has been adopted by researchers on networks as a solution to Next Generation Network requirements. The term 'control plane' in [SOLE03] refers to a network that operates above the transport optical network (which is now known as data plane) and performs the function of calculating optimal paths, as well as establishing and tearing down connections. The emergence of control plane architecture has allowed researchers to make modifications to existing network assumptions and to develop a set of routing and signalling protocols, as well as topology aggregation schemes.

Multi-domain network assumption was adopted shortly after the control plane idea was first proposed. Early during research surrounding control planes, most researchers focused on routing and survivability issues in optical networks, which assumes that the entire global network has a single domain. As the process developed, some of these researchers noticed that the single domain assumption was not a sufficient model for a real optical network and, as a result, they relaxed the single domain assumption and transferred to an old modelling assumption in Internet Protocol (IP) networks, which assumes that the network consists of several domains and that each domain has only limited information about neighbour domains. This assumption has been widely accepted by the research community and is known as the 'multi-domain assumption'.

From the 1990s to 2000s, using the multi-domain assumption, routing protocols regarding inter-domain issues have been studied with great interest. Extensive research has been

done with the goal of transferring Border Gateway Protocol (BGP), as discussed in [QUOI03] [FONT08] [CAES05] [MANO10] [BUTL10], to optical network, as BGP has been in use for 15 years and is proved to be stable and scalable. Optical Border Gateway Protocol (OBGP) was proposed as the extension of BGP in optical networks; later, OBGP+ was introduced by [TRUO09] in order to replace OBGP. However, both OBGP and OBGP+ are based on BGP, and so they both suffer from the same problems as BGP: they do not carry link attributes nor do they allow for multi-path calculation. Considering the disadvantages of transferring BGP to optical networks, researchers grappled with another inter-domain routing strategy: inter-domain link state routing protocol. Compared with the BGP series, this protocol is able to carry link attributes and is less complicated; however, it is not scalable. This limits the deployment of inter-domain link state routing protocol since existing optical networks tends to be extendable and flexible.

Besides inter-domain routing, one of the other key elements in designing a control plane of multi-domain survivable optical network is intra-domain routing. Link state routing algorithms have been studied for years and are considered to be the most suitable algorithm for completing intra-domain routing tasks. In [LIU06a], the authors proposed a two-level inter-domain and intra-domain hierarchical routing scheme. In this two-level hierarchical routing scheme, a link state algorithm is implemented as the intra-domain routing algorithm and intra-domain routing is executed separately with inter-domain routing. Only when both of these two routing levels have occurred can the signalling part signal the calculated path.

Another factor to consider in designing a control plane of multi-domain survivable optical network is the topology aggregation scheme. With the utilization of a two-level hierarchical routing scheme the topology aggregation scheme plays a significant role in reducing the complexity of routing strategy. In [FANG00], the authors introduced three existing topology aggregation schemes, single-node topology aggregation, star topology aggregation, and fully-mesh topology aggregation. Of these three schemes, fully-mesh topology aggregation is widely used because of its superior connectivity advantage. However, a potential

problem in using the fully-mesh topology aggregation scheme is the complex manner in which it maintains the state of a single domain. When the number of border nodes in a domain is large, this complexity can be very high, making the use of this scheme undesirable.

Signalling issues are not considered as important as routing issues in the design of a control plane. However, the deployment of NGN requires the design of a signalling protocol. Generally, two signalling protocols are commonly used: RSVP-TE and CR-LDP. RSVP-TE protocol reserves resources after all on-path domains have been notified; in essence, RSVP-TE reserves resources in a regressive fashion. In contrast to RSVP-TE, CR-LDP reserves resources when the signalling message reaches each domain; CR-LDP is also known as forward reservation signalling protocol.

Survivability considerations are also an essential part in designing a control plane algorithm. Two ways of realizing survivability are protection and restoration. For protection, a backup path is created before network failures are detected, while in restoration, a backup path is created after failures are recognized. However, in both of these schemes, resources are reserved after a backup path is established. In [CHAM09], the authors proposed pre-configuring and pre-allocating resources for inter-domain traffic. This simple idea is realistic and can greatly improve the recovery time of a failed connection.

1.2: Motivation and Objectives

BGP series are widely used as the inter-domain routing algorithm in control architecture of optical transport networks. Although BGP has some disadvantages compared with link state protocol (such as inability of carrying link information and a failure to recognize high complexity), BGP is considered to be scalable. OBGp+ is a variation of the BGP series and it overcomes the load balancing problem of OBGp. However, the components of a BGP series have one common drawback - the possibility of many hops on a calculated path. This occurs because BGP is a path vector protocol which calculates paths based on the network information that was passed on from the previous domain. In other words, the scalability

feature of the BGP series makes it possible that calculated path will have a large occurrence of undesirable hops on the identified routes. The long-term effect of this situation is not currently understood, but with the continual increase of network service providers, this problem may become more serious in the next 10 years.

Existing link state algorithms are sufficient to fulfill traffic engineering requirements for intra-domain routing. However, to perform intra-domain routing, topology aggregation schemes have to be established before intra-domain routing can be executed. And yet, a fully-mesh topology aggregation scheme is not scalable because of its high complexity in regards to the increasing number of border nodes used in a single domain. Therefore, topology aggregation schemes need to be studied to further abstract internal connectivity and traffic information for the benefit of inter-domain routing purposes.

Since Next Generation Networks requires fast and dynamic connection establishment, signalling protocol should be able to provide the least setup delay for connection establishment requests. RSVP-TE is commonly used in research area today. However, to further shorten the lightpath establishment time of RSVP-TE, the working mechanism of RSVP-TE needs to be reconsidered.

In regards to survivability issues, protection is preferable to restoration. Most existing protection schemes share resources with primary paths and the protection path is calculated beforehand, but the resources are allocated only if the protection path is activated. Eventually, this makes these protections schemes less robust because if insufficient resources are discovered, the failure cannot be recovered. Moreover, in a practical sense, fibres are much less expensive now than they were ten years ago and so it is possible to deploy sufficient fibres so that all the resources on the backup paths be pre-defined and pre-allocated.

This thesis aims to develop a multi-domain survivable control architecture framework which deals with hop number problem in inter-domain routing, a topology aggregation scheme,

the design of signalling protocol, and the survivability of current optical networks. The objectives are as follows:

- To address the possible large number of hop problem in inter-domain routing
- To provide an intra-domain topology aggregation scheme for the benefit of inter-domain routing
- To propose a signalling protocol that minimizes the establishment delay of network requests
- To promote the robustness of the proposed framework by pre-allocating sufficient backup resources.

1.3: Thesis Contributions

This thesis intends to provide a framework for a control plane in multi-domain optical network environments. The designed control plane discussed herein contains an inter-domain routing algorithm, topology aggregation scheme, intra-domain routing algorithm, and signalling protocol. The contributions of this proposed framework are summarized as follows:

- It implements OBGp+ with a hop-limit parameter and modified 'best path selection' strategy
- It illustrates a ring-based topology aggregation scheme, which reduces the complexity of maintaining the state of a single domain in comparison to a fully-mesh topology aggregation scheme
- It proposes an intra-domain routing algorithm based on the k edge disjoint shortest path algorithm with two essential link attributes, WAV and ENAW
- It proposes a modified RSVP-TE signalling protocol to reduce the establishment time of integrated inter-domain and intra-domain optimal path

- It proposes a solution to survivability problem by pre-configuring and pre-allocating resources inside a single domain for the purpose of inter-domain traffic
- It introduces a versatile simulation program which has been developed in Java language to integrate the proposed algorithms, schemes and protocols.

1.4: Thesis Outline

This thesis consists of five chapters. Chapter 1 introduces the background of the control plane in multi-domain optical network environment. The motivations, objectives and contents of this thesis are also included in this chapter. Chapter 2 provides a review of the literature on inter-domain routing, intra-domain routing, topology aggregation, and signalling; state-of-art of survivability issues is also presented in this chapter. Chapter 3 provides detailed design considerations and architectures of the proposed control plane framework. Inter-domain routing algorithm, intra-domain routing algorithm, topology aggregation scheme, and signalling protocol are also discussed in this chapter. Chapter 4 provides a simulation model, which includes network environment settings and parameter combinations; simulation results are also listed and performance analysis is presented based on the numerical results. In the final chapter, conclusions and future streams of research are discussed.

Chapter 2 STATE OF ART OF CONTRL PLANE OF MULTI-DOMAIN OPTICAL NETWORKS

2.1: Introduction

In this chapter, several comments are made regarding the nature of the work proposed in this thesis regarding control architecture of survivable multi-domain optical networks. In the first part of this literature review, an introduction to the concept of a control plane is provided.

According to [LEHM07], generally the design of a control plane has to address two major problems: routing and signalling. However, in multi-domain research, the routing requirements can be divided into two sub-sets: inter-domain routing and intra-domain routing. Both of these routing levels have been the focus of research for decades. To integrate intra-domain routing with inter-domain routing, topology aggregation is introduced. Thus, in order to design an optical multi-domain control plane, four problems need to be addressed: inter-domain routing, intra-domain routing, topology aggregation and signalling. Figure 2-1 shows the interactions among these four design challenges:

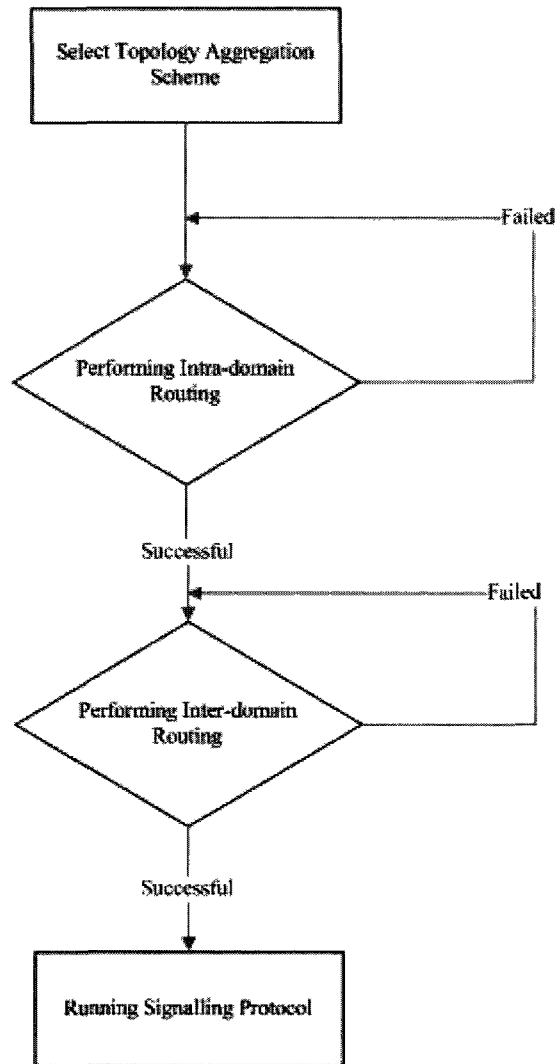


Figure 2-1 Interactions among four design challenges

After the introduction of a control plane framework, issues concerning survivability then need to be considered. Since the quality requirements of networks are growing, control planes have to be designed with strong survivability considerations.

The objective of this chapter is to introduce recent research on the issues addressed in this thesis, that is to say control architecture of survivable multi-domain optical networks.

2.2: Control Plane of Optical Networks

With the implementation of large optical networks, dynamic lightpath provisions are desired and only the data plane framework is unable to meet this requirement. Because of this dynamic, configuration of control planes attracts the interest of researchers. In [BARO06] [LEHM08] [GHAN08], the authors gave design considerations to control plane frameworks in multi-domain optical networks. From their perspective, the key capability of a control plane framework is the definition of Inter-Domain Communications (IDC), which would effectively peer and interoperate diverse networks with different data planes. In [SAHA03], the authors presented four main control plane functions which have to be taken into consideration when designing a control plane framework. These four main functions are:

- **Neighbour discovery:** a network element automatically determines the details of its connectivity to all its data plane neighbours. These details include the identity of the neighbours, the identity of the link terminations, and so on
- **Routing:** Routing broadly covers two control aspects: automatic topology and resource discovery and path computation
- **Signalling:** Signalling denotes the syntax and semantics of communication between control agents in establishing and maintaining connections. Signalling involves the use of standard communication protocols across the whole network
- **Local resource management:** Concise resource representation is essential for the scalability of routing mechanisms.

These four functions are the major design considerations in the proposed control architecture framework found herein.

IP-over-optical control architecture, as discussed in [CHUN01] [OLIV10], is the most widely used control plane prototype. Figure 2-2 provides an example of how IP networks are used as the control network over optical transport network:

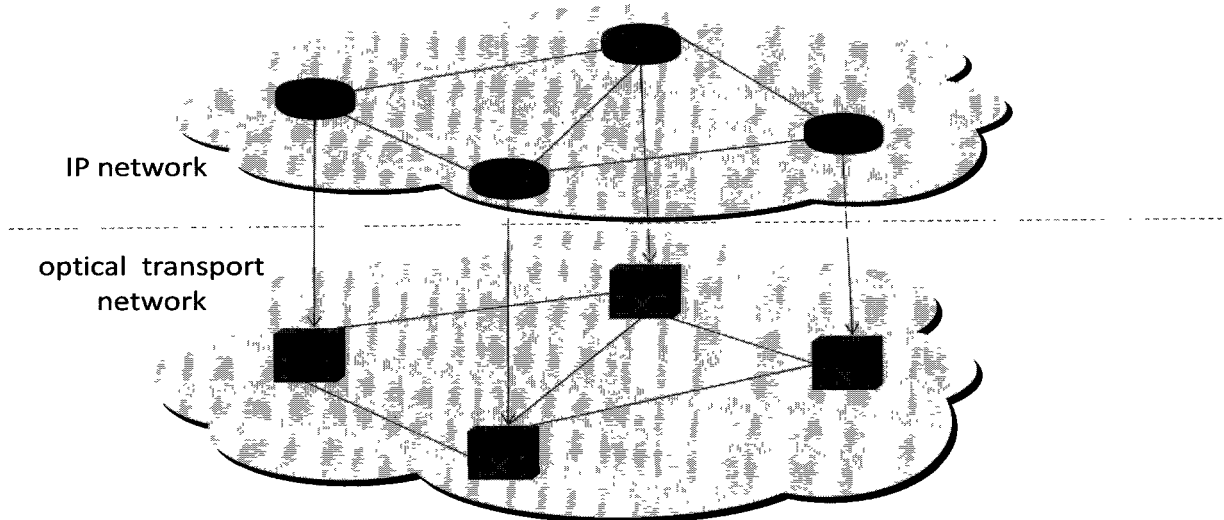


Figure 2-2 IP control network over optical transport network

Under IP-over-optical control architecture, two different control planes are proposed: the overlay model and the peer model. Figures 2-3 and 2-4 provide representations of these models:

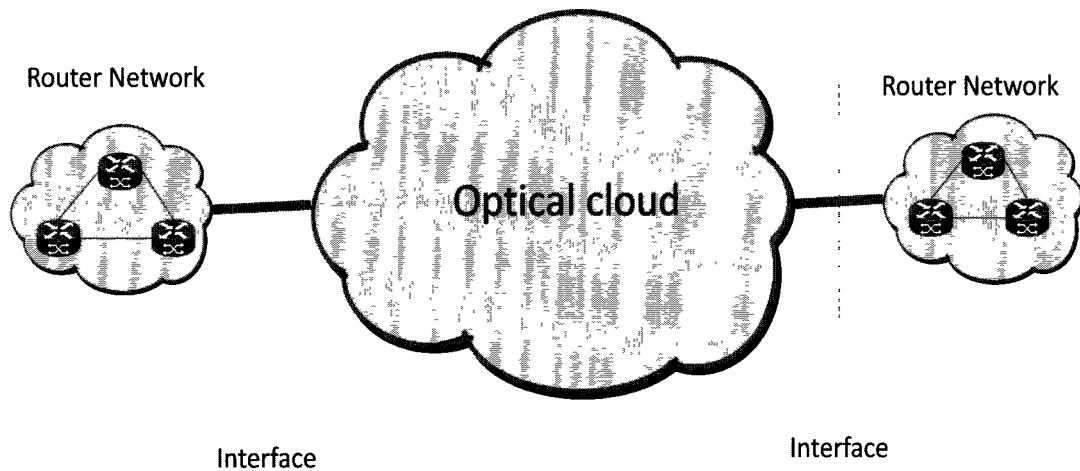


Figure 2-3 Overlay model

The above overlay model has the following features:

- Independent addressing schemes
- Topology opacity (the optical network is invisible to routers)

- No routing information is exchanged across the interface
- Lightpaths may be treated as point-to-point links at the IP layer after set-up

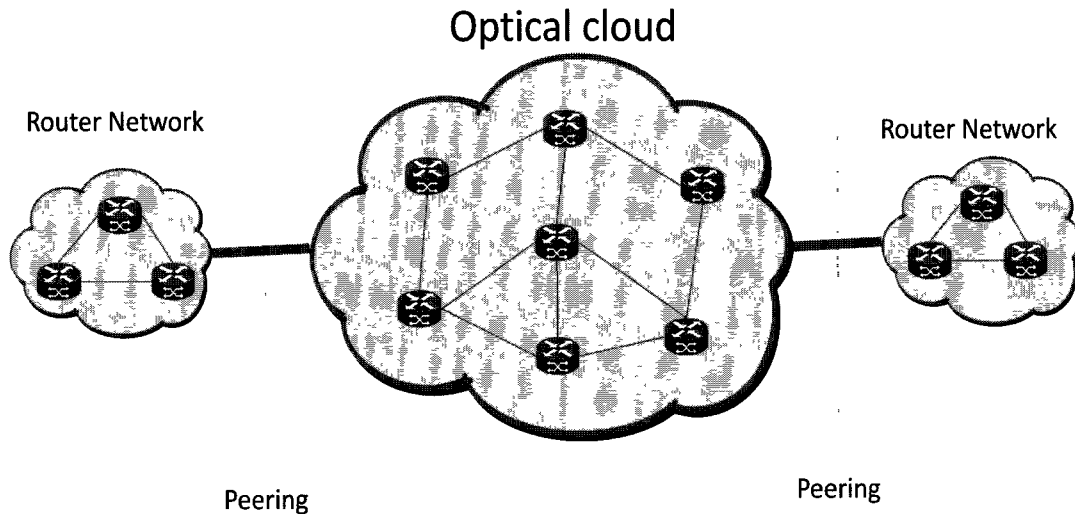


Figure 2-4 Peer model

The above peer model has the following features:

- A common addressing scheme
- Full topology exchange (routers and optical switches OXC are peers)
- Routing information can be exchanged transparently
- There is a common control plane similar to IP/MPLS model

The advantages and disadvantages of implementing these two models into optical transport networks have been discussed for years. Recently, in [SHEN06], the author argued that the lightpath selecting and assigning mechanisms in overlay structure are not or part under the control of the control plane. In contrast, the peer model aims to provide a more efficient and flexible control method, in which the optical wavelength and bandwidth allocation can be managed by the control plane framework transparently. Thus, the peer model is the preferable model to use when designing control architecture for optical networks.

By utilizing the peer model, researchers have begun trying to build a control plane architecture for present optical transport network, and even a next generation network. In [DUGE08] [FARR06], Path Computation Element (PCE) was utilized to represent a domain in order to perform path computation functions. PCE is defined as an entity (component, application, or network node) that is capable of computing a network path based on a network graph and constraints. Although details of configuring PCE have yet to be discussed herein, the idea of assigning a representative for each domain in a multi-domain environment is a commonly accepted research practice. In [YU04], the author presented a Photonic Inter-domain Negotiator (PIN) as the secure global optical control plane architecture to interoperate multiple wavelength-routed network domains with incompatible local control planes. However, [YU04] only proposed the framework - further numerical test results have to be provided in support of the authors' proposals.

2.3: Inter-domain Routing

Of the four components in the design of control architecture, inter-domain routing is the essential part. According to [BESH10] [CHAM09a] [YANN05b] [JAGG05] [SHRI10], inter-domain routing has to deal with two major problems: the size of a network and the reluctance of different providers to share information. In the 1990s, BGP was proposed to solve these two problems. Since 1993, BGP has become widely deployed as the core inter-domain routing protocol in the industrial field because of its capability for routing policy control and scalability advantage compared with IGP (Interior Gateway Protocol). Issues of implementing BGP were discussed in [FEAM07] [GOTH03] [GRIF02] [LAD04] [ZHON10]. However, BGP has several limitations that need to be resolved. In [YANN08], the authors listed three major limitations of BGP, which are identified as:

- The inability to convey useful traffic engineering (TE) information and exploit it in practise
- The lack of multi-path routing capabilities

- Slow convergence, which impedes fast detection and response to network impairments

In order to overcome limitations of BGP, two possible methods are often considered by researchers. One is to make modifications to the existing BGP model/framework, and the second is to develop an inter-domain routing protocol to replace BGP. Remedies for the situation have been proposed in the past. In [FRAN02], the author defined OBGP as an approach to extending BGP routing protocol to support lightpath setup and management across an optical network. However, OBGP is based on BGP and it has inherited all three of the inherent weaknesses of BGP. In [YANN09], the authors provided readers with a possible modification to OBGP, which is called OBGP+. While OBGP+ is still based on BGP, instead of only considering the Network Reachability Information (NRI), OBGP+ has taken both Network Reachability Information (NRI) and Path State Information (PSI) into consideration. The NRI message conveyed by OBGP+ consists of:

- A set of destination networks $\{d\}$ and their associated AS-paths
- The Next-Hop (NH) to reach those destinations
- A set of pairs $(\lambda_i, M_{\lambda_i}), i \in \{1, \dots, N\}$ available for each destination d , where λ_i denotes a particular wavelength and M_{λ_i} denotes the maximum multiplicity of λ_i . In other words, M_{λ_i} can be treated as the number of fibres that contains λ_i .

In summation, the NRI message distributed between OBGP+ nodes is composed of:

$$\phi_{NRI}(d) = \{AS-path, NH, (\lambda_i, M_{\lambda_i})\}_d \quad (2.1)$$

OBGP+ advertises PSI messages by aggregating and assembling the following three pieces of information:

- Intra-domain PSI

- PSI related to the inter-domain links toward its downstream domains
- The already aggregated PSI contained in the inter-domain advertisements received from downstream domains

To illustrate, let $W(\lambda_i)$ be the effective number of available wavelengths of type λ_i (number of fibres that contains λ_i), r and q be a pair of OXCs inside an AS, $P(r, q)$ be a candidate path between r and q , and l be a link in the path $P(r, q)$. The Effective Number of Available Wavelengths (ENAW) of type λ_i between the OXCs, r and q , is calculated by (2.2):

$$W_{r,q}(\lambda_i) = \max_{P(r,q)} \left\{ \min_{l \in P(r,q)} W_l(\lambda_i) \right\} \quad (2.2)$$

Figure 2-5 shows an example of exchanging PSI between optical domains:

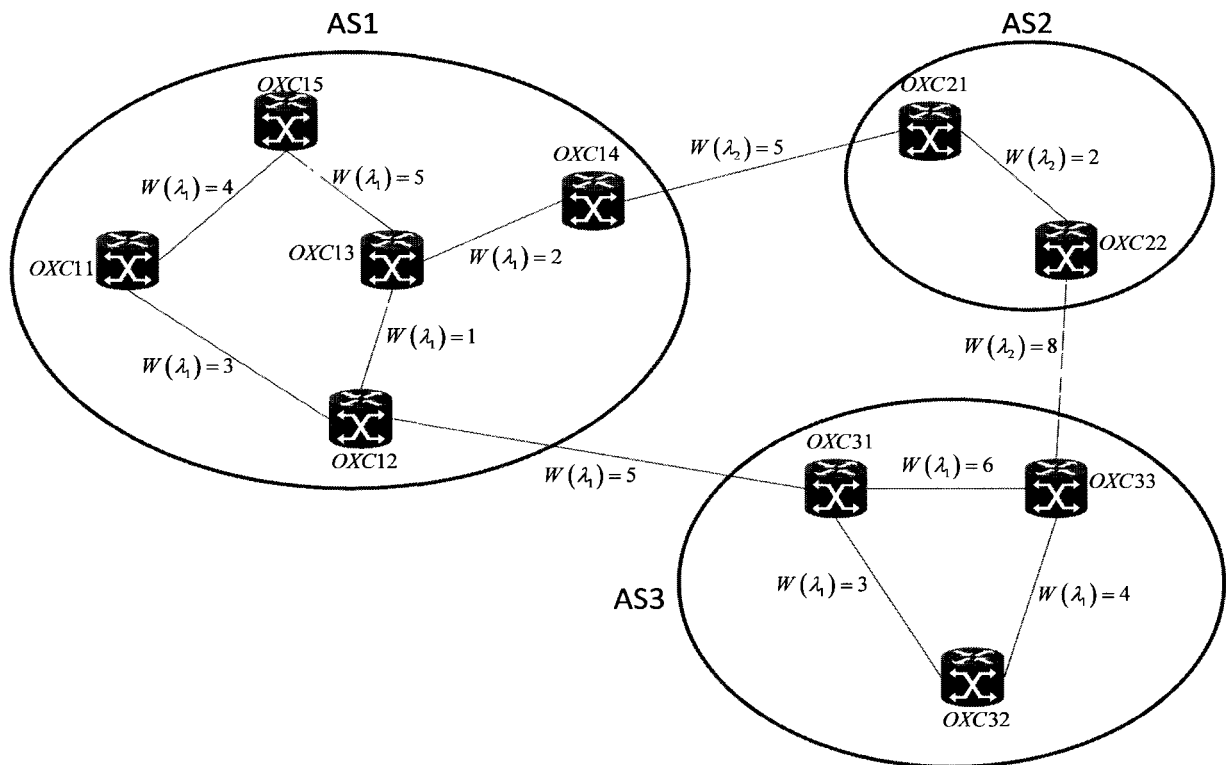


Figure 2-5 PSI (Path State Information) exchanged between optical domains

Let $W_{l_b, r_b}(\lambda_i)$ denotes the effective number of available wavelengths of type λ_i (number of fibres that contains λ_i) in the inter-domain link between the local border node l_b and a neighbour border node r_b . For instance, in figure 2-5, $W_{12,31}(\lambda_1) = 5$. Similarly, let $W_{r_b, d}^{adv}(\lambda_i)$ denotes the ENAW of type λ_i between the neighbour border node r_b and the destination node d , advertised by r_b .

Based on the above two inter-domain components and (2.2), the ENAW between a local border node l_b and a distant destination node d is:

$$W_{r_b, d}^{adv}(\lambda_i) = \min\{W_{l_b, l_b}(\lambda_i), W_{l_b, r_b}(\lambda_i), W_{r_b, d}^{adv}(\lambda_i)\} \quad (2.3)$$

For example, in Figure 2-5, the border OXC14 advertises to its neighbour OXC21 that the effective number of available wavelength of type λ_1 to reach OXC32 is:

$$W_{14,32}^{adv}(\lambda_1) = \min\{W_{14,12}(\lambda_1), W_{12,31}(\lambda_1), W_{31,32}^{adv}(\lambda_1)\} = \min\{2, 5, 4\} = 2$$

Besides OBG and OBG+, the authors of [QUOI05] presented another modification of BGP, which is known as C-BGP. With C-BGP, the ISPs should be able to manipulate a model of their network in order to allow for the investigation of changes to the routing or topology of such a large network. The working process of C-BGP can be summarized as follows:

- The network topology information at layer 3 is collected
- The configuration information of all the routers in the topology is collected
- The BGP routes learned by ISP network on their border routers are collected
- By applying C-BGP, each router knows the routes selected toward all the inter-domain prefixes.

To illustrate the application of C-BGP, the authors of [QUOI05] studied two scenarios: the impact of changes in Internet connectivity, and the impact of a failure inside an ISP's network. However, multiple domains scenario has not yet been studied. To fully understand

the uses and application of C-BGP, additional studies should be undertaken on this aspect in the future.

In contrast to modifying existing BGP series, some researchers have developed replacement protocols for BGP. In [LIU06a], the authors proposed an inter-domain routing protocol to replace the existing OBGp protocol. The proposed routing scheme uses a two-level hierarchical link-state approach; one for intra-domain routing and the other for inter-domain routing. Figures 2-6 and 2-7 illustrate this approach:

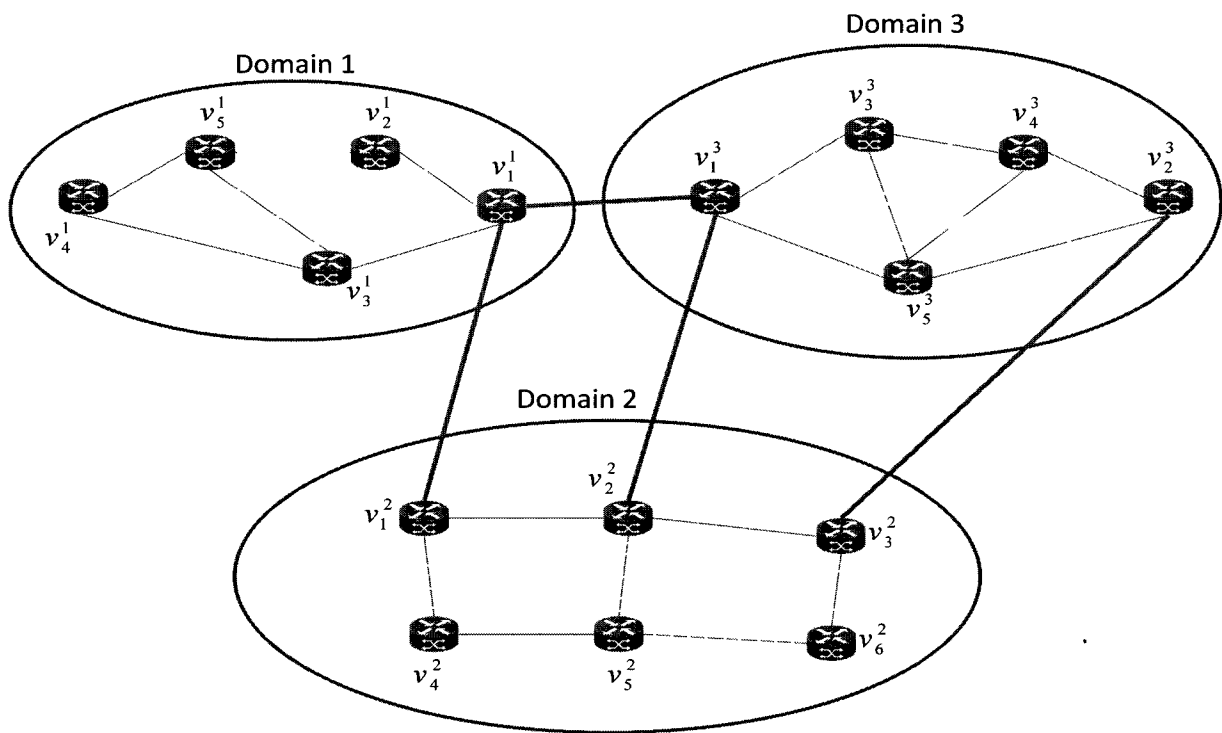


Figure 2-6 Physical level routing

Physical level routing is also known as intra-domain routing. At this level, every domain does routing within itself.

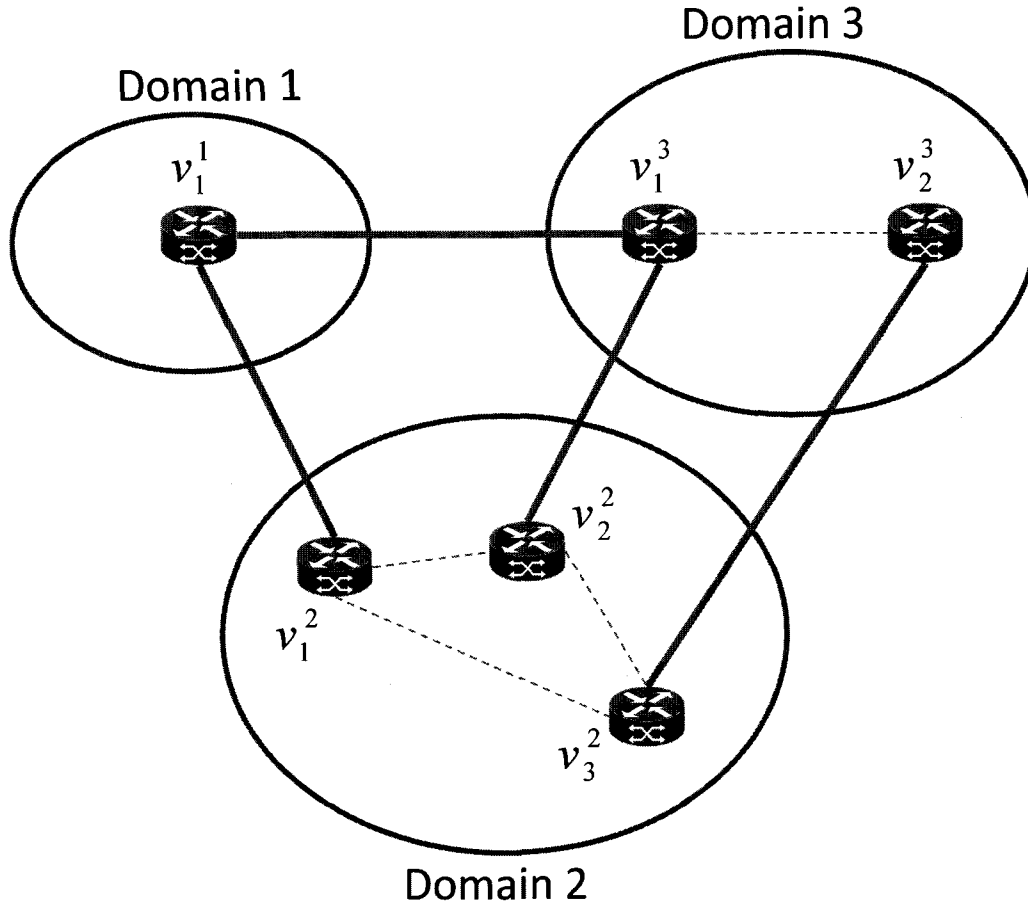


Figure 2-7 Virtual level routing

Virtual level routing is known as inter-domain routing. At this level, the border nodes that are used to represent a domain cooperate and perform the routing function. The selection of which border nodes will represent this domain is determined by the topology aggregation scheme, which will be discussed later in this chapter.

The major difference between two-level hierarchical link-state protocol and OBGp+ is that the two-level hierarchical link-state protocol uses a link state algorithm at the inter-domain level, while OBGp uses path vector algorithm at the inter-domain level. Advantages and disadvantages of implementing link state algorithm and path vector algorithm are

illustrated in [TRUO06] [SHAV10]. Table 2-1 provides comparison results for these two routing algorithms:

	Path Vector Algorithm	Link State Algorithm
Message complexity	<ul style="list-style-type: none"> o Exchanges between neighbours only o no specific number of messages 	With n nodes, E links, $O(nE)$ messages needed
Speed of Convergence	<ul style="list-style-type: none"> o Convergence time varies o count-to-infinity problem o may be routing loops 	$O(n*n)$ requires $O(nE)$ messages
Robustness	<ul style="list-style-type: none"> o Node can advertise incorrect path cost o Each node's routing table is shared by other nodes o Error propagate through network 	<ul style="list-style-type: none"> o Node can advertise incorrect link cost o Each node only computes its own table

Table 2-1 Comparison between path vector algorithm and link state algorithm

In considering the specific requirements of inter-domain routing, instead of using link-state approach, path-vector algorithm is the more desirable option because of the comparison made above. Based on a path-vector algorithm, the authors of [YANN05a] proposed a combined routing scheme, known as Inter-Domain Routing Agency (IDRA), which acts as the connection between the inter-domain routing and the intra-domain routing schemes.

Figure 2-8 illustrates the IDRA scheme:

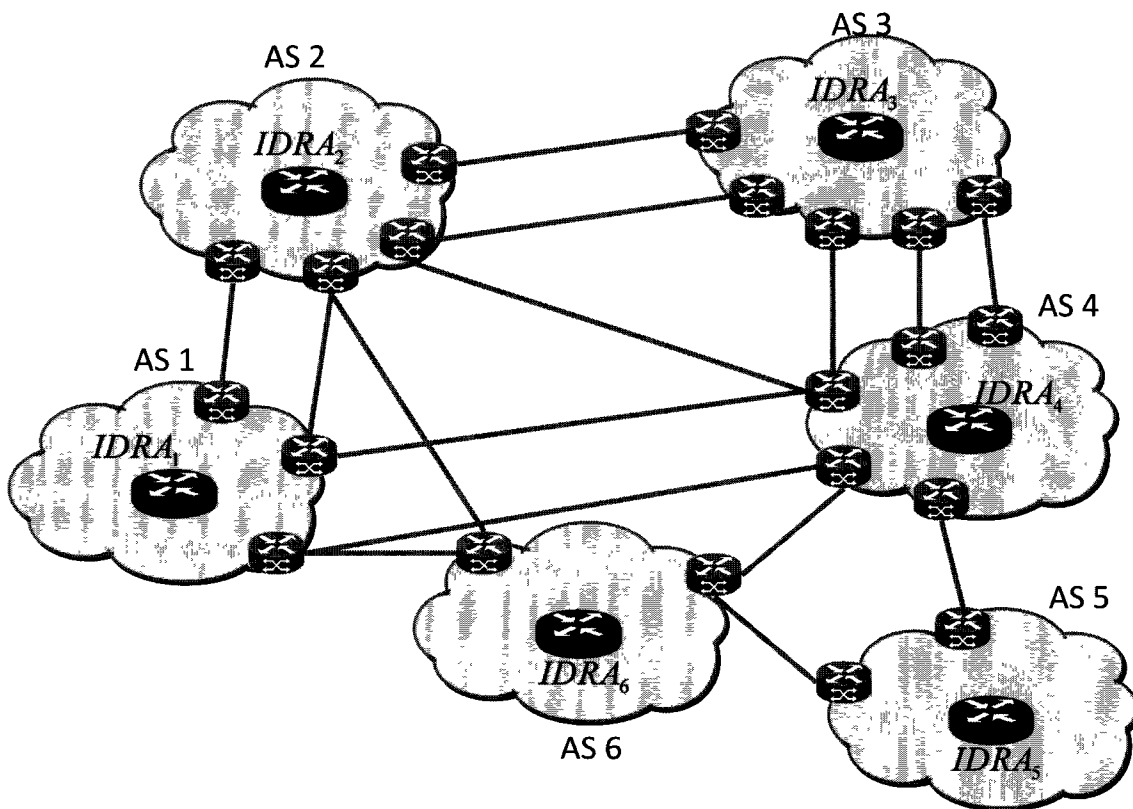


Figure 2-8 IDRA routing scheme

The IDRAs in the above figure are responsible for computing inter-domain and intra-domain optimal lightpaths. One benefit of this approach is that the IDRA model is almost independent from either inter-domain routing or intra-domain routing. Thus, any modifications, or the complete replacements of either protocol, would have no influence on the other. So far, IDRA has achieved the best results in comparison with OBGp and OBGp+ in terms of blocking probability.

Although IDRA achieves the best blocking performance, it does not address survivability issues in conducting inter-domain routing. The authors of [SPRI07] proposed a distributed routing algorithm for finding two link disjoint paths across multiple domains. This algorithm uses PCE architecture and assumes that the PCEs run a joint distributed routing algorithm which is decoupled from BGP. The major contribution of [SPRI07] to the field is the

proposition of distributed routing algorithm based on proposed aggregated representation of a multi-domain network. Figure 2-9 (a-b-c-d) provides an illustrative example of running the proposed distributed routing algorithm in a multi-domain network:

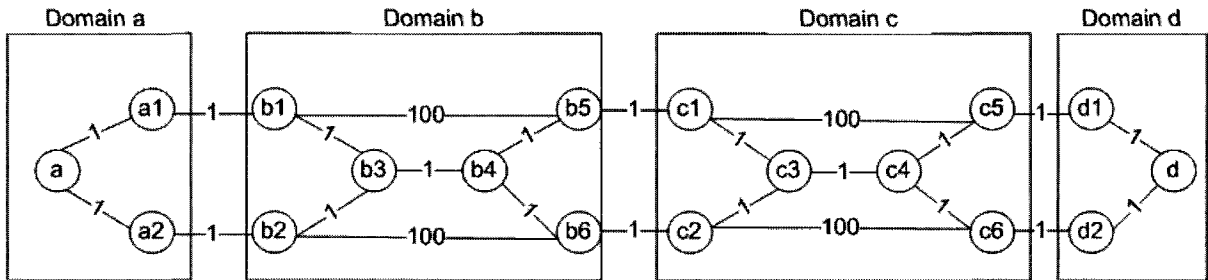


Figure 2-9 (a) The underlying communication network with two transit domains, b and c

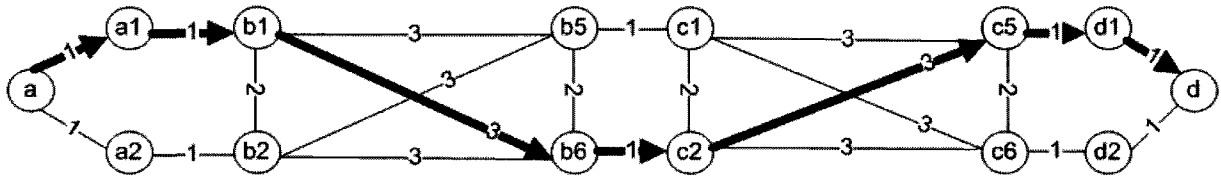


Figure 2-9 (b) The auxiliary network with weights assigned according to proposed algorithm

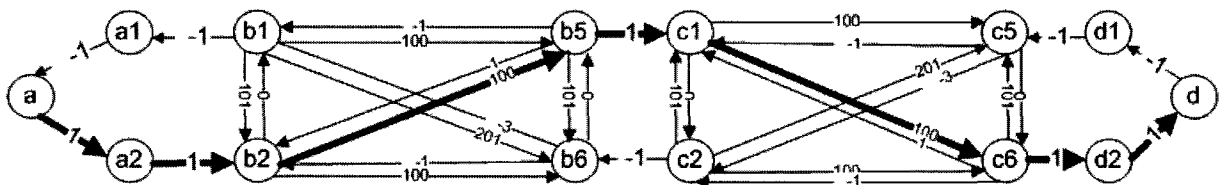


Figure 2-9 (c) The auxiliary network with weights assigned according to proposed algorithm

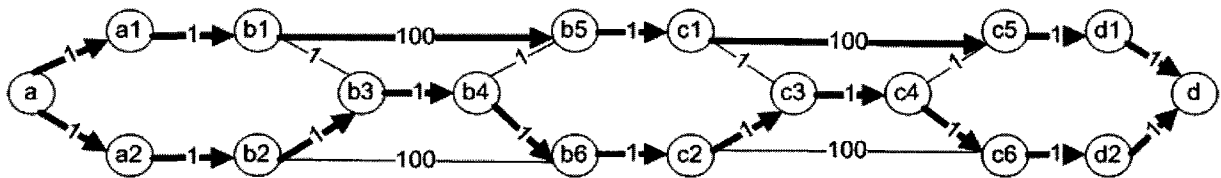


Figure 2-9 (d) Two link disjoint paths in underlying network

In Figure 2-9 (b) and Figure 2-9 (c), the aggregated representation of two transit domains is calculated by running the proposed algorithm. This algorithm works in two steps: first, the shortest path is found between the source and the destination; then, an augmenting path

built on the previous shortest path is found based on a network graph that reverses and negates weights of all links in the original graph.

The other contribution of [SPRI07] to the field is the idea of the line graph. This concept can be used to solve the export policy limitations which are imposed by customer/provider and peer relationships between routing domains.

2.4: Intra-domain Routing and Topology Aggregation

Intra-domain routing and topology aggregation have been researched for decades. OSPF, as discussed in [PEDR08], has been deployed by most service providers as their intra-domain routing protocol since 1990. However, to integrate intra-domain routing protocols with different inter-domain routing protocols is a challenge, as the internal traffic and topology information of one domain is supposed to be hidden from its neighbouring domains.

Topology aggregation schemes provide a solution for a single domain to share part of its topology and traffic information with other domains. In [FANG00], topology aggregation was defined as one way to achieve scalability by hiding the detailed traffic and topology information inside a domain from the outside; other domains would only have an abstract view of the domain in question. In [LIU07], the authors introduced two topology aggregation schemes: simple node aggregation and full-mesh aggregation. Figures 2-9 and 2-10 illustrate these two schemes:

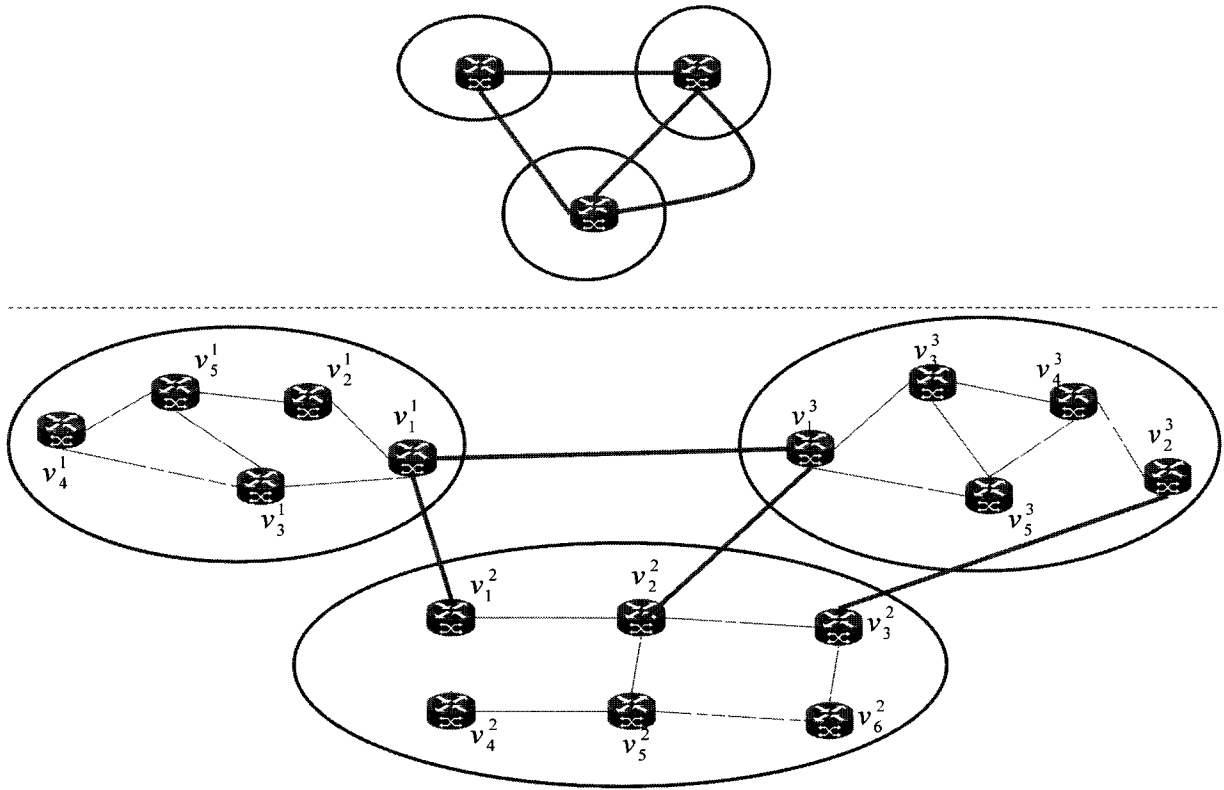


Figure 2-10 Simple-node topology aggregation

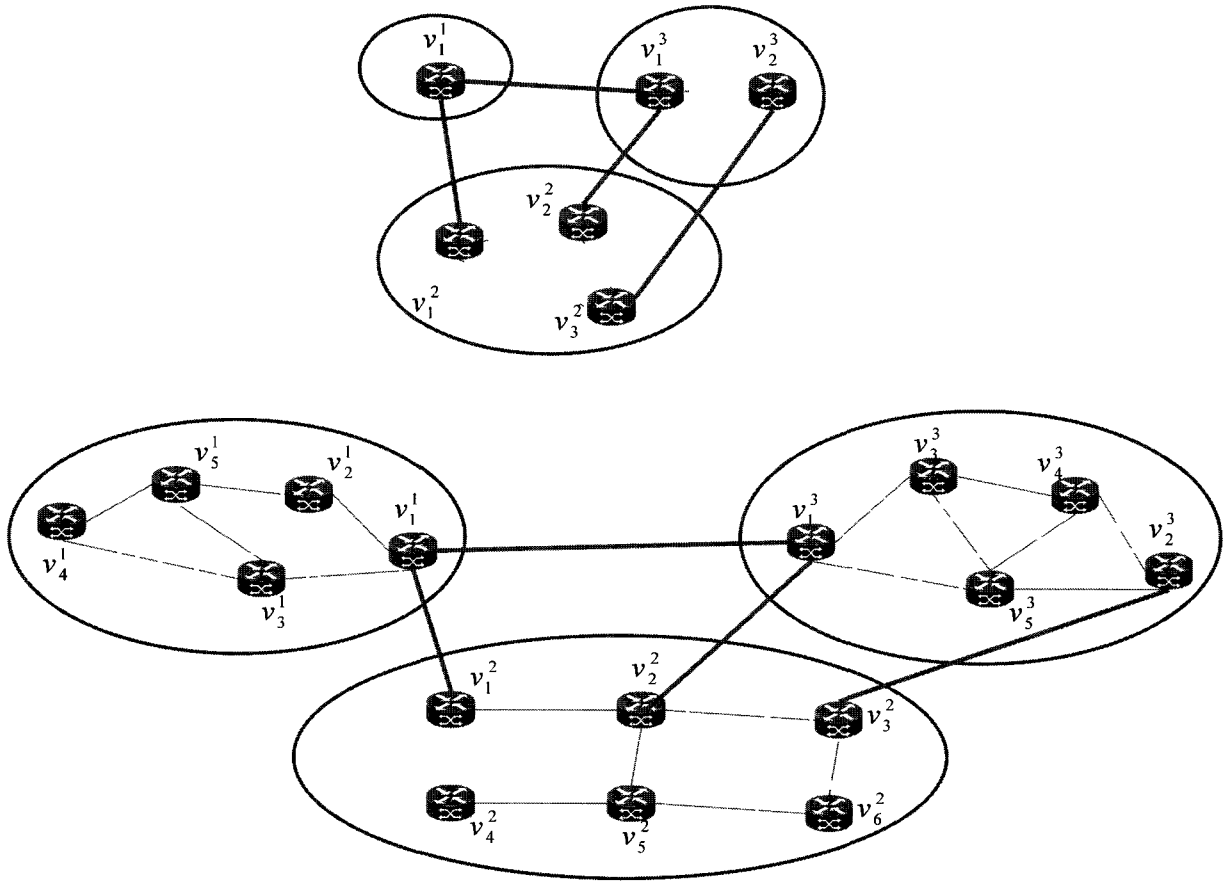


Figure 2-11 Fully-mesh topology aggregation

According to [LIU06b], the simple node model is the most basic of all the topology aggregation schemes and condenses a domain into a single virtual node emanating all physical inter-domain links, while fully-mesh aggregation is designed to perform intra-domain state summarization. This transforms one domain into a sub-graph containing the border nodes interconnected via a fully-meshed set of virtual links.

Fully-mesh aggregation is preferable to simple node aggregation because fully-mesh aggregation can convey summarised topology and traffic information of one domain to its neighbouring domains. However, the fully-mesh model is not scalable when the number of border nodes of one domain is very large. For example, if border nodes are N , then the complexity of maintaining the state of this domain is $O(N * (N - 1)) = O(N^2)$, which is very high if N is large. Thus, researchers are attempting to find a more scalable topology

aggregation scheme which can perform summarised intra-domain topology and traffic information even in the above described conditions.

2.5: Signalling

With the increasing demand of connection establishment time, today's research on the control architecture of optical transport network, specifically the subject of signalling protocols, are of great interest. The most widely used lightpath reservation model is Immediate Reservation. In [CHAS06], the signalling protocol was described as being handled by the sender and the receiver in two different domains, while the authors of [HUDE95] gave three signalling schemes of Immediate Reservation: "Connect/Confirmation" (CC), "Tell-And-Go" (TAG) and "Reservation/scheduling with Just-in-Time Switching" (RIT). The most commonly used signalling protocols are RSVP-TE, as described in [KOM07], and CR-LDP. They belong to MPLS protocols stacks and both of them use the "Connect/Confirmation" scheme.

MPLS stands for Multi-Protocol Label Switching and it was first proposed to optimize traffic engineering in IP networks. According to [RAHM08] [XU10], MPLS carries differentiated services across the Internet through a virtual path, and it also has the capability to engineer traffic tunnels by avoiding congestion and utilizing all available bandwidth in an efficient manner. Normally, the transmission delay of data plays an important role in limiting the speed of the network, thus routing problems become the major difficulties. However, with the deployment of optical transport networks, the transmission delay in the data plane can almost be ignored, thus the signalling delay in the control plane becomes the major factor in effecting the speed of establishing connections.

RSVP-TE and CR-LDP have two types of implementation: the four-phase scheme and the two-phase scheme. Figures 2-12 illustrates the four-phase scheme and two-phase scheme is illustrated in Chapter 3:

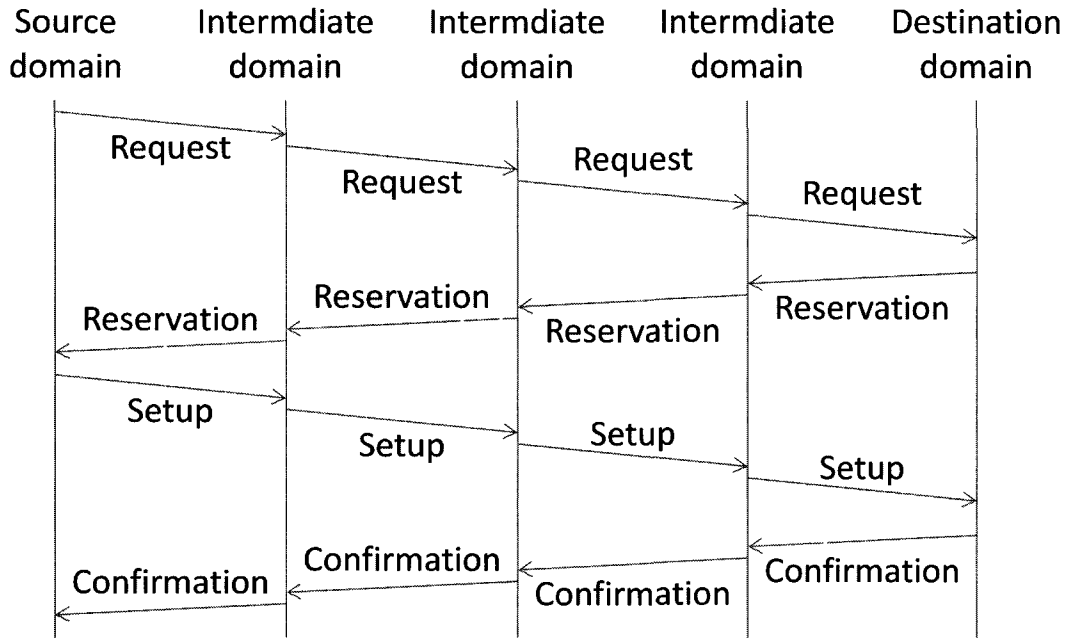


Figure 2-12 Four-phase signalling scheme

Based on RSVP-TE, the authors of [TACH08] proposed a lightpath establishment method to establish inter-domain lightpaths across multiple domains. In [TACH08], this method was based on aggressive rank accounting so that ranking databases were updated frequently. The process of this method can be summarized as follows:

- The border-node information and wavelength usage information are collected
- The accuracies of wavelength usage information for each node are computed based on the border-node information
- The ranking database for each node is updated.

According to [TACH08], with this aggressive rank accounting method, the blocking probability of lightpath establishment in a multi-domain network environment can be reduced by 60%. However, [TACH08] does not provide an analysis of the complexity of exchanging signalling messages when a ranking database is updated. The tradeoffs of decreasing the blocking probability and increasing the complexity of signalling message should be further considered.

Other than the Immediate Reservation model, another way of realizing resource reservation in signalling is Advance Reservation. According to [HE06], Advance Reservation is different from Immediate Reservation as a way of identifying holding time. In Advance Reservation, a specific holding time must be clearly defined. Usually, this holding time is an estimate or a safe upper boundary. In [HE06], the authors proposed the idea of relaxing time parameter in Advance Reservation to improve the acceptance rate. This proposition is reasonable since there are two parameters in Advance Reservation: the time-parameter and the resource-parameter. The relaxation of one parameter may result in improvement of the operations of the other.

Although there is as of yet no universal signalling protocol in today's optical network framework, some researchers have already started looking for a signalling solution for the future. In [LIU09], the authors presented a network called PATON which uses a unified signalling, switching and reservation framework, called Polymorphous Optical Burst Switching (POBS). POBS is supposed to seamlessly support various types of services. Thus, the implementation of POBS can lead to the deployment of unified signalling.

2.6: Survivability Issues

Survivability issues also need to be considered in the design of a control plane framework for multi-domain optical networks. According to [DRID10], survivability can be provided on different layers of an optical network, such as IP, MPLS, SONET/SDH and WDM. To achieve quick recovery time, efficient resource utilization, and transparency of protocols, it is preferable to ensure survivability at the WDM layer. The authors of [DRID10] also introduced several methods for performing protection and restoration in a single domain WDM network. In [YURO04], the authors proposed the concept of Link Resource Availability (LRA) parameter to capture the physical layer availability and resource status. Based on this, the authors of [YURO04] also proposed a generalized protection scheme which can better utilize network resources and achieve a faster failure recovery time.

However, when it comes to multi-domain optical network, new research challenges should be addressed. In [DRID10], various solutions were proposed in order to solve the challenges of survivability in multi-domain optical networks, such as reliability in single domain versus multi-domain optical mesh networks, subpath protection for scalability, fast recovery in optical WDM mesh networks, shared path protection in multi-domain optical mesh networks, and local segment-shared protection for multi-domain optical mesh networks.

According to [ZHAO09] [LARR05] [ASKA10], multi-domain optical network survivability has to cope with one significant problem; this is the scalability constraint, which means that no domain is aware either of the global network topology or the bandwidth allocation on all physical links. The authors of [ZHAO09] also gave an example of two resilience methods: domain-segment protection and seamless end-to-end recovery. However, [ZHAO09] does not provide any details on how one might implement these methods. In [TRUO06], the author presented a two-step Extend-Path-Shared Protection (EPSP), which maintains end-to-end inter-domain pair with one primary path and one backup path. Figure 2-13 provides an example of a network with primary and backup paths calculated by EPSP.

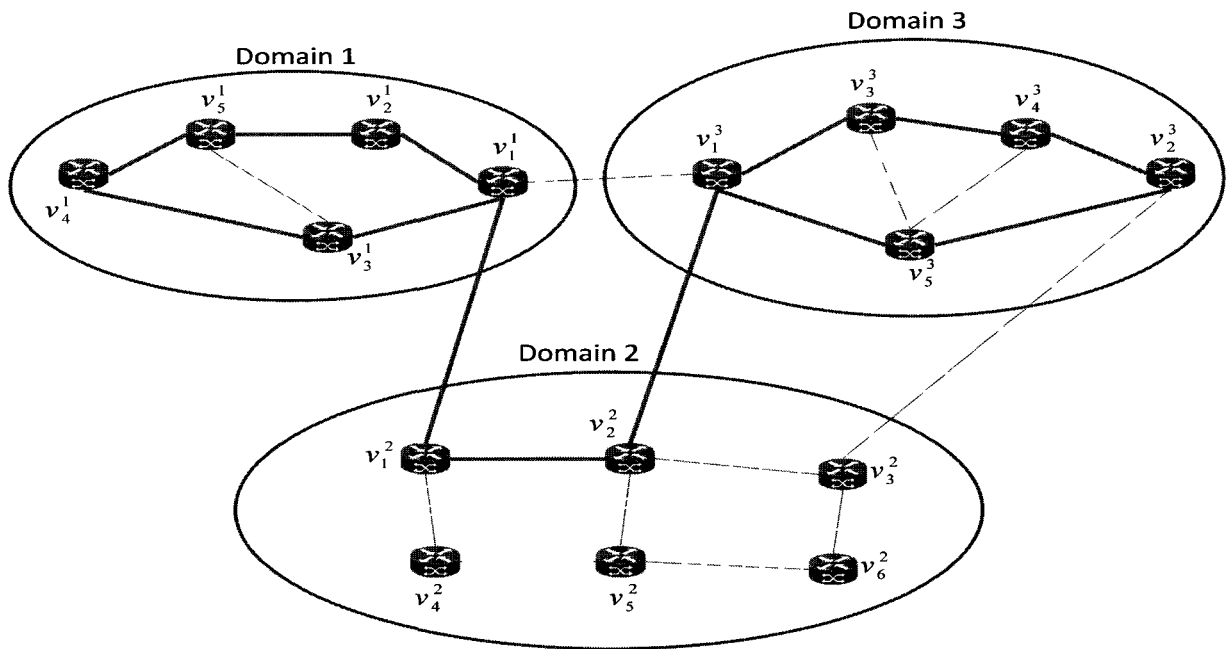


Figure 2-13 EPSP

The operation of EPSP is as follows:

- A rough routing solution is performed in the virtual network that is the abstraction of the multi-domain network
- A complete routing is determined by solving routing problems within each original single-domain network
- An end-to-end inter-domain routing pair with one primary path and one link-disjoint backup path is established from source node to destination node.

In Figure 2-13, two inter-domain edge-disjoint calculated paths exist between v_4^1 and v_3^2 ; one is the primary path and the other is the backup path. However, the major problem of EPSP is that it only considers a single failure situation, while in a real-world optical network, multiple failures may occur. To overcome this limitation, Lei Guo proposed a multi-domain optical protection scheme, which is known as Local Segment-Shared Protection (LSSP). According to [GUO07], LSSP first computes one inter-domain primary path for each connection request and continues on to compute one intra-domain link-disjoint local segment-backup path for each primary-segment path in each single-domain, respectively. In each domain, the backup resources can be shared by different segment-backup paths if the corresponding primary-segment paths are link-disjoint. Figure 2-14 illustrates the result of implementing LSSP.

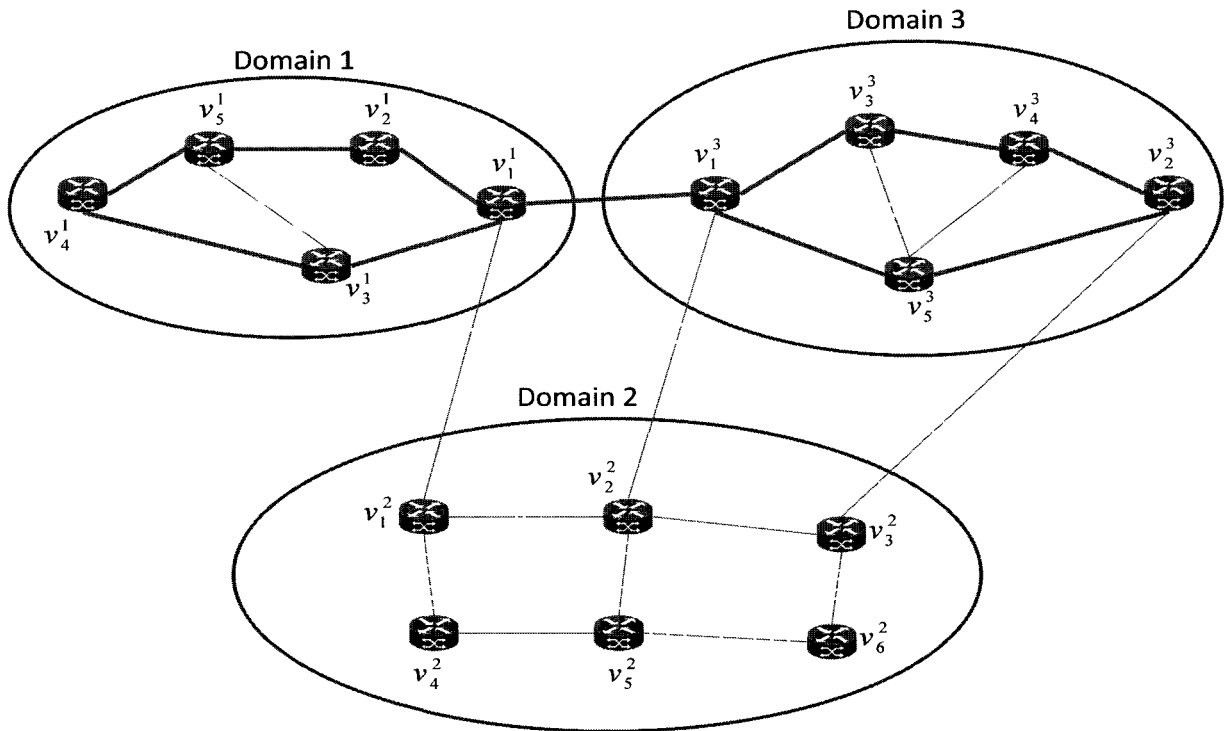


Figure 2-14 LSSP

Based on LSSP, the authors of [ZHAN] proposed a protection algorithm called Enhanced LSSP. Although LSSP and Enhanced LSSP are designed to solve the multiple failures problem, it assumes that only one failure may/will occur in each domain, which is not realistic.

Besides path protection, p-cycle protection is another well known protection scheme. Although p-cycle protection schemes have been studied for single domain situations, the shift from single domain areas to multi-domain areas has triggered multiple research challenges. In [CLOU05] [FARK05] [SZIG09] [KAMA10], the authors proposed one p-cycle solution for multi-domain survivability problem which was based on the decomposition of the multi-domain resilience problem into two sub-problems, known as higher level inter-domain protection and lower level intra-domain protection. In [CINK07], the authors explained the benefits of using Multi-Domain P-Cycle protection; according to [CINK07], in a multi-domain network environment, it is impossible to share protection resources information due to security and scalability reasons. Thus, to avoid a flood of information on

working and protection paths while sharing resources, the Multi-Domain P-Cycle technique is the preferred method of protection. Figure 2-15 details the p-cycle protection scheme in a multi-domain environment.

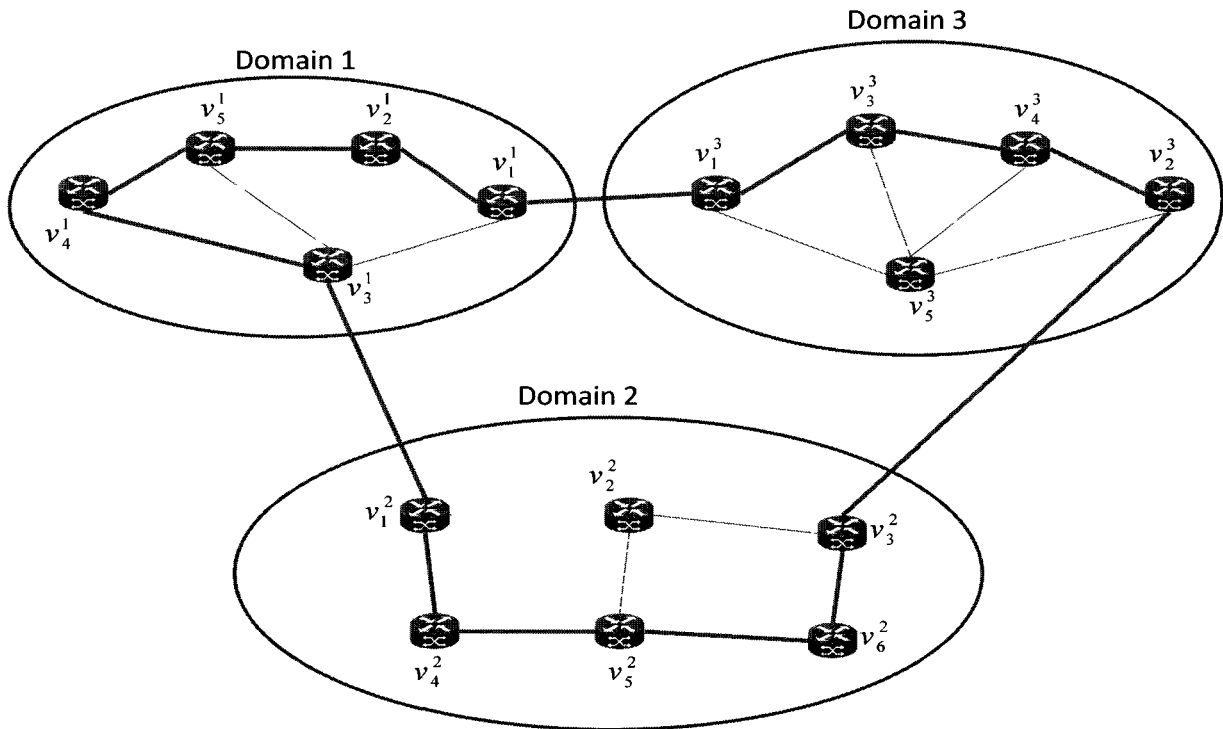


Figure 2-15 P-cycle protection

2.7: Summary

In this chapter, recent works have been discussed in relation to the control plane concept, inter-domain routing, intra-domain routing, topology aggregation, signalling protocols, and survivability issues. Section 1 provides an outline of this chapter. In section 2, four design considerations for control plane frameworks in multi-domain optical network are provided and two types of control model are introduced. Compared with the overlay model, the peer model has been proven more scalable and has been widely accepted as the control architecture in multi-domain optical research. In section 3, three limitations of BGP are discussed, and three inter-domain routing protocols are introduced (OBGP, OBGP+ and

IDRA, with detailed examples). Compared with OBGp and OBGp+, IDRA has achieved the highest performance in terms of blocking probability, however, as has been discussed, IDRA consumes more resources than OBGp and OBGp+. Section 3 also introduces a joint distributed routing algorithm which is decoupled from BGP. In section 4, intra-domain routing and topology aggregation are introduced. In contrast to inter-domain routing, intra-domain routing has been heavily researched and the existing solutions have been proven to be sufficient. Topology aggregation is another challenging topic and two existing solutions, simple-node abstraction and fully-mesh abstraction, have both been shown to be inadequate to support inter-domain routing. Section 5 introduces two basic signalling schemes: Immediate Reservation and Advance Reservation. Two signalling protocols, RSVP-TE and CR-LDP, were also introduced in this chapter. Section 6 provides a summary of three recently proposed protection schemes: EPSP, LSSP and P-cycle. These three schemes have been commonly implemented to realize survivability requirement in optical networks. Section 7 summaries this chapter and gives a brief introduction of next chapter.

In the next chapter, detailed algorithm definitions are discussed along with illustrating figures and operation flowcharts. Comparisons between mathematical analysis and simulation results of the network simulator are also presented in the next chapter.

Chapter 3 ALGORITHM DEFINITION AND MATHEMATICAL ANALYSIS

3.1: Introduction

This chapter provides a detailed description of algorithms in relation to proposed control architecture of multi-domain survivable optical networks. The proposed control architecture consists of inter-domain routing algorithm, intra-domain routing algorithm, topology aggregation scheme and modified RSVP-TE signalling protocol.

The inter-domain routing algorithm is designed by implementing path vector algorithm with a hop-limit parameter. The intra-domain routing algorithm is based on a link state algorithm. The topology aggregation scheme in this control architecture aims to overcome the drawbacks of the existing topology aggregation strategy and is implemented at the intra-domain level. The purpose of proposing a modified RSVP-TE signalling protocol is to shorten the connection establishment delay. At the end of this chapter, a mathematical analysis of the network simulator is provided, while testing results show that the queuing performances of the network simulator discussed herein matches the mathematical analysis results.

This chapter is organised in seven sections. Section 1 outlines the purpose of this chapter and each section. Section 2 introduces the design objectives and a working flowchart of the inter-domain routing algorithm. Section 3 provides comparison results between existing topology aggregation schemes and the proposed topology aggregation scheme. Section 4 includes the design purposes and flowchart of intra-domain routing algorithm. Section 5 describes the details of modified RSVP-TE signalling protocol, design purposes and

operation flowcharts. Section 6 presents the mathematical analysis and testing results of the queuing performance of network simulator. Finally, Section 7 concludes and provides a summary of this chapter.

3.2: Inter-domain Routing Algorithm

The inter-domain routing algorithm implemented in this control architecture is based on a path vector algorithm, which maintains path information and gets updated dynamically; it is supposed to detect, and then discard, looped calculated paths in the network. According to [JAGG05], there are three major goals in designing path vector protocols and in order to achieve multiple goals in any one protocol, inherent trade-offs need to be considered.

These three design goals are:

- **Robustness:** Each network should have a unique stable set of paths to a given destination. A network, and every subnetwork, all have unique stable sets of routing paths obtained by deleting some subsets of edges and nodes from the original network
- **Expressiveness:** Occurs if the network is running a protocol that is guaranteed to be robust; it may achieve this by allowing a restricted set of routing policies.
- **Autonomy:** In looking at particular classes of protocols, the router operators should be able to investigate specific types of autonomy that characterize different degrees of freedom.

The following figure is an example of running path vector algorithm in a network:

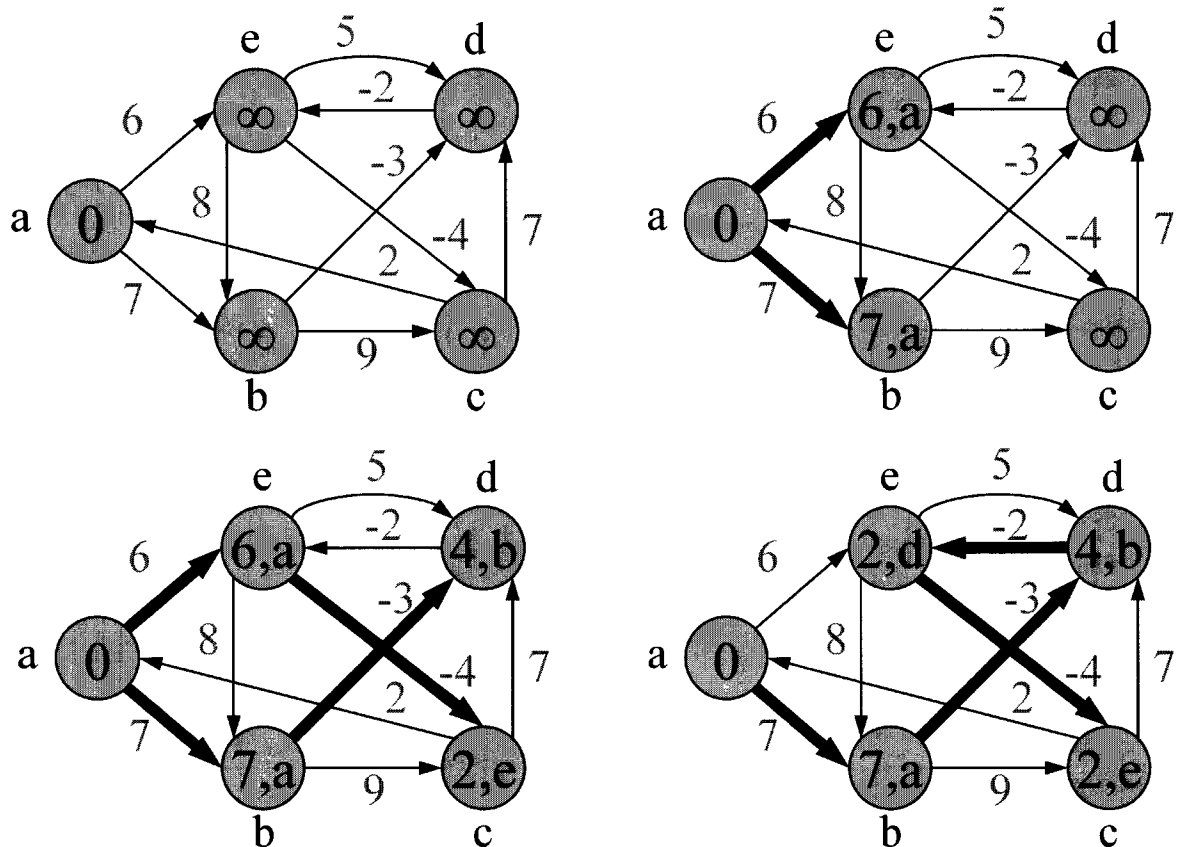


Figure 3-1 Path Vector Algorithm

In Figure 3-1, numbers on links represent the link attributes in two directions. Numbers in circles are distances from that node to source node and letters in circles are next-hop. From top left to bottom right, these four small figures show the operation of path vector algorithm. First, node a and b are checked and distances and next-hop are calculated. Then, the procedure is repeated on every node until all the nodes know the distance and next-hop to the source node. When all the nodes know the shortest path to the source node, the algorithm is done.

In path vector algorithm, every node not only knows the distance to the source node, but also to the previous node. In the BGP application, this means that every AS not only knows the distance to the source AS but also the previous AS number. This makes path vector algorithm scalable because added nodes only have to know the shortest path to the

neighbouring nodes and not the topology information for the whole network. In the control architecture, the path vector algorithm is used as the core routing algorithm at the inter-domain level because of its scalability issue.

Based on this path vector algorithm, the proposed inter-domain routing algorithm considers three parameters: WAV, ENAW and hop-limit. WAV stands for Wavelength Availability Vector and is a component of OGBP, which is an extension of BGP in optical networks. The following figure shows an optical network with WAV attribute on the links.

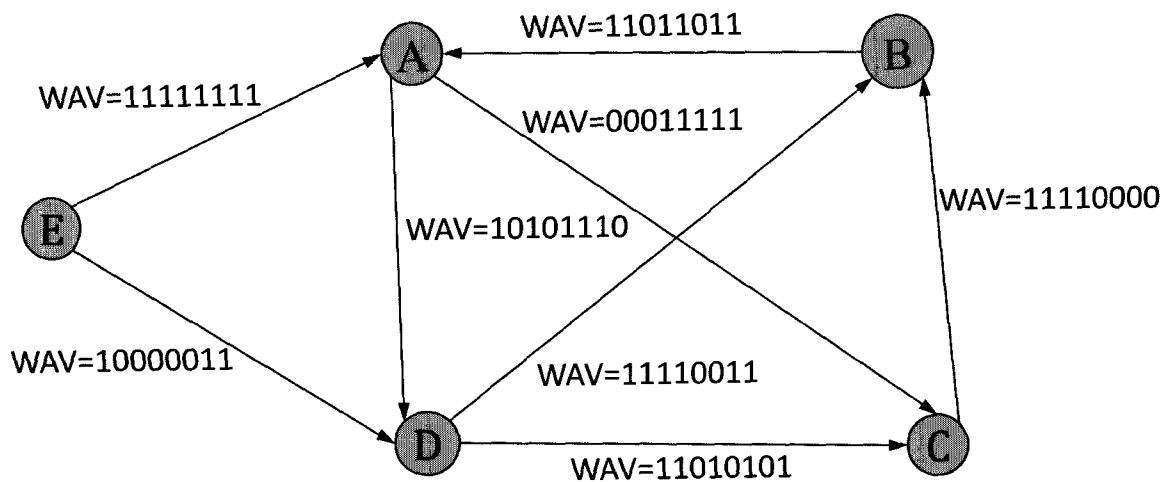


Figure 3-2 Concept of WAV

WAV is a series of bits and the length of this series represents the number of wavelength, 1 or 0 of each bit position represents the availability of the corresponding wavelength: 1 means that the corresponding wavelength is available, while 0 means that the corresponding wavelength has been occupied. For example, if the WAV attribute on one link is 11001100, this means that this link has eight wavelengths and only four of them are available.

Besides WAV, another important parameter that is implemented in our inter-domain routing algorithm is ENAW. ENAW stands for Effective Number of Available Wavelengths. The idea of ENAW was first introduced in [YANN09] to overcome the wavelength utilization

problem of OBGP. With ENAW, OBGP+ protocol can perform load balancing. The following figure shows an optical network with ENAW attribute on some links:

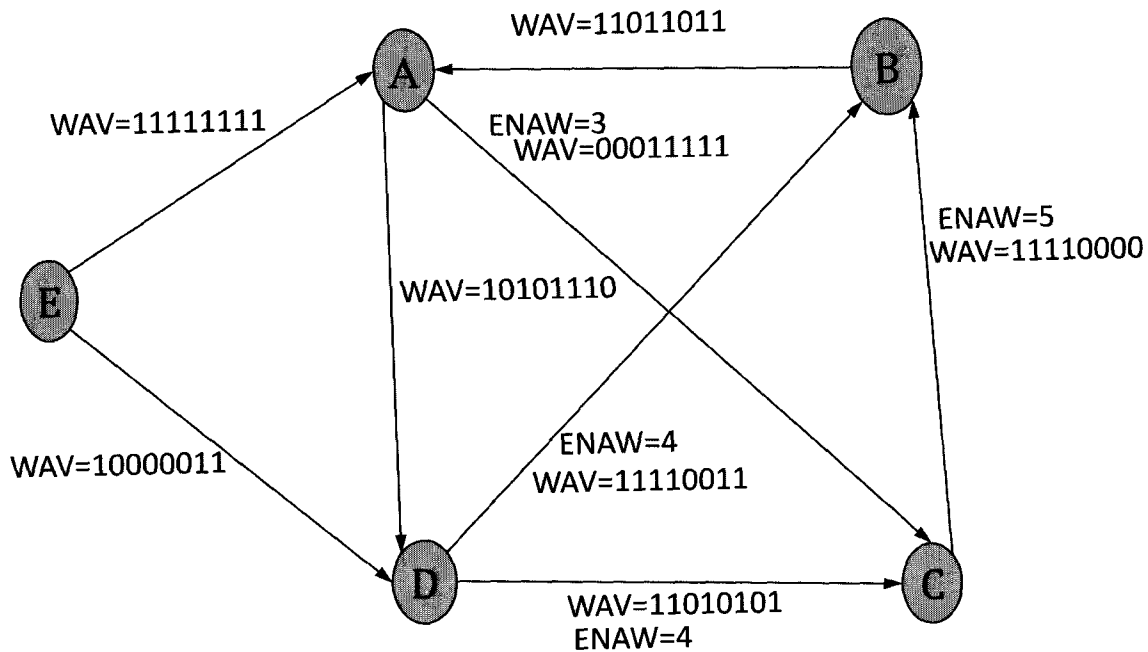


Figure 3-3 Concept of ENAW

ENAW is associated with WAV; if the WAV on one link is 11000011 and the ENAW on the same link is 4, this means that every available wavelength on this link has an effective number of 4. This effective number represents how many times the corresponding wavelength can be used before its availability vector goes to zero. The effective number can be different for every wavelength on the same link, but to simplify the simulation complexity, in our simulation, we assume that all the wavelengths on the same link have the same effective number.

With ENAW, the OBGP+ protocol proposed in [YANN09] can perform load balancing in inter-domain routing, but it still has drawbacks. For instance, OBGP+ selects the best AS path based on the calculated ENAW value. Thus, it may not select the least hop AS path and it may select an AS path with many hops on it, which is not desirable. To reduce the impact

of this potential problem, we add a hop-limit parameter to control the total number of hops on the selected AS path.

Besides adding hop-limit parameter, AS path selection strategy is also modified to select the best AS path; in OBG, the best AS path is selected by choosing the least hop AS path. In OBG+, the best AS path is selected by choosing the highest ENAW AS path. However, both of these two protocols do not consider the delay attribute in the selection of best AS path. Taking the delay attribute into AS path selection strategy is preferable because it may result in less set-up time. The following figures show the results of using three different inter-domain routing algorithms to select best AS path. The hop-limit parameter has been set to 4 in the following figures:

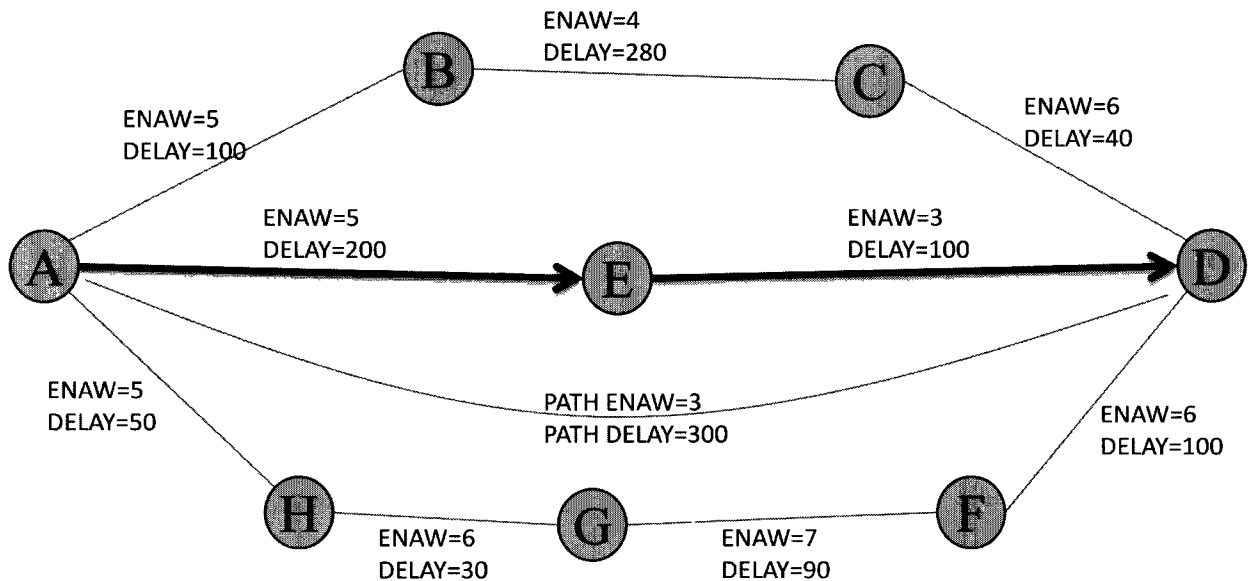


Figure 3-4 Best AS path selected by OBG

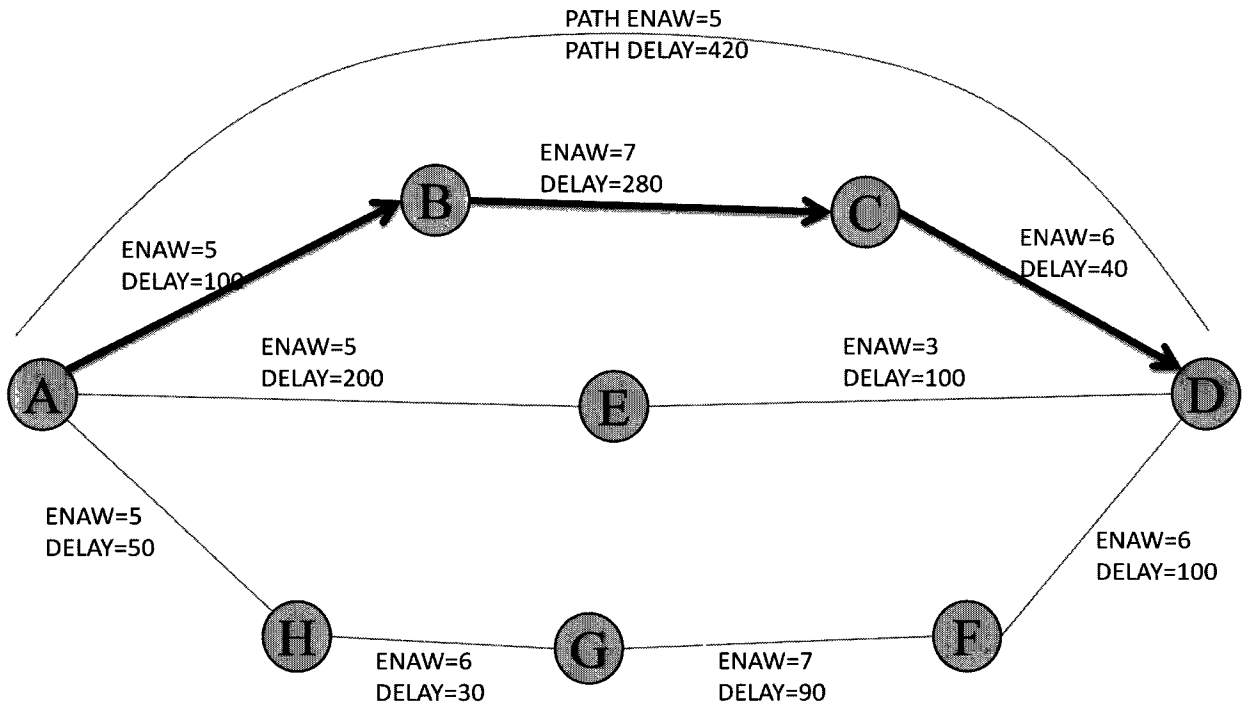


Figure 3-5 Best AS path selected by OBG+

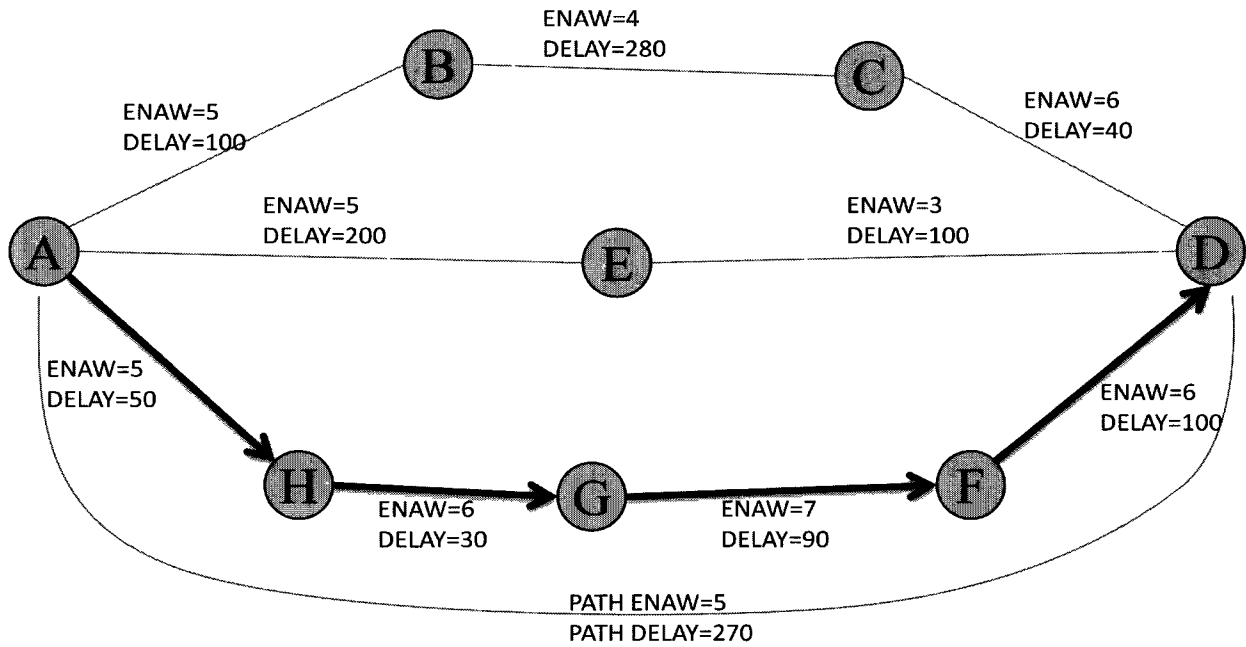


Figure 3-6 Best AS path selected by proposed inter-domain routing algorithm

Compared with OBGp and OBGp+, the inter-domain routing algorithm proposed herein would select the AS path with the least delay instead of the least hop AS path. The benefit of making this selection is that it can reduce the connection establishment time. Figure 3-7 proposes the inter-domain routing algorithm:

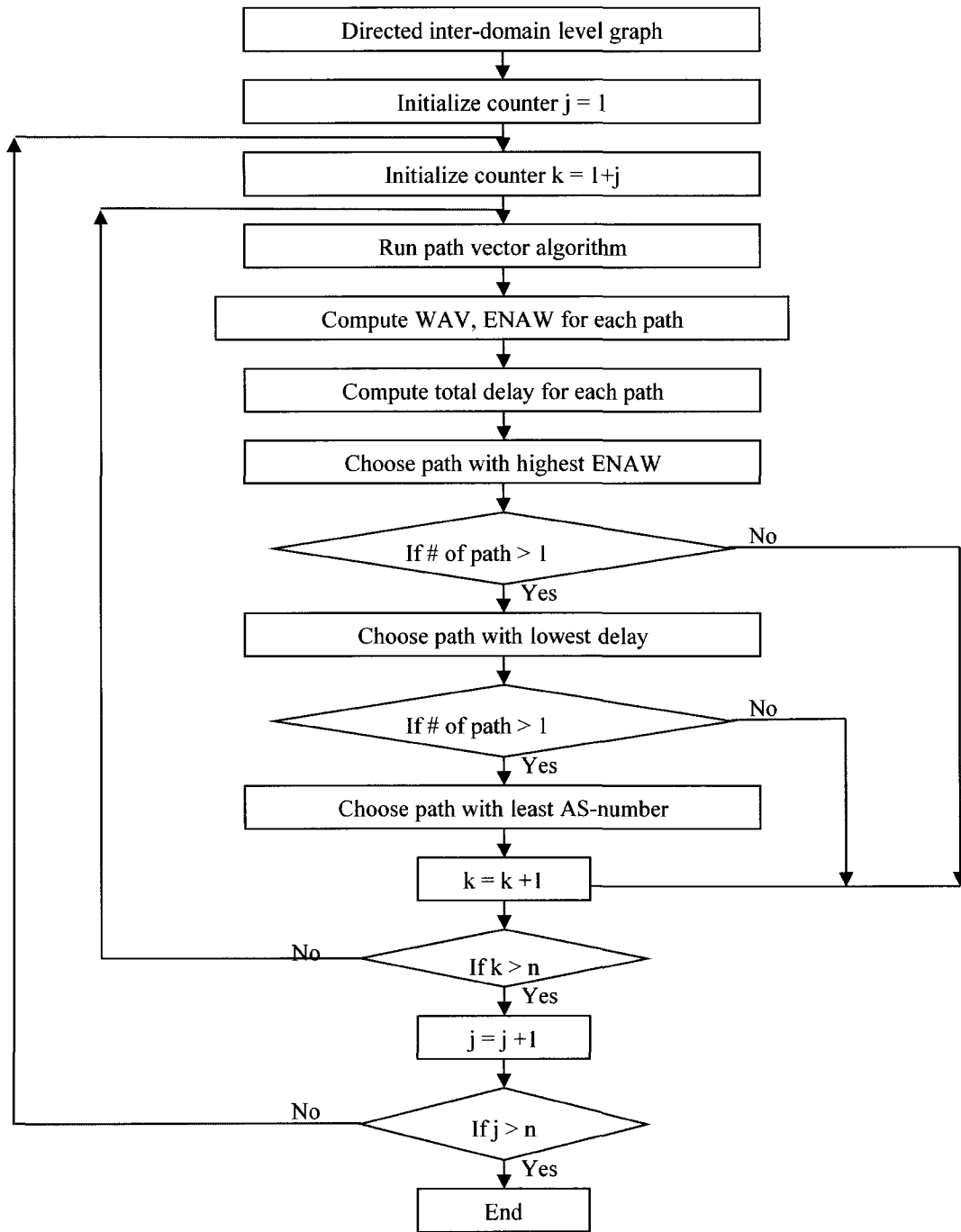


Figure 3-7 Flowchart of proposed inter-domain routing algorithm

3.3: Topology Aggregation Scheme

Topology aggregation is a way to create an abstract network, as it selects some nodes in a given domain to represent the whole. Since the scale of networks is becoming larger, it is impossible for a single node in one domain to maintain routing tables to every other node in a network with many domains. Thus, some nodes have to be chosen as representatives of each individual domain. Usually, border nodes of a single domain have been selected to represent this domain because they maintain connections with both intra-domain nodes and external domain nodes. The following figure is an example of using border nodes to represent a single domain:

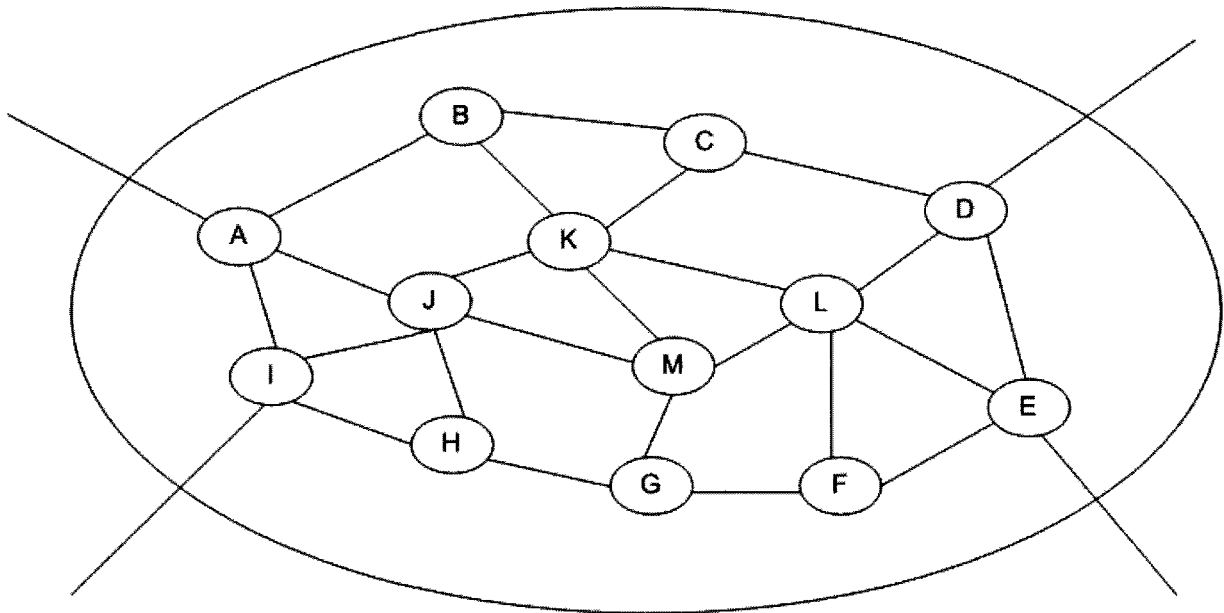


Figure 3-8 Using border nodes to represent a domain

In Figure 3-8, every letter in a circle represents a single node inside a domain. Node A, D, E and I are border nodes and these four border nodes are used to represent a domain in a multi-domain network environment. In other words, all the nodes that locate outside of this domain only see these four border nodes instead of all the nodes inside this domain.

Using border nodes to represent a single domain requires additional research to determine how to make the connections between border nodes abstract. The fully-mesh aggregation

scheme is used because it can provide every border node with the highest connectivity in relation to all other border nodes. The benefit of high connectivity is that it can provide sufficient backup paths when resources on the primary path are unable to meet the demands, which enhances the survivability of the network. The following figure provides an illustration of the fully-mesh topology aggregation scheme (A B C D and E are border nodes):

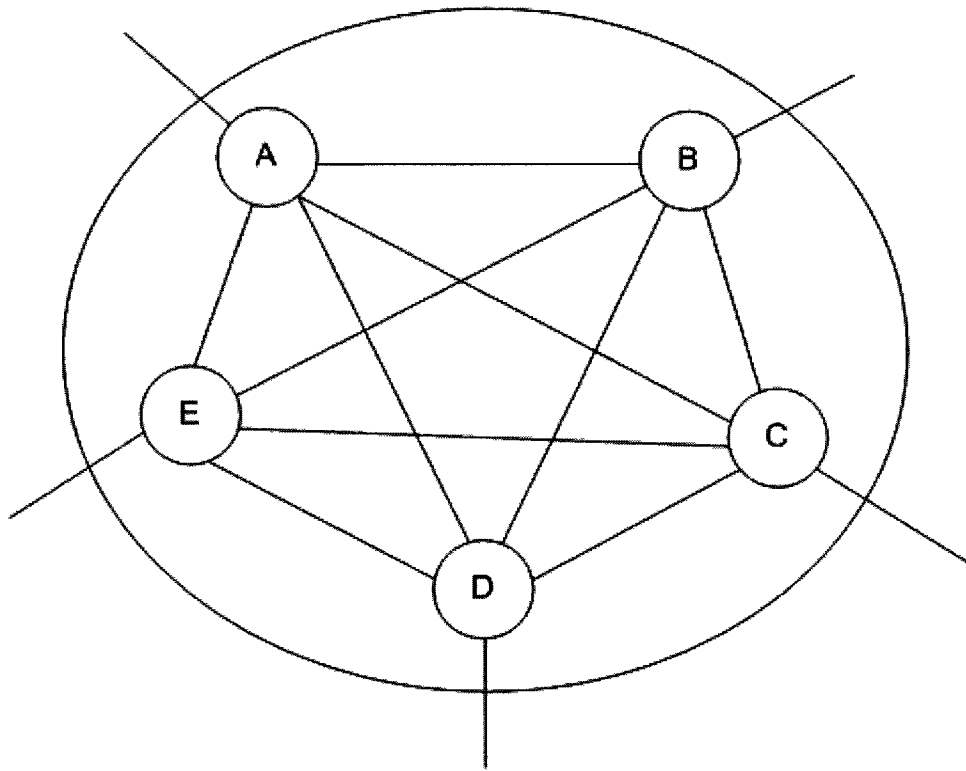


Figure 3-9 Fully-mesh topology aggregation

Although the fully-mesh topology aggregation scheme can provide each border node with the highest connectivity, its complexity in maintaining the state for a domain is very high. If the number of border nodes in a domain is N , the complexity of maintaining state of this domain is $O(|N| * |N - 1|)$, which could be very high when N is large. To overcome this problem, a ring-based topology aggregation scheme is proposed herein. The following figure shows ring-based topology aggregation scheme:

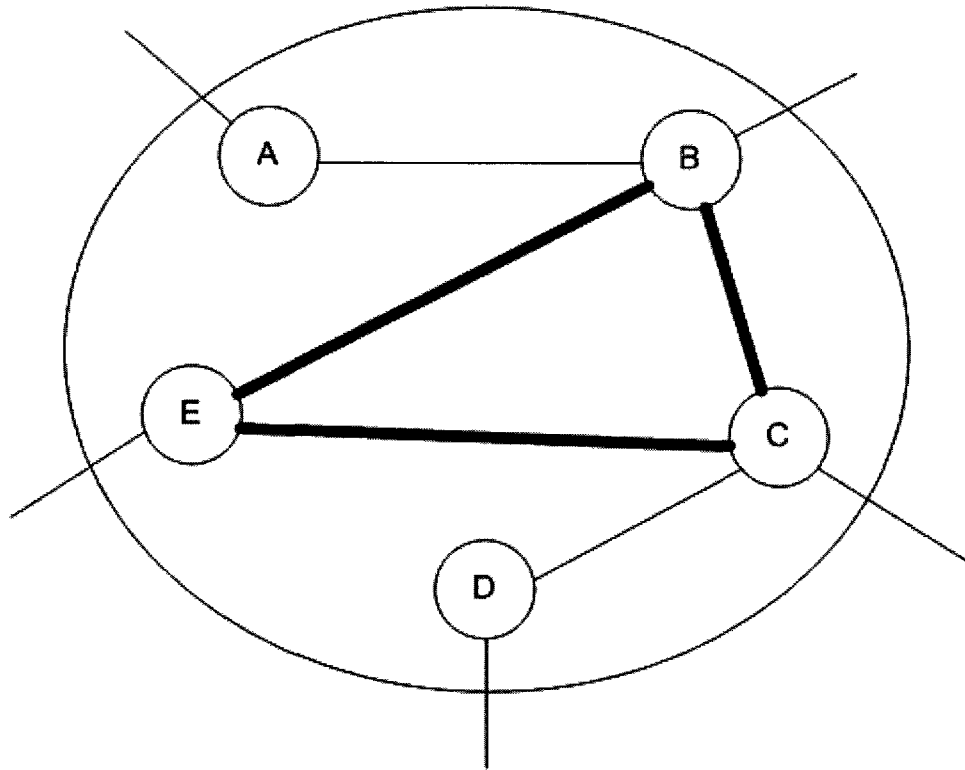


Figure 3-10 Ring-based topology aggregation

In Figure 3-10, border nodes B, C and E are used to form a ring and border nodes A and D are only directly connected to one of the three on-ring border nodes. By utilizing a ring-based topology aggregation scheme, the complexity of maintaining a domain state with N border nodes has been reduced to $O(2|N|)$, which is very low compared with $O(|N|*|N-1|)$ when N is large.

However, since the proposed ring-based topology aggregation scheme has less connectivity than the fully-mesh topology aggregation scheme, it is less robust. To raise the robustness of the proposed topology aggregation scheme, the assumption has been made herein that all the resources on the ring that traverses all the border nodes are pre-configured and pre-allocated for inter-domain traffic. This assumption is realistic since the costs of deploying fibres and wavelengths are considerably less in today's technology industries than they were in years past.

3.4: Intra-domain Routing Algorithm

After addressing the topology aggregation issue, intra-domain routing algorithm has to be specified to calculate optimal paths between each pair of border nodes. The intra-domain routing algorithm used in this control architecture is based on Dijkstra's shortest path routing algorithm. Other than path vector algorithm, Dijkstra's shortest path algorithm is a link state routing algorithm. Figure 3-11 shows an example of running Dijkstra's algorithm in a network:

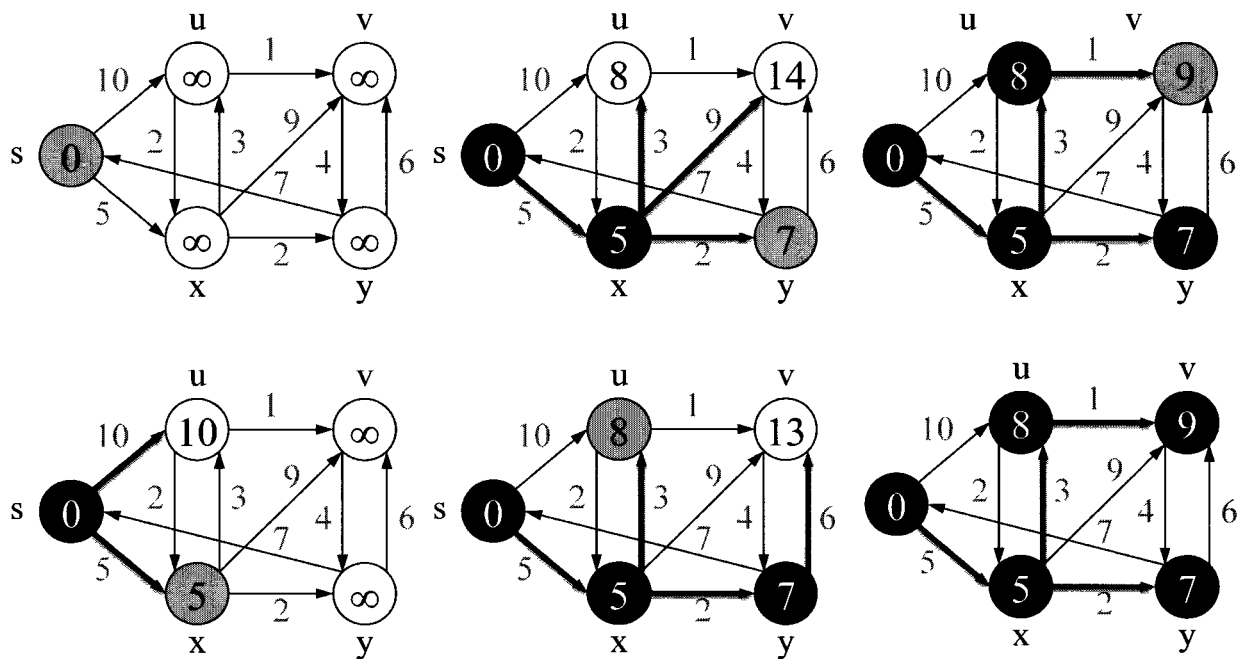


Figure 3-11 Dijkstra's shortest path algorithm

In Figure 3-11, numbers on the arrowed links are link attributes and numbers in circles indicate distances from that node to source node. From left up to right bottom, six small figures show the operation of Dijkstra's shortest path algorithm. First, the shortest distance from source node to other nodes is five and node x is the next hop. Thus, node x is marked black to indicate that it was already checked. This procedure is repeated on every node until all the nodes are marked black. When all the nodes are marked black, the algorithm is done and all the nodes know the distance from itself to source node.

In the above illustrated algorithm, all the destination nodes know only the distance to the source node. Compared with a path vector algorithm, this feature makes the link state algorithm less scalable. For example, incoming nodes to the network have to know all the network topology information in order to calculate the routing table to every other node. However, the benefit of this feature is that it has a lower routing complexity than a path vector algorithm. In the control architecture proposed herein, the link state algorithm is used as the base intra-domain routing algorithm because the topology and traffic information are transparent in each domain. In other words, all the nodes in a domain are fully visible to the whole domain topology and traffic information. Figure 3-12 illustrates the result of implementing the proposed intra-domain routing algorithm to find primary and backup paths in a single domain:

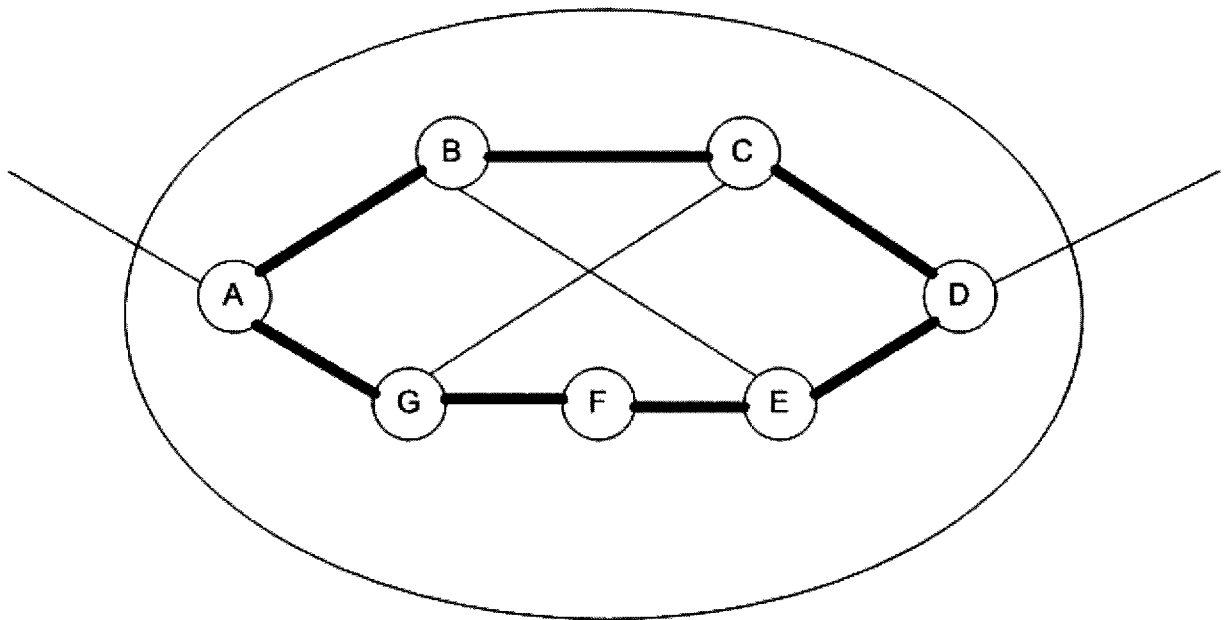


Figure 3-12 Intra-domain routing algorithm

In Figure 3-12, A and D are border nodes. Illustration of proposed intra-domain routing algorithm is as follows:

- As displayed, the k edge disjoint shortest path algorithm is performed for finding k paths between each pair of border nodes. This algorithm is based on Dijkstra's

shortest path algorithm and still belongs to the link state algorithm. In Figure 3-12, k is set to 2 for simplicity. In the simulation, k is set to 3 to provide higher connectivity.

- The link cost that is used in the calculation of k shortest paths is delay, and both of the WAV and ENAW parameters are still calculated for inter-domain routing purposes.
- To realise survivability, all the resources on the calculated paths are assumed to be pre-configured and pre-allocated to meet the requirements of inter-domain demands.

Figure 3-13 is the operation flowchart of the proposed intra-domain routing algorithm:

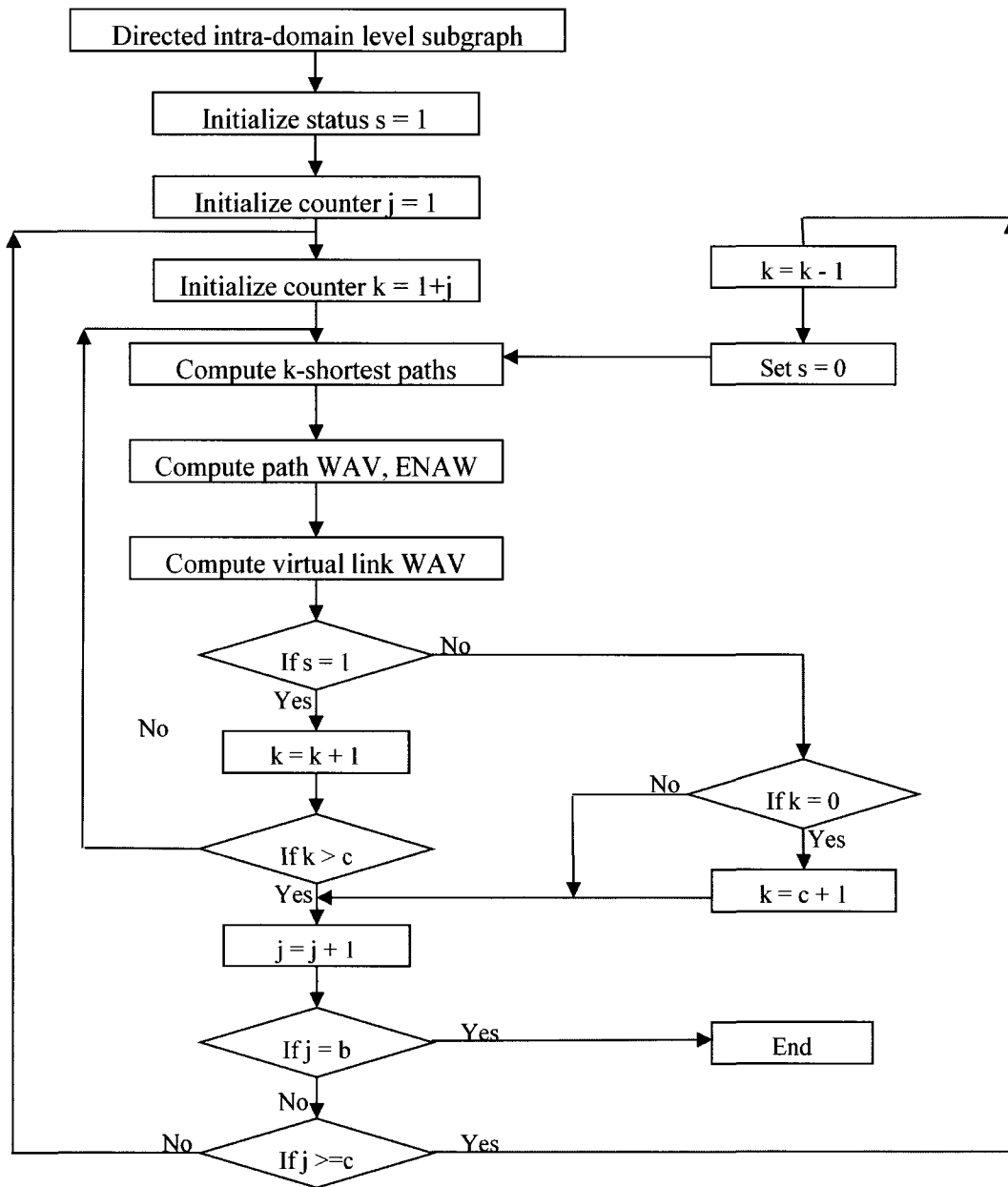


Figure 3-13 Flowchart of proposed intra-domain routing algorithm

3.5: Modified RSVP-TE Signalling Protocol

Besides inter-domain and intra-domain routing, design of signalling protocol is another challenge. In today's technology industry, RSVP-TE signalling protocol has been widely adapted. Figure 3-14 demonstrates the operation process of RSVP-TE protocol:

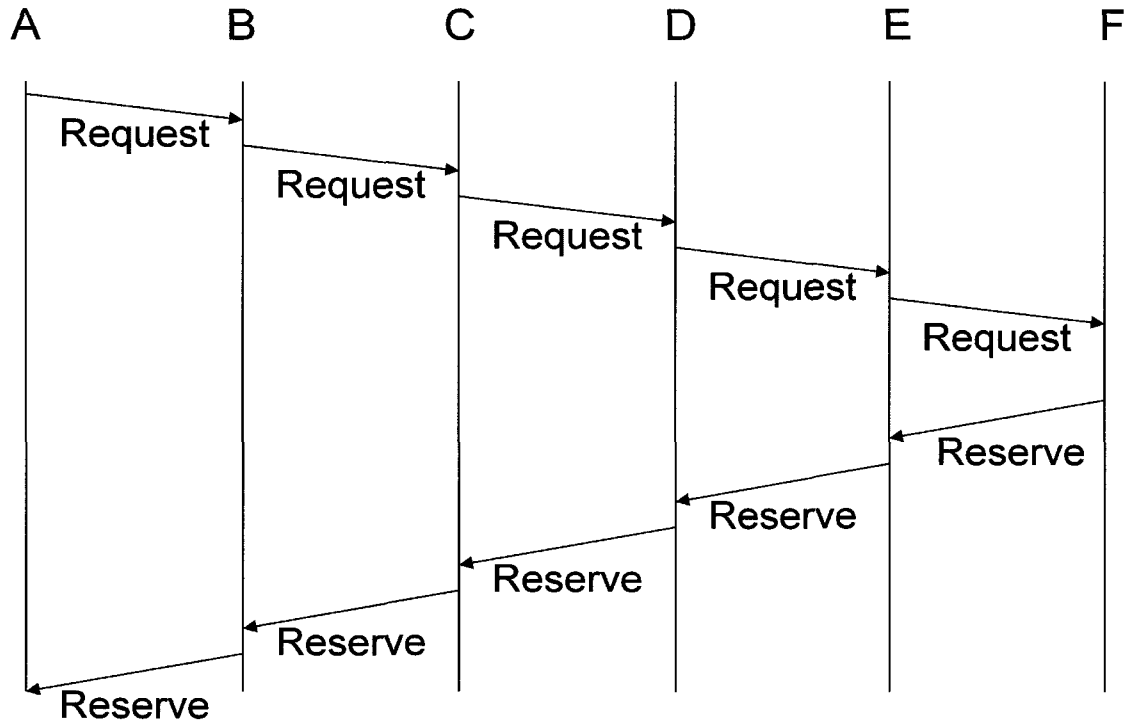


Figure 3-14 RSVP-TE two-phase protocol

In Figure 3-14, $A, B, C, D, E,$ and F represent six different domains; A is the source domain and initializes the connection setup request. F is the destination domain. The path $A-B-C-D-E-F$ is selected as the best AS path based on the previous proposed inter-domain routing algorithm. $L_{i,j}$ is used to represent the transmission delay between domain i and domain j , P_i is used to represent the processing delay inside domain i and R_i means the reservation delay when domain i is performing resource reservation function.

The working process of RSVP-TE can be summarized as follows:

- 1) The source domain sends a connection request to the next domain that is on the selected AS path. In Figure 3-14, source domain A sends a setup request to next domain B .

- 2) After receiving the connection request, domain *B* spends time processing this request. This processing delay is composed of several parts, including intra-domain transmission delay and message header modification.
- 3) After finishing processing the received request from domain *A*, domain *B* has modified the header of the received message and forwards this request message to next domain, domain *C*.
- 4) Domain *C* operates the same functions as domain *B* and forwards the received message to next domain. Steps 2, 3 and 4 are repeated until the destination domain receives the connection setup request from its previous domain.
- 5) When the destination domain receives the request message, it performs the same processing functions as intermediate domains and sends back a reserve message to the previous domain.
- 6) Every intermediate domain reserves intra-domain resources and sends back a reserve message to its previous domain.
- 7) Finally, when the source domain receives the reserve message, the signalling is done and the selected path can be used to transmit the control messages.

Based on the working steps of RSVP-TE protocol, the total signalling delay $D_{A,F}$ can be calculated as follows:

$$D_{A,F} = 2 * (L_{A,B} + P_B + L_{B,C} + P_C + L_{C,D} + P_D + L_{D,E} + P_E + L_{E,F} + P_F) + R_B + R_C + R_D + R_E + R_F \quad (3.1)$$

By carefully analyzing the working process of RSVP-TE, an important observation has been made; during the forwarding time for modifying the request message, the intermediate domain does nothing but waiting for the reserve message. This waiting time can be utilized by modifying RSVP-TE protocol. Figure 3-15 demonstrates the operation process of the proposed modified RSVP-TE protocol:

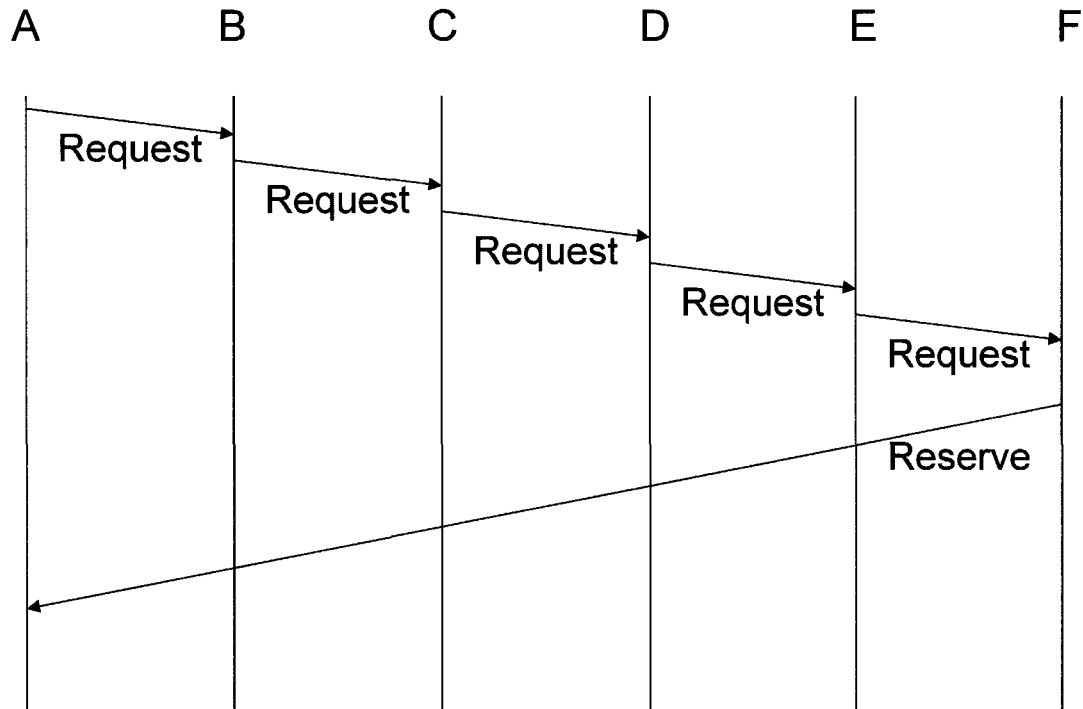


Figure 3-15 Modified RSVP-TE

In Figure 3-15, the notations and assumptions are the same as in figure 3-14; $A, B, C, D, E,$ and F represent six different domains; A is the source domain and initializes the connection setup request; F is destination domain; the path $A - B - C - D - E - F$ is selected as the best AS path based on the previous proposed inter-domain routing algorithm; and $L_{i,j}$ is used to represent the transmission delay between domain i and domain j , and P_i is used to represent the processing time inside domain i .

The working process of modified RSVP-TE can be summarized as following:

- 1) The source domain sends a connection setup request message to the next domain on the selected AS path.
- 2) After receiving the request message, the intermediate domain spends time processing the request and modifying the header of the request message. This step is the same as illustrated in Figure 3-14.

- 3) When finished processing the request, the intermediate domain forwards the modified request message to the next domain on the selected AS path. Meanwhile, the intermediate domain reserves required intra-domain resources and waiting for the reservation message from downstream domain.
- 4) When the source domain receives the reservation message from the destination domain, the connection establishment is done and the calculated path can be used to transmit the control messages.

Based on the above steps, the total signalling delay $D_{A,F}$ can be computed as following:

$$D_{A,F} = 2*(L_{A,B} + L_{B,C} + L_{C,D} + L_{D,E} + L_{E,F} + P_B + P_C + P_D + P_F) \quad (3.2)$$

Based on (3.1) and (3.2), it is clear that proposed modified RSVP-TE can shorten the signalling time by utilizing the waiting time. The total signalling delay can be reduced by $(R_B + R_C + R_D + R_F)$. While reservation delay in a single domain is high, the total signalling time could be significant and the proposed modifications to RSVP-TE can be more efficient than the standard RSVP-TE model.

In consideration of the proposed methodology above, Figure 3-16 shows the working flowchart of source domain. m in the chart represents the number of AS hops on the selected path, while Figure 3-17 shows the flowchart of intermediate domains, and Figure 3-18 shows the flowchart of destination domain:

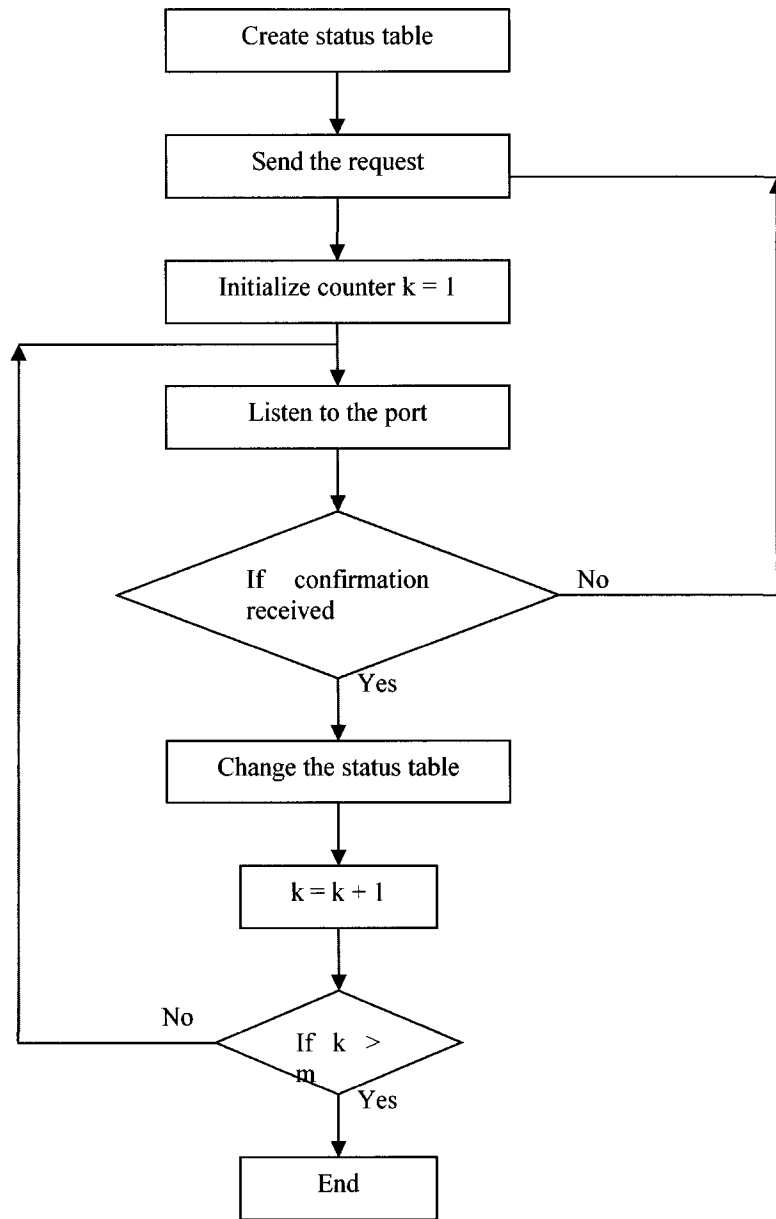


Figure 3-16 Flowchart of source domain

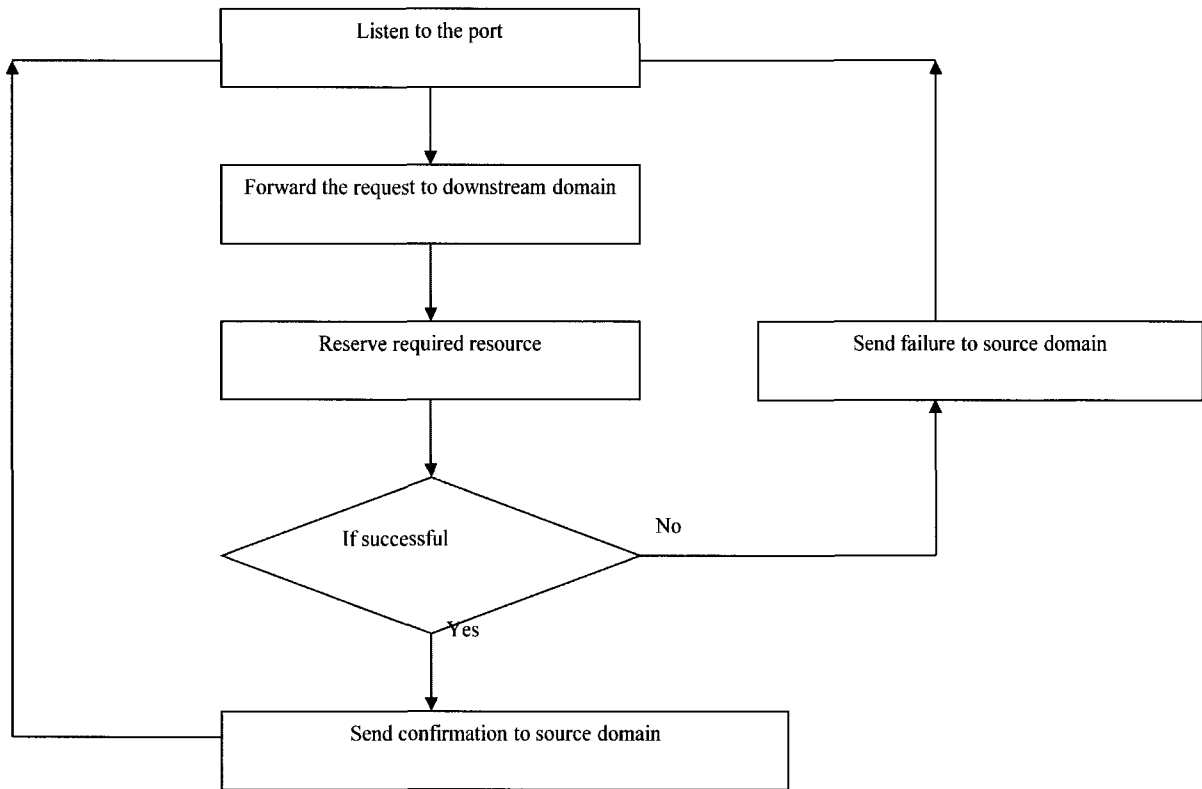


Figure 3-17 Flowchart of intermediate domains

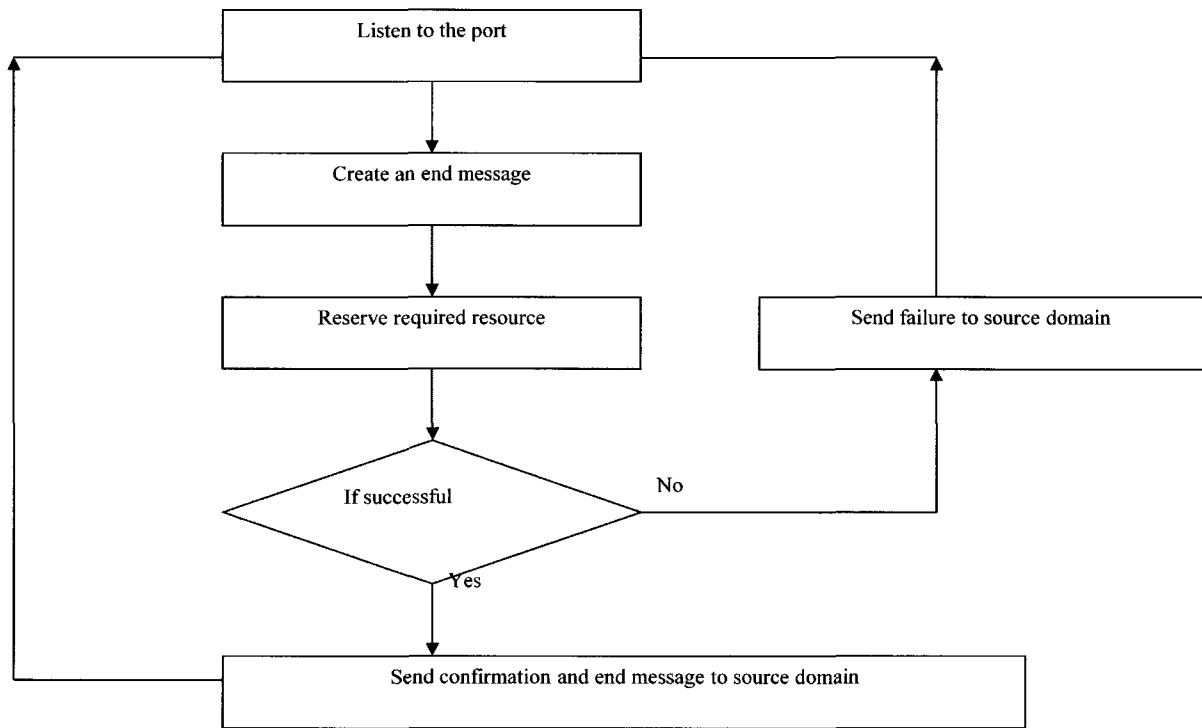


Figure 3-18 Flowchart of destination domain

3.6: Summary

In this chapter, the design considerations and objectives of all the components of the proposed control architecture was discussed in detail. On the whole, control architecture deals with four design challenges: inter-domain routing, intra-domain routing, topology aggregation, and signalling.

The proposed inter-domain routing algorithm brings in hop-limit parameter and, when making path selection, takes into consideration the delay attribute. These two features solve the hop number problem in OBGp+ and allow for the creation of the signalling protocol proposed herein.

Ring-based topology aggregation scheme has less state-maintaining complexity than fully-mesh topology aggregations scheme. However, since the proposed TA scheme holds less connectivity, the survivability issue has to be further considered. In [CHAM09a], the authors presented the possibility of pre-configuring and pre-allocating resources for the purpose of inter-domain traffic. This assumption has been utilized in the proposed control architecture and it has been assumed that all the resources for inter-domain traffic inside one domain are pre-configured and pre-allocated. This assumption could enhance the robustness of the proposed system.

The intra-domain routing algorithm utilizes the k edge disjoint shortest path algorithm and calculates the three shortest delay paths between each pair of border nodes. The improvement made to this algorithm is the intra-domain path selection strategy. By calculating path WAV and ENAW as well as total delay, intra-domain paths are made suitable for inter-domain traffic usage.

Finally, the modified RSVP-TE protocol has been theoretically proven to shorten the signalling delay compared with RSVP-TE protocol. However, the down-side to this compromise is that the source domain may have more responsibilities in processing received messages.

In the next chapter, simulation configurations are discussed with detailed commentary, and simulation results are presented. The analysis and comparison of the results are also provided in the next chapter.

Chapter 4 PERFORMANCE EVALUATION

4.1: Introduction

In this chapter, issues regarding simulation objectives and configuration are introduced. To evaluate the performance of the proposed control architecture, intensive simulations have been undertaken. First, simulations were conducted to prove that the proposed inter-domain routing and path selection strategy was able to solve the drawbacks presented by OBGp+. Secondly, the use of a ring-based topology aggregation scheme, as outlined in the previous chapter, was used as it lowers the complexity of maintaining the state of a single domain. It is the aim of this chapter to prove that a ring-based topology aggregation scheme can still perform well in relation to blocking probability. Finally, the total estimated delay was utilized in this simulation to measure the improvement that the proposed modified RSVP-TE protocol had made.

The simulation process is made up of 3 parts:

- 1) *Inter-domain path calculation and selection.*** After the simulation had begun, a proposed inter-domain routing algorithm was run when a request came to the network. Then, among these calculated inter-domain paths, the proposed inter-domain path selection strategy was performed to select the best AS path.
- 2) *Intra-domain routing strategy.*** The k shortest path algorithm discussed in [EPPS99] was conducted to calculate three intra-domain paths between each pair of border nodes. However, the intra-domain path selection strategy differs with different topology aggregation schemes. With fully-mesh topology aggregation, every border node knows the three shortest intra-domain paths to all the other border nodes. In

this case, if a pair of border nodes was chosen to carry inter-domain traffic, they were able to directly select the best intra-domain path among three calculated paths. In contrast, with the ring-based topology aggregation, only three border nodes that form a ring had direct connections between one another. In this case, if the selected pair of border nodes was on the ring, they were able to select the most direct intra-domain path among three calculated paths. If the selected pair of border nodes was not on the ring, they have to traverse at least one on-ring border node to make an indirect connection. The best intra-domain path was established by identifying the best paths among all the involved border nodes, either on-ring or off-ring.

- 3) ***Blocking probability and estimated signalling delay.*** Blocking probability was used to measure the performances of the proposed inter-domain routing algorithm and ring-based topology aggregation scheme. According to [CHUN93] [JUNG02] [SRID04] [SHIM10], blocking is calculated when there are no available wavelengths on an on-path link. In this simulation the wavelength convertibility of every node was assumed, thus, the wavelength continuity constraint was relaxed. The total estimated signalling delay of a selected path was computed based on the estimated transmission delay of a link; it consisted of inter-domain delay and intra-domain delay.

4.2: Specification of Simulation

4.2.1 Test Networks

All simulations were performed based on a multi-domain network environment assumption, as proposed by [DIAN06]. In this simulation two network topologies were implemented: inter-domain level network topology and intra-domain level network topology. For inter-domain level network topology, the NSF backbone network, as introduced by [CHAM09b], was utilized. For intra-domain level network topology, a network which is suitable for

measuring the performance of ring-based topology aggregations scheme is proposed.

Figures 4-1 and 4-2 show these two network topologies:

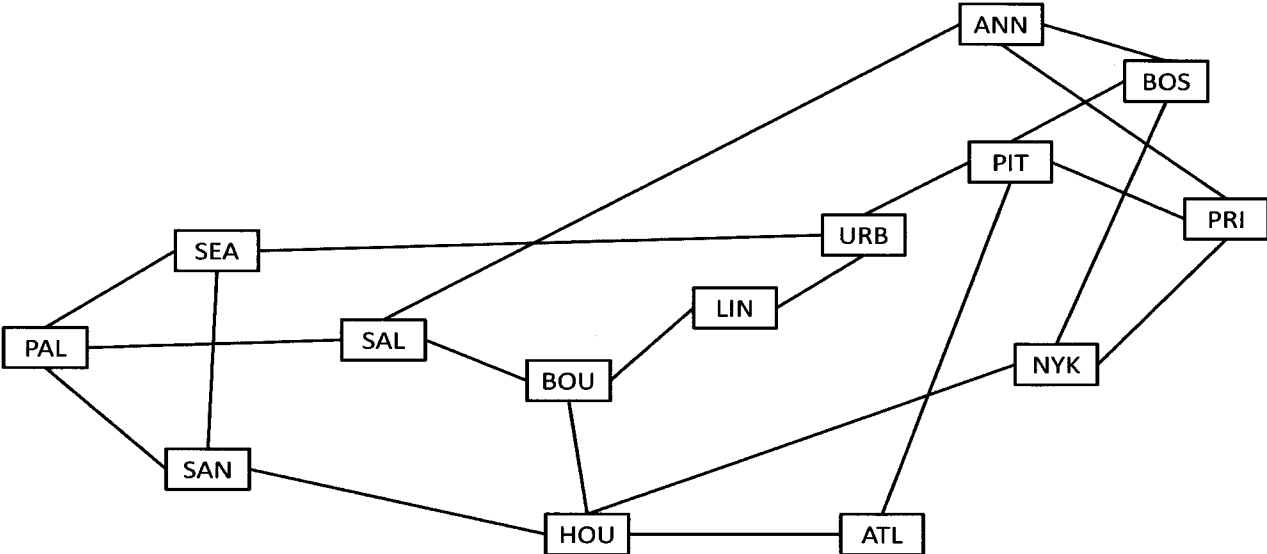


Figure 4-1 Inter-domain level network topology (NSFNET)

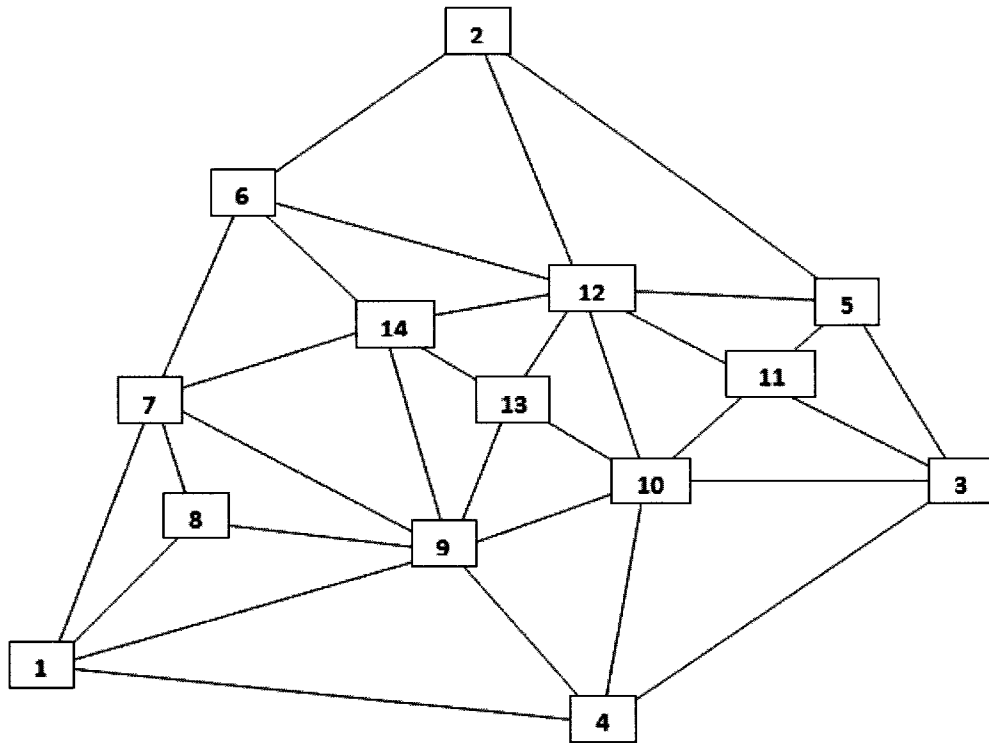


Figure 4-2 Intra-domain level network topology

In Figure 4-2, node 1, 2, 3, and 4 are pre-assigned to be border nodes. If a domain only has two border nodes, like LIN in NSFNET, then two of these pre-defined four nodes would be selected randomly as the border nodes. If a domain has three border nodes, like PAL in NSFNET, then three of these identified nodes would be randomly selected. If a domain has four border nodes, like HOU in NSFNET, then all four of these nodes would be used as border nodes.

According to [KIMB93], the estimated delay time between every two nodes is used as a link attribute in calculating optimal path. Based on this assumption, the connectivity issues of these two network topologies are illustrated in Tables 4-1 and 4-2:

	SEA	PAL	SAN	SAL	BOU	HOU	LIN	URB	PIT	ATL	ANN	BOS	PRI	NYK
SEA	0	47	70	inf	inf	inf	infi	112	inf	inf	inf	inf	inf	inf
PAL	47	0	28	35	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf
SAN	70	28	0	inf	inf	84	inf	inf	inf	inf	inf	inf	inf	inf
SAL	inf	35	inf	0	28	inf	inf	inf	inf	inf	91	inf	inf	inf
BOU	inf	inf	inf	28	0	56	35	inf	inf	inf	inf	inf	inf	inf
HOU	inf	inf	84	inf	56	0	inf	inf	inf	49	inf	inf	inf	84
LIN	inf	inf	inf	inf	35	inf	0	35	inf	inf	inf	inf	inf	inf
URB	112	inf	inf	inf	inf	inf	35	0	35	inf	inf	inf	inf	inf
PIT	inf	inf	inf	inf	inf	inf	inf	35	0	35	inf	14	14	inf
ATL	inf	inf	inf	inf	inf	49	inf	inf	35	0	inf	inf	inf	inf
ANN	inf	inf	inf	91	inf	inf	inf	inf	inf	inf	0	28	35	inf
BOS	inf	inf	inf	inf	inf	inf	inf	inf	14	inf	28	0	inf	14
PRI	inf	inf	inf	inf	inf	inf	inf	inf	14	inf	35	inf	0	7
NYK	inf	inf	inf	inf	inf	84	inf	inf	inf	inf	inf	14	7	0

Table 4-1 Connectivity in inter-domain level network topology (NSFNET)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	0	inf	inf	20	inf	inf	9	5	11	inf	inf	inf	inf	inf
2	inf	0	inf	inf	15	6	inf	inf	inf	inf	inf	8	inf	inf
3	inf	inf	0	16	3	inf	inf	inf	inf	12	9	inf	inf	inf
4	20	inf	16	0	inf	inf	inf	inf	7	11	inf	inf	inf	inf
5	inf	15	3	inf	0	inf	inf	inf	inf	inf	1	5	inf	inf
6	inf	6	inf	inf	inf	0	4	inf	inf	inf	inf	5	inf	6
7	9	inf	inf	inf	inf	4	0	3	9	inf	inf	inf	inf	4
8	5	inf	inf	inf	inf	inf	3	0	5	inf	inf	inf	inf	inf
9	11	inf	inf	7	inf	inf	9	5	0	3	inf	inf	2	7
10	inf	inf	12	11	inf	inf	inf	inf	3	0	2	4	3	inf
11	inf	inf	9	inf	1	inf	inf	inf	inf	2	0	2	inf	inf
12	inf	15	inf	inf	5	5	inf	inf	inf	4	2	0	1	4
13	inf	inf	inf	inf	inf	inf	inf	inf	2	3	inf	1	0	2
14	inf	inf	inf	inf	inf	6	4	inf	7	inf	inf	4	2	0

Table 4-2 Connectivity in intra-domain level network topology

In Tables 4-1 and 4-2, '0' means self-connected, and a number in a cell denotes the estimated transmission delay between two domains (Table 4-1) or nodes (Table 4-2) in (milliseconds). The term 'inf' in a cell means that there is no direct connection between corresponding domains (Table 4-1) or nodes (Table 4-2). For example, in Table 4-1, the corresponding number of HOU and BOU means the estimated delay is 56 milliseconds, while in Table 4-2, the corresponding term 'inf' of 1 and 2 means that there is no direct connection between node 1 and node 2.

4.2.2 Simulation Configuration

From statistics provided in Appendix B, the simulator was able to measure the proposed control architecture. To better understand the data collected from the simulation results, different combinations of simulation configuration were implemented.

In our proposed inter-domain routing algorithm, the ENAW parameter was set to 5 and the number of wavelengths was set to 8 for all of the inter-domain and intra-domain links. Although NSFNET has a diameter of three, the proposed inter-domain algorithm is able to calculate multiple inter-domain paths, thus, the diameter of the network does not affect the calculation and selection of inter-domain paths. OBGP was also implemented in this simulation in order to make a comparison between the proposed inter-domain routing algorithm and OBGP. As shown in Table 3-1, it is clear that the simulator was more stable when a large number of network requests were applied. To attain a better statistical base, 50,000 network requests were applied to the simulator. Each simulation was run five times in order to calculate the average value and the confidence interval as introduced in Appendix A. In each simulation, traffic load is in Erlang and the value is increased from 0.1 to 0.9. The following combinations were configured in order to retrieve statistics for analyzing the performances of proposed control architecture:

- The fully-mesh topology aggregation was utilized to measure the effectiveness of the hop-limit parameter on blocking probability
- OBGP and OBGP+ were implemented first and then the fully-mesh topology aggregation was utilized in order to compare the performance of proposed inter-domain routing algorithm with OBGP and OBGP+
- The hop-limit parameter was set to 3 and the topology aggregation scheme was fully-meshed to measure network utilization
- The hop-limit parameter was set to 3 to measure the fully-mesh topology aggregation
- The hop-limit parameter was set to 3 to measure the ring-based topology aggregation
- The fully-mesh topology aggregation scheme was implemented, the traffic load was set to 0.6 and the hop-limit parameter was set to 3 to measure the RSVP-TE signalling protocol

- The fully-mesh topology aggregation scheme was selected, the traffic load was set to 0.6 and the hop-limit parameter was set to 3 to measure the modified RSVP-TE signalling protocol

4.3: Results and Performance Analysis

4.3.1 Numerical results

4.3.1.1 Hop-limit parameter

In this simulation, the proposed inter-domain routing algorithm and path selection strategy was implemented and the fully-mesh topology aggregation scheme was utilized. Figure 4-3 demonstrates the changes of blocking probability with different hop-limit parameters.

Figures 4-4 and 4-5 illustrate the trends of blocking probability with different traffic load for certain hop-limit parameter:

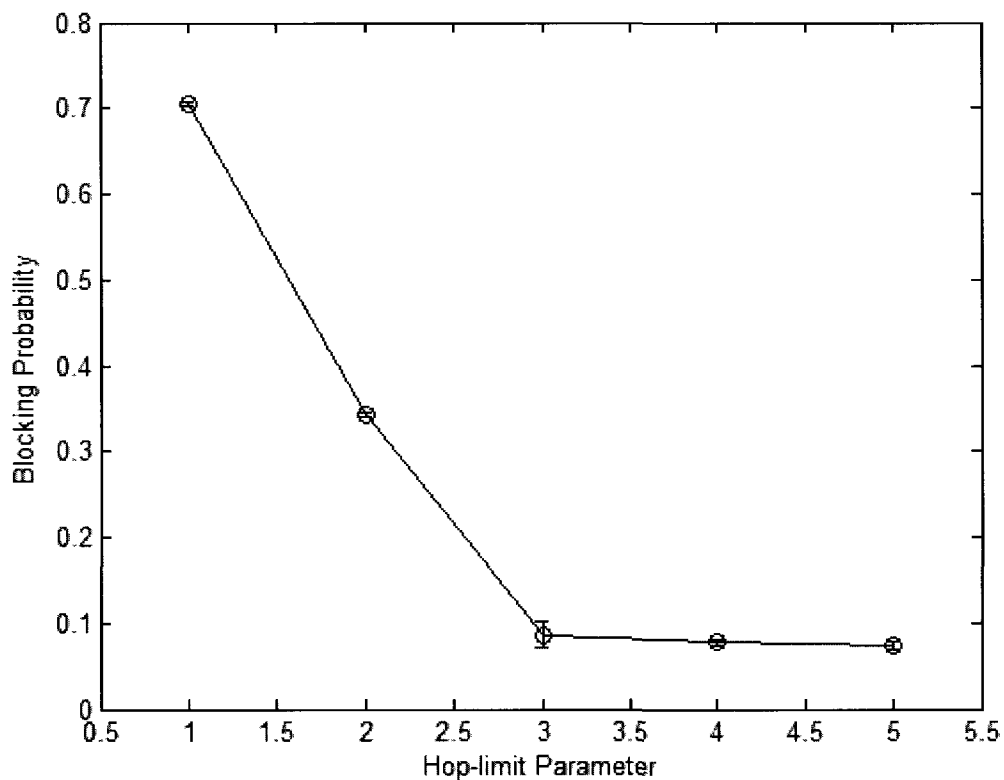


Figure 4-3 Blocking probability with hop-limit parameter

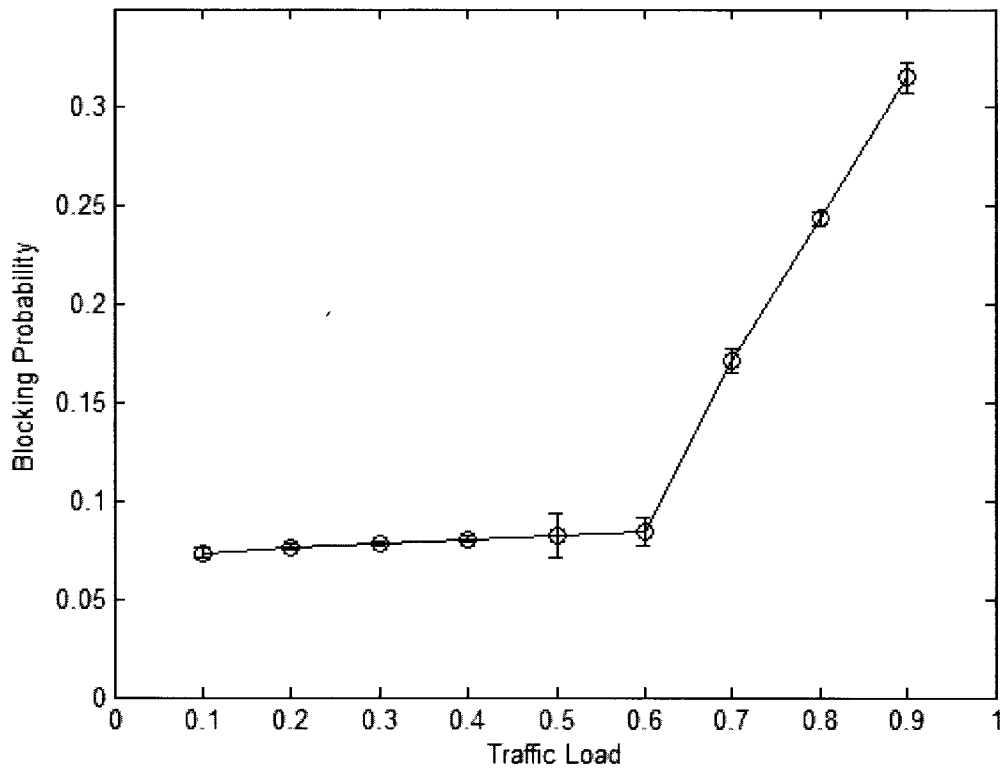


Figure 4-4 Blocking probability with different traffic load when hop-limit number is 3

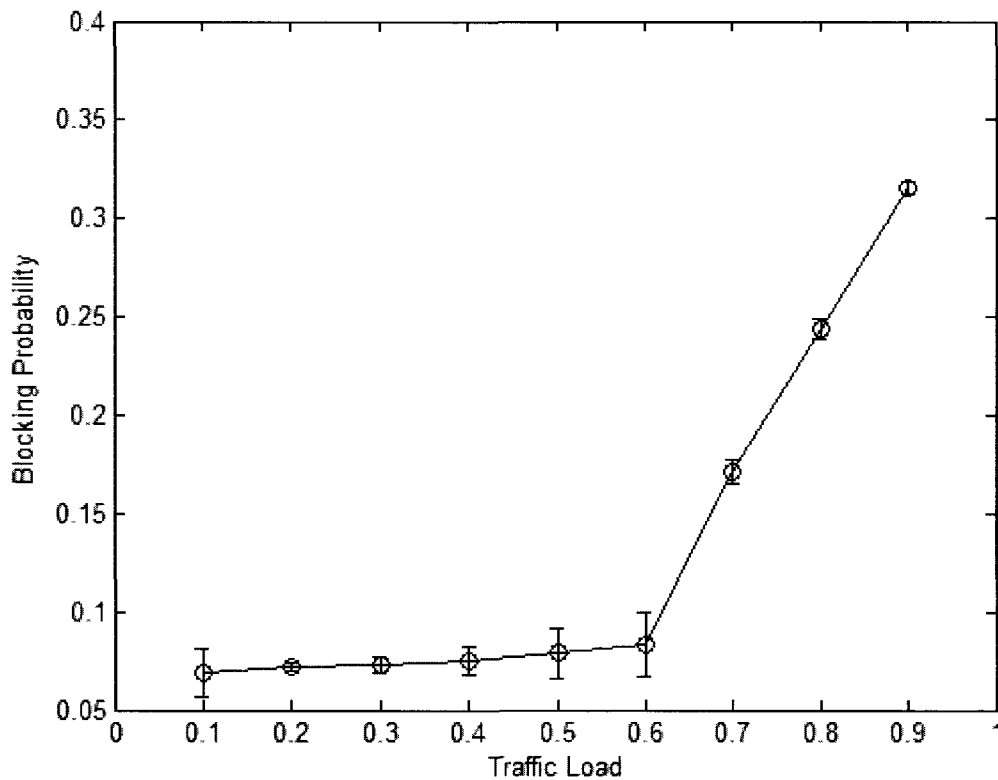


Figure 4-5 Blocking probability with different traffic load when hop-limit number is 4

In Figure 4-3, because NSFNET has a diameter of three, increasing hop-limit parameter to four or higher would have a small affection on the number of inter-domain paths that can be calculated. Although with the increasing of hop-limit parameter, the change of blocking probability is not obvious, setting hop-limit parameter to four would result in a lower blocking probability, which is preferable in comparison. Thus, in Figure 4-14 and Figure 4-15, the hop-limit parameter was set to four to make the comparison.

In Figure 4-4 and Figure 4-5, when the traffic load is 0.6, the network utilization is close to 100% (illustrated in Figure 4-10), thus, the blocking probability starts to have a sharp increase after the traffic load is higher than 0.6.

4.3.1.2 OBGP with fully-mesh topology aggregation

In this simulation, to compare proposed inter-domain routing algorithm with existing OBGP, OBGP was tested. For the intra-domain level, the fully-mesh topology aggregation scheme was utilized. Figure 4-6 demonstrates the blocking performance of OBGP with different traffic load:

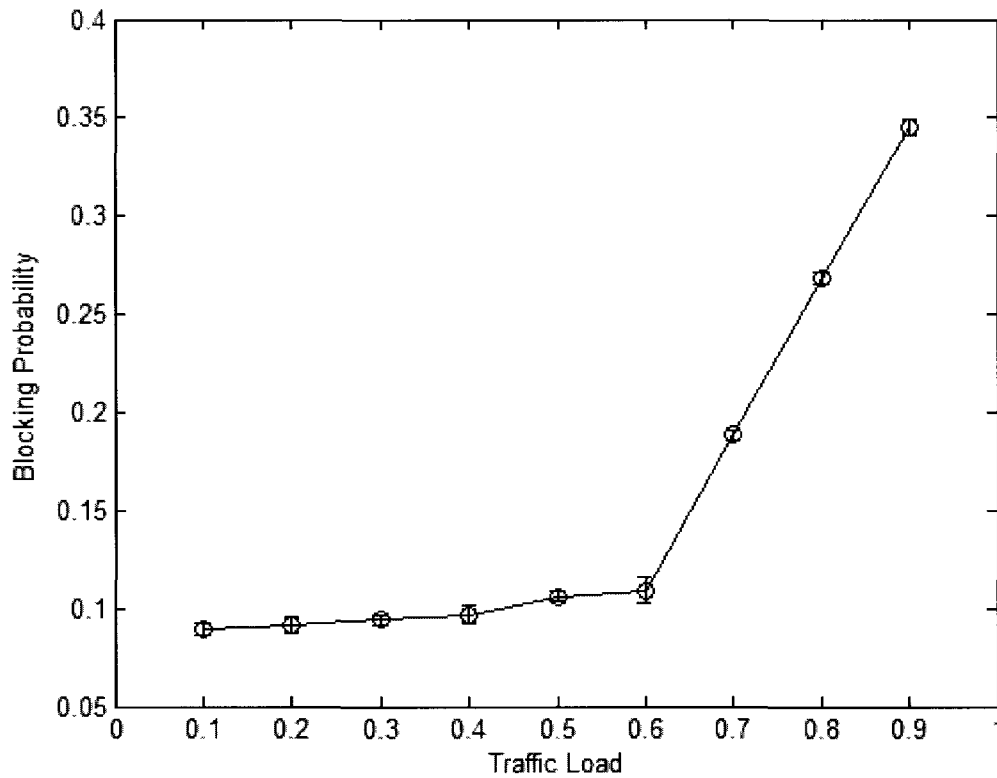


Figure 4-6 Blocking probability of OBGP with different traffic load

4.3.1.3 OBGP+ with fully-mesh topology aggregation

In this simulation, OBGP+ was used as a comparison with the proposed inter-domain routing algorithm; the fully-mesh topology aggregation scheme was implemented in the intra-domain level. Figure 4-7 shows the blocking probability of OBGP+ with different traffic load:

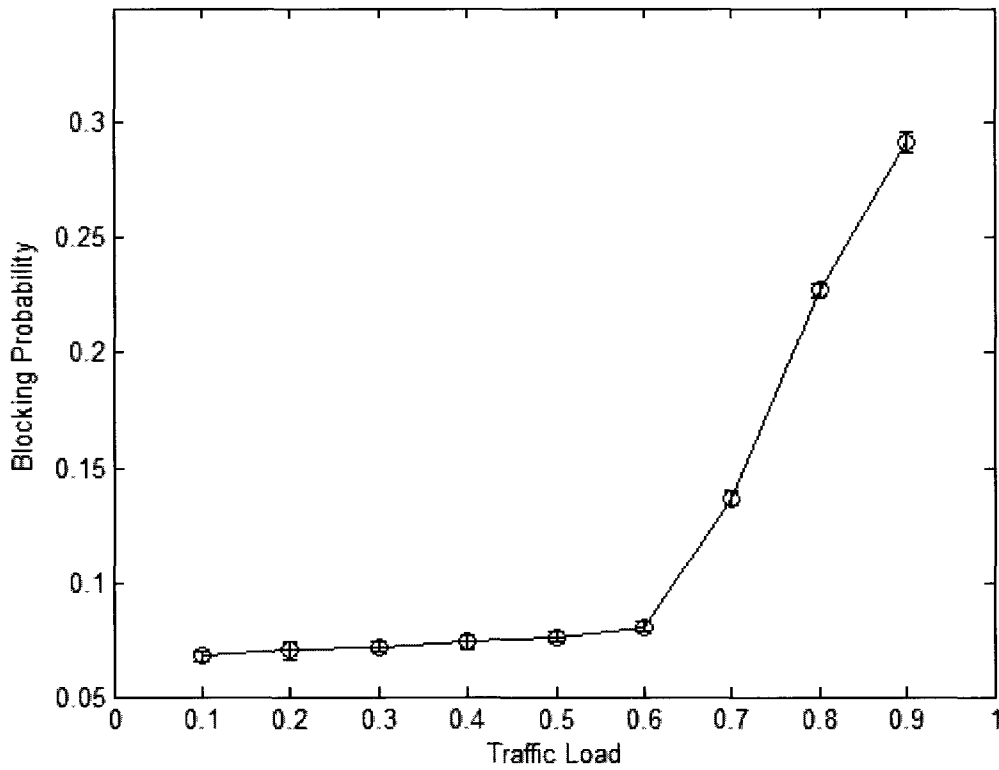


Figure 4-7 Blocking probability of OBGp+ with different traffic load

4.3.1.4 Fully-mesh topology aggregation

In this simulation, the performance of the fully-mesh topology aggregation was evaluated. As demonstrated in Figure 4-3, when the hop-limit parameter was equal to, or greater than 3, the blocking probability is less than 0.1 and the system works well. Since the diameter of the NSFNET topology is 3, the hop-limit was set to 3.

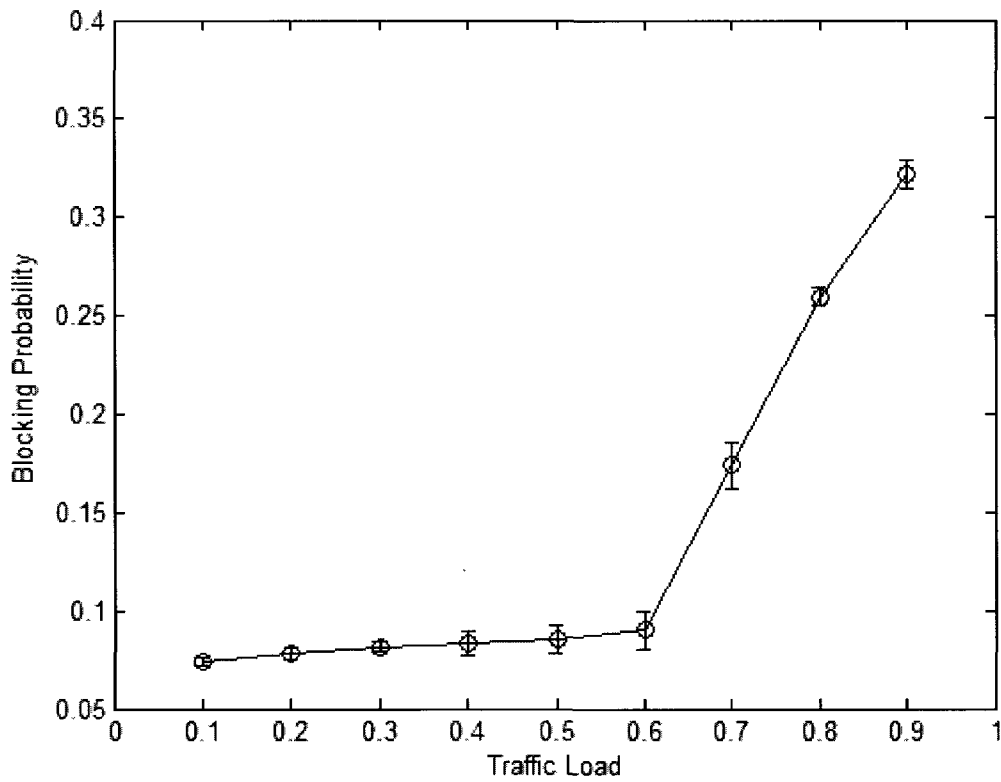


Figure 4-8 Blocking probability with different traffic load (hop-limit parameter is 3)

4.3.1.5 Ring-based topology aggregation

As discussed in 4.3.1.4, in this simulation, the hop-limit parameter was set to 3 and the performance of ring-based topology aggregation scheme was evaluated.

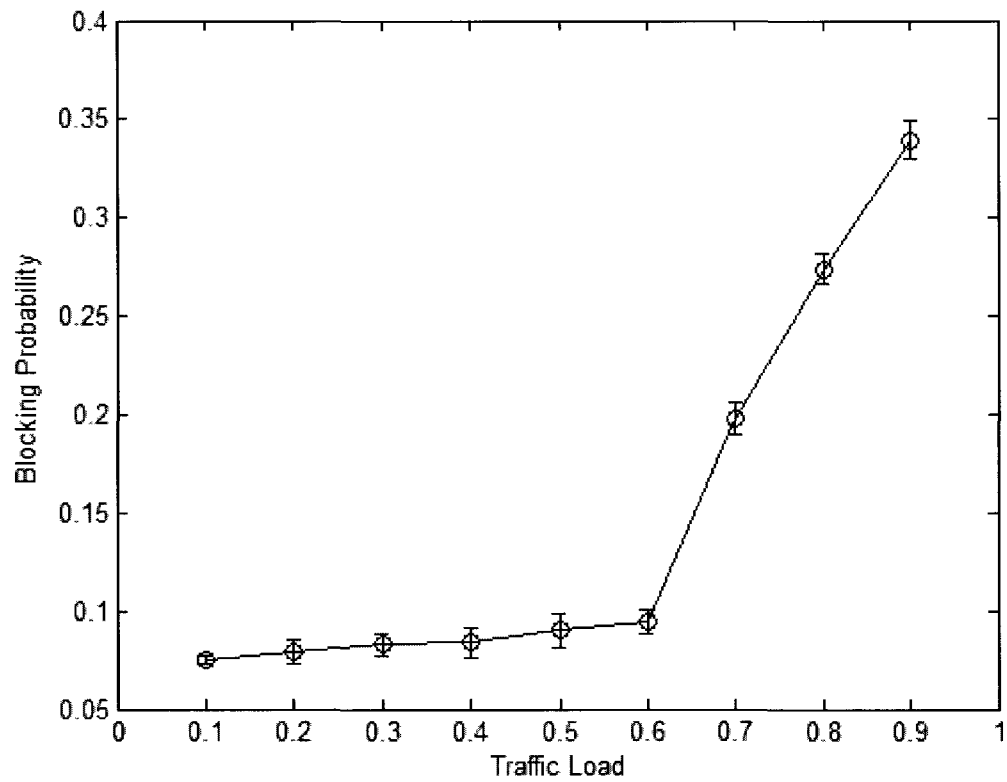


Figure 4-9 Blocking probability with different traffic load (hop-limit parameter is 3)

4.3.1.6 Network utilization

Finally, in this simulation, network utilization was tested under the configuration of fully-mesh topology aggregation and the hop-limit parameter was equal to 3.

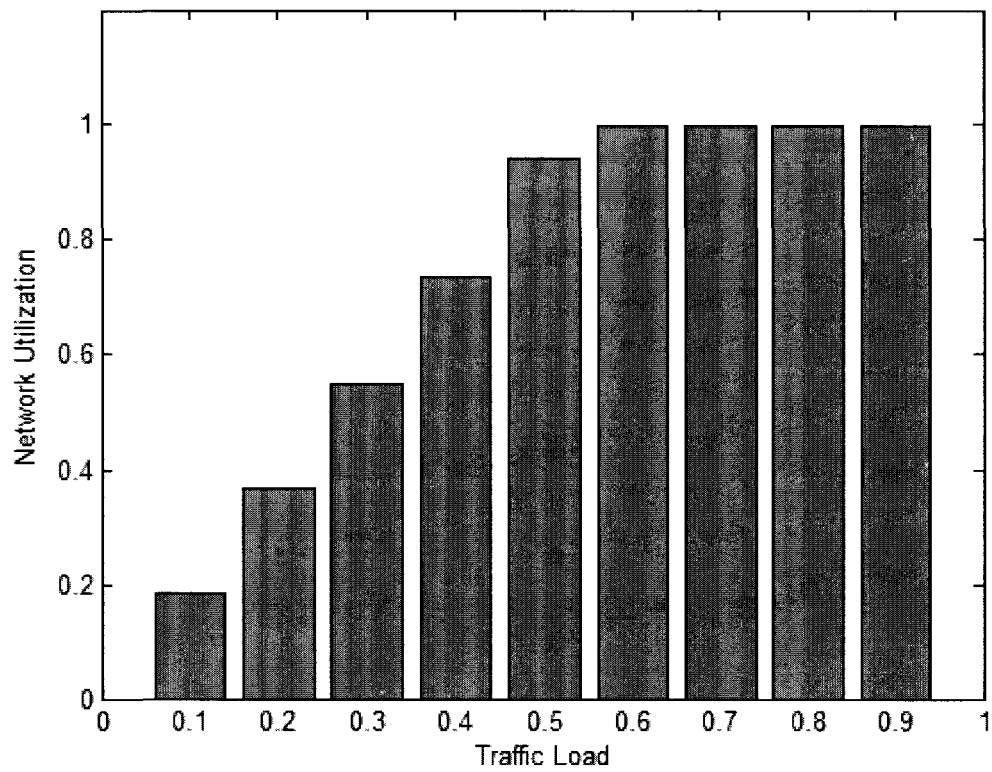


Figure 4-10 Network utilization with different traffic load (hop-limit parameter is 3)

4.3.1.7 Simulated RSVP-TE

To calculate the estimated total signalling delay, traffic load is set to 0.6, the hop-limit parameter was set to 3 and the fully-mesh topology aggregation scheme was implemented.

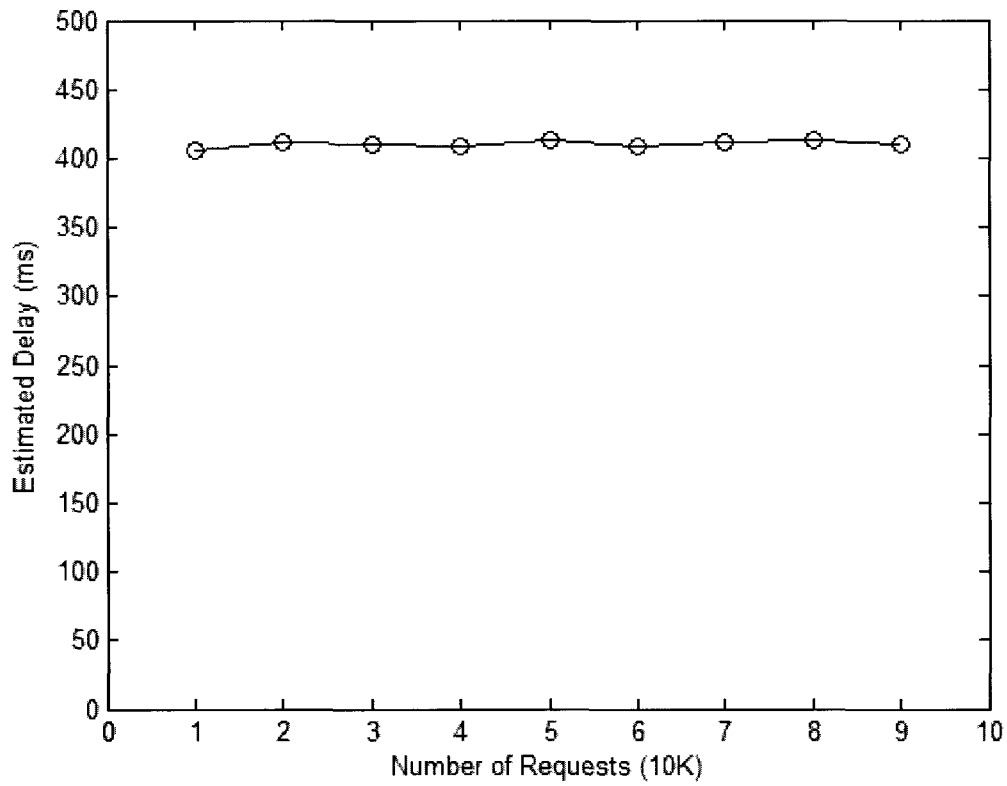


Figure 4-11 Estimated total delay with different requests (hop-limit parameter is 3)

4.3.1.8 Simulated modified RSVP-TE

Similar to data found in section to 4.3.1.7, traffic load was set to 0.6, the hop-limit parameter was again set to 3 and fully-mesh topology aggregation scheme was utilized for analyzing the performance of modified RSVP-TE.

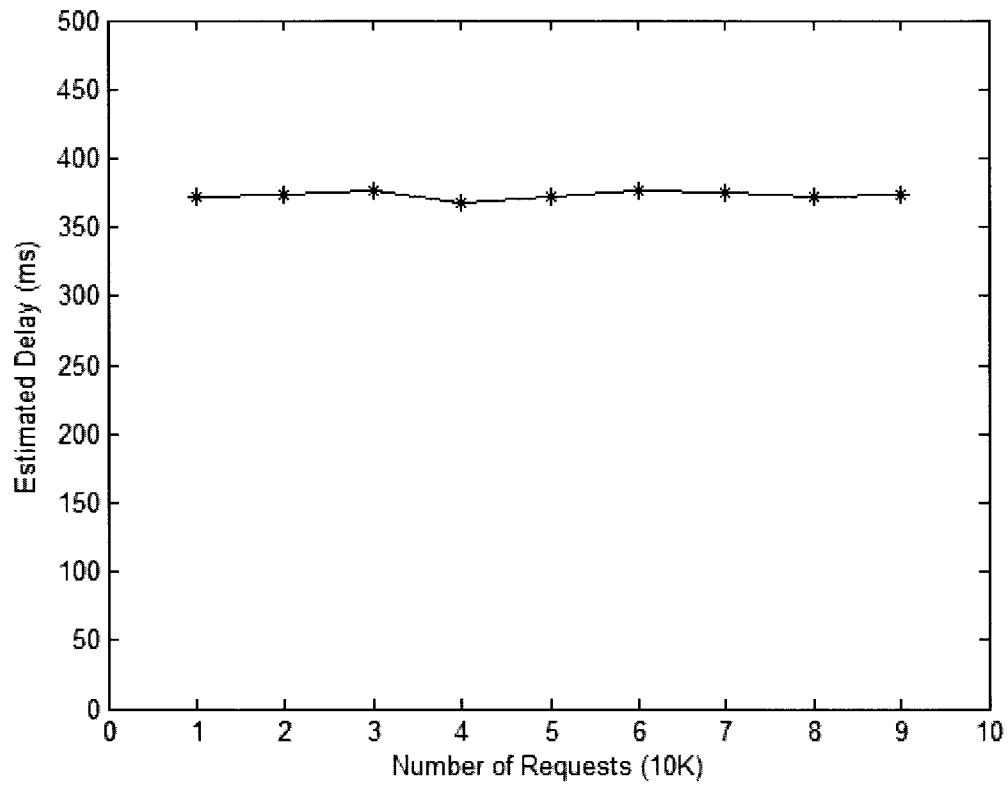


Figure 4-12 Estimated total delay with different requests (hop-limit parameter is 3)

4.3.2 Performance analysis

4.3.2.1 Comparison of two different hop-limit parameters

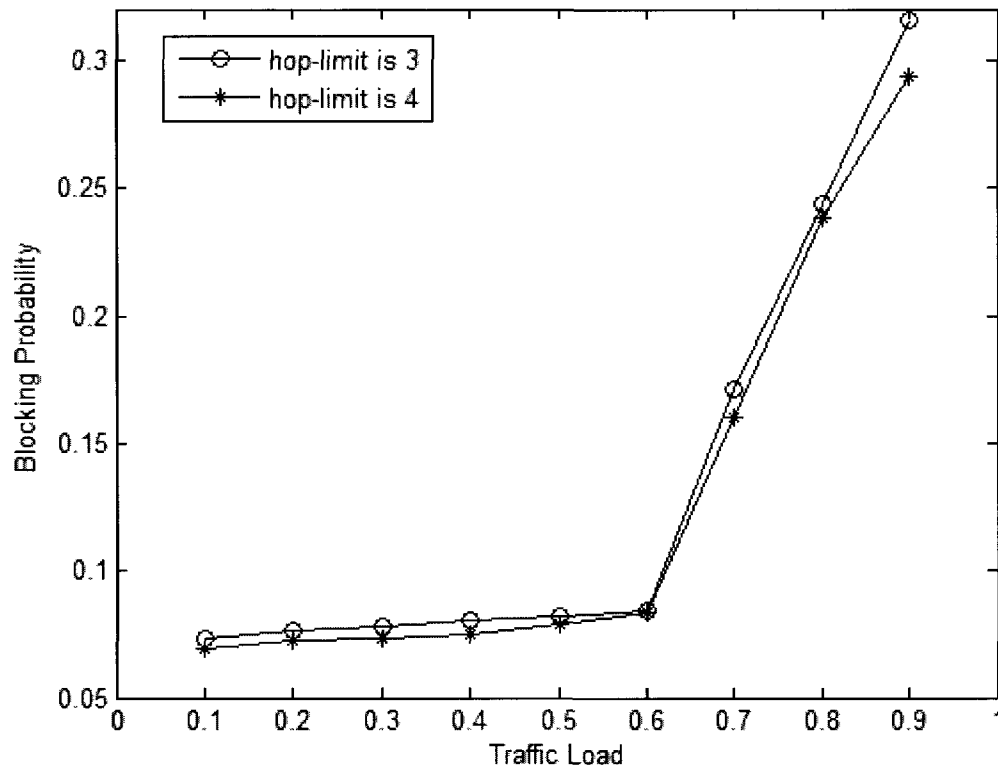


Figure 4-13 Hop-limit is 3 vs Hop-limit is 4

As shown in Figure 4-13, it is clear that when the hop-limit parameter is set to 4, the blocking probability of the system is slightly lower than when the hop-limit parameter was set to 3. This is because the proposed inter-domain routing algorithm is able to support multiple inter-domain paths calculation. For example, when the hop-limit parameter is set to 4, the simulator is able to calculate all the inter-domain paths between a pair of nodes that meet this hop-limit requirement. When the hop-limit parameter is set to 3, the available inter-domain paths between a pair of nodes may be less than when the hop-limit parameter is 4. This hop-limit parameter solves the problem of a potentially large number of hops in OBGP+, but the trade-off is a slight increase of the blocking probability performance.

4.3.2.2 Comparison of proposed inter-domain routing algorithm and OBGP

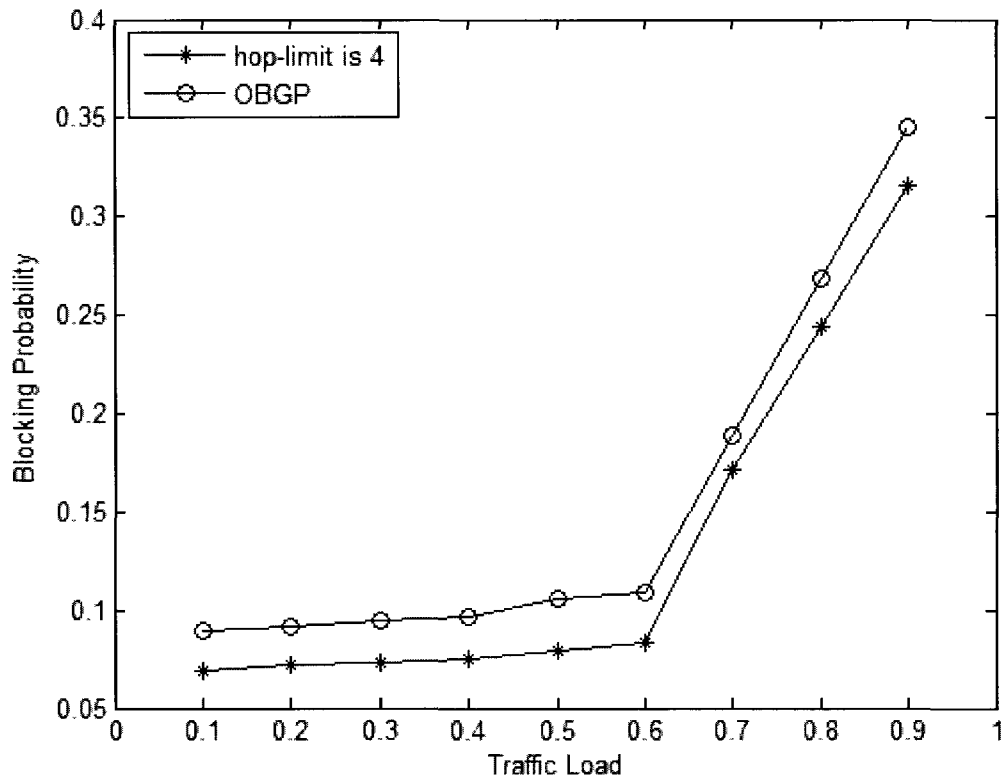


Figure 4-14 Proposed inter-domain routing algorithm vs OBGP

In Figure 4-14, it is obvious that when the hop-limit was set to 4, the proposed inter-domain routing algorithm outperforms OBGP. The reason for this is that OBGP does not consider the possibility of multiplicity of a certain wavelength. In Figure 4-12, as has already been demonstrated, with the increasing of the hop-limit parameter, the blocking performance of the proposed system is decreased. Thus, it can be concluded that the proposed inter-domain routing algorithm can out-perform OBGP in regards to blocking probability when the hop-limit parameter setting is 4 or higher.

4.3.2.3 Comparison of proposed inter-domain routing algorithm and OBGP+

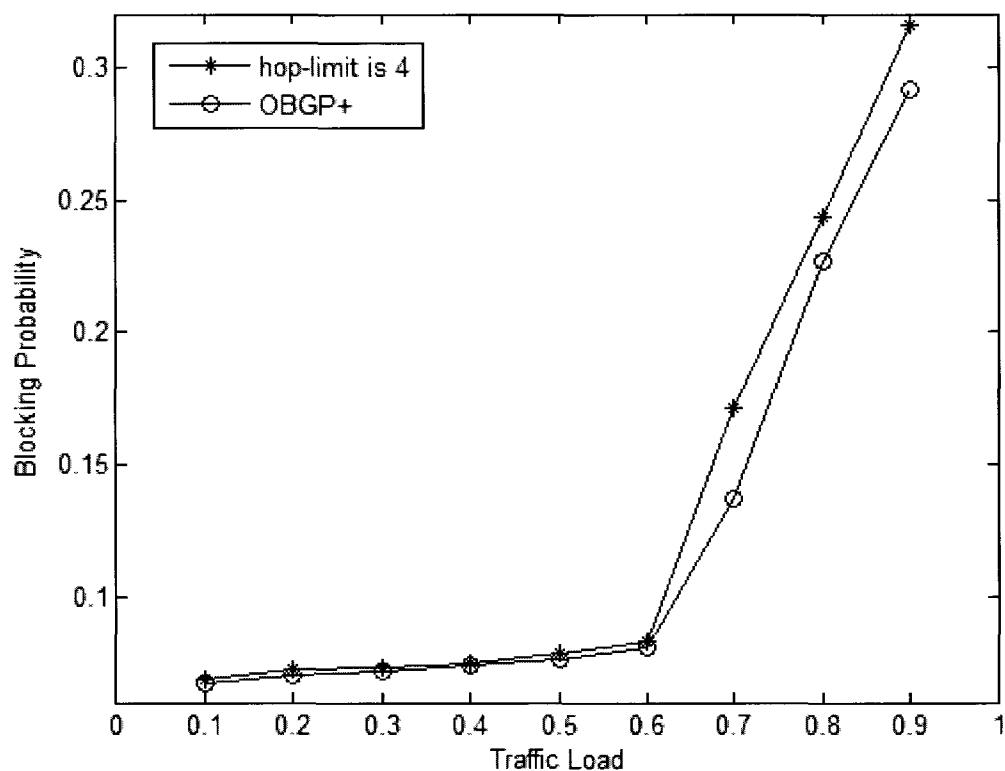


Figure 4-15 Proposed inter-domain routing algorithm vs OBGP+

In Figure 4-15, compared with OBGP+, when the hop-limit parameter is set to 4, the proposed inter-domain routing algorithm has a higher blocking probability. Since the proposed inter-domain routing algorithm is based on OBGP+, and an extra parameter was added to limit the possible inter-domain paths that are calculated by OBGP+, the total inter-domain paths that were calculated by the proposed inter-domain routing algorithm are less than OBGP+. But, considering that hop-limit parameter can solve the large number of hops problem, a slight increase to the blocking probability is preferable.

4.3.2.4 Comparison of two topology aggregation schemes

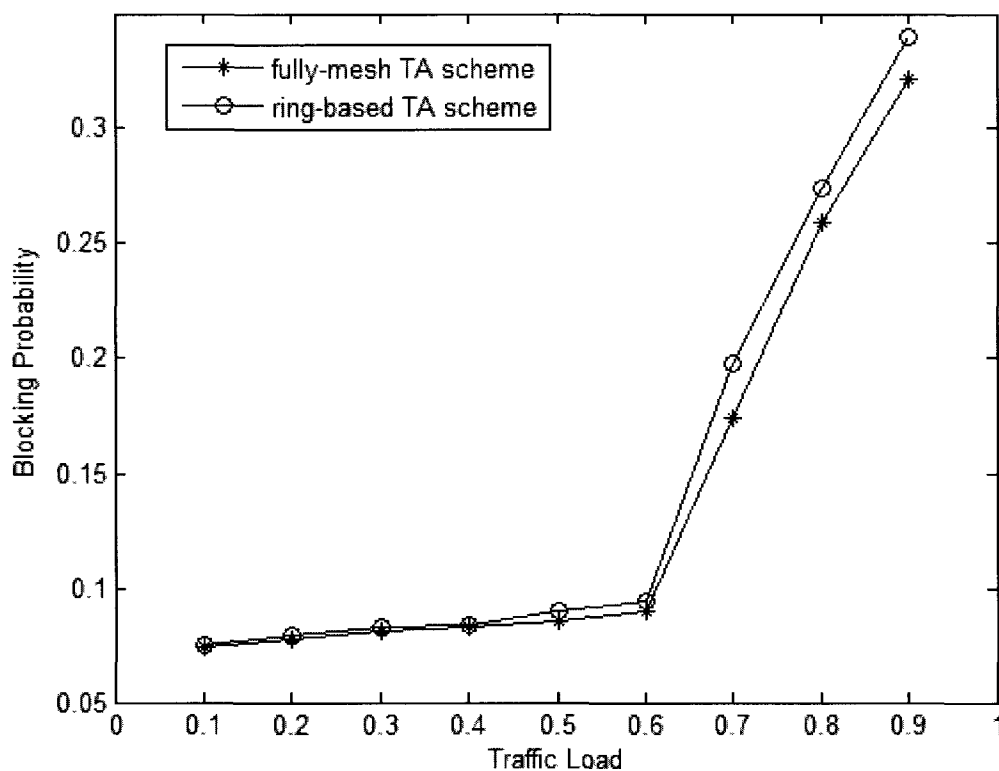


Figure 4-16 Fully-mesh TA scheme vs ring-based TA scheme

In Figure 4-16, it is clear that ring-based TA scheme achieves a higher blocking probability compared with fully-mesh TA scheme.

In NSFNET topology, the two domains have four connections, PIT and HOU. According to Chapter 3, the pre-calculated intra-domain paths in these two domains can be configured to follow either the ring-based TA scheme or the fully-mesh TA scheme. Under the fully-mesh topology aggregation scheme, four border nodes in these two domains have a direct connection to one another. However, under ring-based topology aggregation scheme, one of the four border nodes has to traverse one of on-ring border nodes to have an indirect connection. Thus, the available paths between each pair of border nodes in the ring-based topology aggregation scheme are less than that in the fully-mesh topology aggregation scheme. Although the ring-based topology aggregation scheme reaches higher blocking probability, it has a lower complexity for maintaining the domain's state.

4.3.2.5 Comparison of two signalling protocols

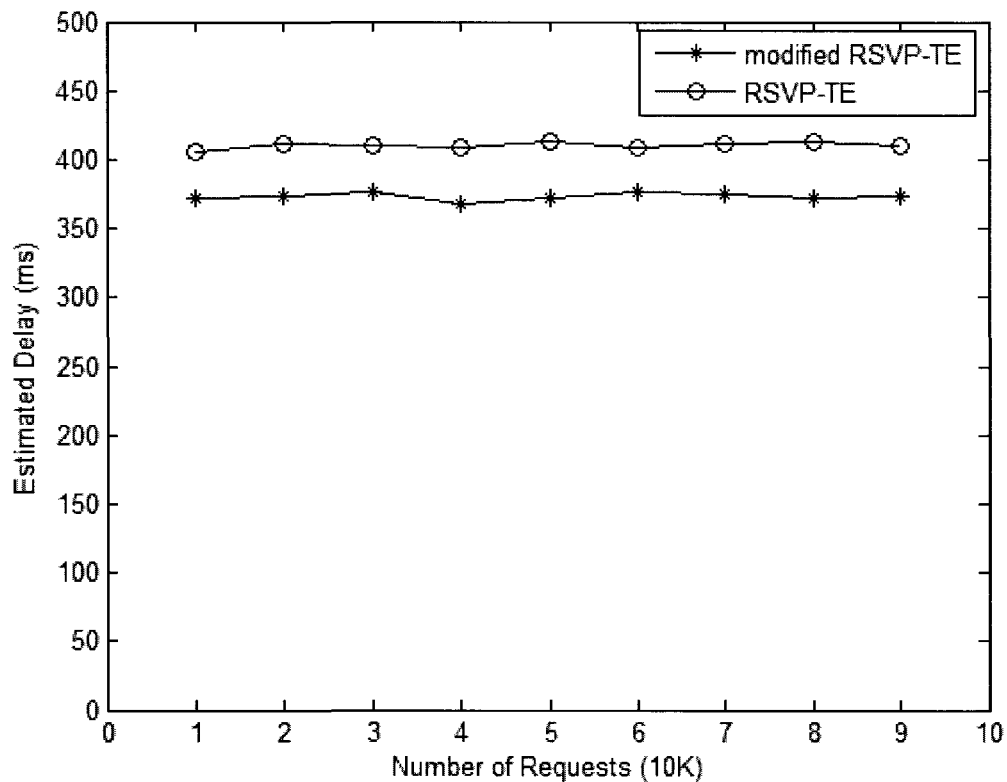


Figure 4-17 RSVP-TE vs modified RSVP-TE

As seen in Figure 4-17, it is clear that with different number of requests, the modified RSVP-TE signalling protocol achieves lower estimated establishment delay compared with the traditional RSVP-TE signalling protocol. The reason for this is that the proposed modified RSVP-TE is able to shorten the processing time inside a domain, meaning that the total establishment delay can be reduced. The previous chapter has provided a detailed analysis of this process for the proposed modified RSVP-TE signalling protocol.

4.4: Summary

This Chapter contained the detailed simulation results meant to evaluate the performance of the proposed inter-domain routing algorithm, topology aggregation scheme and

signalling protocol. The simulation results show that the following conclusions can be drawn regarding the proposed control architecture.

Firstly, the proposed inter-domain routing algorithm can solve the hop number problem in OBGp+ without significantly increasing the blocking probability.

Secondly, the proposed inter-domain routing algorithm has a lower blocking probability compared to the OBGp under the same simulation configurations, but has a higher blocking probability compared to OBGp+.

Thirdly, compared with the fully-mesh topology aggregation scheme, the ring-based topology aggregation scheme has a higher blocking probability, but it can achieve a lower state of maintaining lower complexity.

Finally, in comparison with traditional RSVP-TE signalling protocol, the proposed modified RSVP-TE signalling protocol can reduce the establishing delay of lightpath.

In next chapter, concluding marks and future works are discussed.

Chapter 5 CONCLUSIONS AND FUTURE WORK

5.1: Concluding Remarks

This thesis proposes a control architecture for a multi-domain survivable optical transport network. A control plane integrated with inter-domain routing algorithm, ring-based topology aggregation scheme and modified RSVP-TE signalling protocol is introduced based on the two-level inter-domain and intra-domain hierarchical control architecture.

To implement inter-domain routing algorithm, OBGp+ has been adapted and hop-limit parameter has been added. A fully-mesh topology aggregation scheme and RSVP-TE signalling protocol have been employed as a comparison with the proposed ring-based topology aggregation scheme and the modified RSVP-TE signalling protocol.

The proposed inter-domain routing algorithm with hop-limit parameter has been proved to be efficient by the results of simulation, as outlined in Chapter 4. As seen in Figures 4-3, 4-4, 4-5 and 4-11, it can be concluded that when setting the hop-limit parameter to 3 or higher, the blocking performance of the proposed system does not change significantly. This conclusion can be further extended to reduce the routing complexity and routing loops problem in the path vector routing algorithm.

The proposed ring-based topology aggregation scheme, as explained in Chapter 3, is able to reduce the complexity of maintaining a state of a single domain. In Chapter 4, Figure 4-12 proves that the ring-based topology aggregation scheme achieves a slightly higher blocking probability compared with the fully-mesh topology aggregation scheme. However, when the number of border nodes inside a domain is large, the complexity of maintaining this domain becomes relatively high and is undesirable. In this case, by increasing the blocking

probability slightly, in order to reduce the state-maintaining complexity, it is practical and more efficient.

Chapter 3 outlines a detailed analysis of the modified RSVP-TE signalling protocol. The analysis demonstrates that a modified RSVP-TE could reduce the total establishment delay in the control plane of optical networks by shortening the processing time inside a domain. In Chapter 4, Figure 4-13 proves that the proposed modified RSVP-TE is able to reduce the lightpath establishment delay in NSFNET topology by approximately 30ms.

Our control architecture is robust because all the intra-domain topology and resource information are pre-configured and pre-allocated for inter-domain purposes. To make the system more survivable, the intra-domain resources are considered sufficient for establishing not only a primary path, but also a backup path.

5.2: Future Research

This thesis has outlined the development a set of algorithms, schemes and protocols. Two-level inter-domain and intra-domain hierarchical control architecture is utilized to integrate inter-domain routing, intra-domain routing, topology aggregation and signalling. As an extension of the ideas that have been introduced in this thesis, future research, which will build on the findings described herein, should be undertaken on the following subjects:

- In two-level hierarchical control architecture, an entity is needed for integrating inter-domain and intra-domain primary paths. In this proposed framework, the function of this entity has been discussed, but a detailed definition of this entity has not been provided. For example, this entity could be PCE (Path Computation Element) or a selected node. Further work is necessary to address this lack of context
- The proposed inter-domain routing algorithm is performed on NSFNET topology which has a diameter of three. The simulation result shows that when the hop-limit parameter is three, the blocking performance of the system meets the requirements

of the proposed algorithm. Future research can transfer the inter-domain routing algorithm to a more complicated network, which has higher network diameter, in order to measure the impact of the hop-limit parameter

- This thesis simulated a ring-based topology aggregation scheme in NSFNET, which has two domains that have more than three border nodes inside. These two domains both have four border nodes. To make the conclusion more encompassing, simulations can be undertaken on a more complicated network, such as US long haul network or EON network
- This work explored a modified RSVP-TE signalling protocol based on estimated transmission delay attribute in NSFNET. However, the estimated transmission delay varies with the development of technology and future research is required to obtain a more accurate estimated transmission delay
- To simulate the modified RSVP-TE signalling protocol, an assumption of no message loss during signalling time was made. However, this assumption works only in a survivable network environment. If a network environment changes, modifications to retransmission mechanism are needed to supplement the proposed modified RSVP-TE signalling protocol
- In this simulation, all the inter-domain level nodes (nodes in NSFNET) and intra-domain level nodes were assumed with full wavelength convertibility. This assumption was made because without the wavelength continuity constraint, the optical network is more robust and more survivable. Future work can be done by adding the wavelength continuity constraint to make the framework proposed herein more complete.

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APPENDIX A

Confidence Interval

The accuracy of the simulation results is normally described in terms of a confidence interval, which gives an estimated range of values that is likely to include an unknown population parameter. The estimated range can be calculated from a given set of sample data.

Let X be an unknown population parameter and X_1, X_2, \dots, X_N be the simulation results of the same experiment, but produced by N over different runs, and assume these simulation runs are statistically independent.

The sample mean \bar{X} of these results is given by

$$\bar{X} = \frac{\sum_{i=1}^N X_i}{N} \quad (\text{A.1})$$

The sample variance S_x^2 is defined as follows:

$$S_x^2 = \frac{\sum_{i=1}^N (X_i - \bar{X})^2}{N-1} \quad (\text{A.2})$$

The upper bound of the confidence interval regarding these simulation results is defined as the following:

$$\bar{X} + \frac{S_x \times t_{\frac{\alpha}{2}, N-1}}{\sqrt{N}} \quad (\text{A.3})$$

The lower bound of the confidence interval regarding these simulation results is defined as the following:

$$\bar{X} - \frac{S_x \times t_{\frac{\partial}{2}, N-1}}{\sqrt{N}} \tag{A.4}$$

Where $t_{\frac{\partial}{2}, N-1}$ is the upper $100 \times \frac{\partial}{2}$ percentage of the t distribution with $N - 1$ degrees of freedom, and its value can be obtained from tables.

The intervals thus obtained are referred to as the intervals with $100 \times (1 - \partial)$ percent confidence and $(N - 1)$ degrees of freedom. These confidence intervals can be made as small as desired by increasing the number of independent runs of a single experiment. In this thesis, 95% confidence intervals were obtained.

APPENDIX B

Mathematical Analysis of the Network Simulator

Our network simulator is based on the $M / M / 1$ queuing system. According to [FISH01], there are several parameters that can be used to measure the queuing performance of the network simulator, such as mean queue length, mean waiting time and server utilization.

The components of the equations in this section are listed below (for $t > s \geq 0$):

$A(s, t)$: Number of arrivals in time interval $(s, t]$

$N(s, t)$: Number of completions in time interval $(s, t]$

$Q(t)$: Queue length at time t

$B(t)$: Number of busy servers at time t

W_i : Waiting time of departure i

The mathematical equation used to compute mean queuing length of our network simulator is:

$$\bar{Q}(s, t) = \frac{1}{t-s} \int_s^t Q(u) du \quad (\text{B.1})$$

The mathematical equation used to compute mean waiting time of our network simulator is:

$$\bar{W}(s, t) = \frac{1}{N(s, t)} \sum_{i=N(s)+1}^{N(t)} W_i \quad (\text{B.2})$$

The mathematical equation used to compute busy period of our network simulator is:

$$\bar{B}(s, t) = \frac{1}{t-s} \int_s^t B(u) du \quad (B.3)$$

Before the simulator is used to test the previously discussed algorithms, schemes and protocols, the simulator has to be tested to demonstrate that its queuing performances match the mathematical computation results. Table 3-1 lists the test results:

Number of Requests	Mean Queue Length	Mean Waiting Time
10000	3.117	15.586
20000	3.231	16.153
30000	3.169	15.844
40000	3.197	15.987
50000	3.210	16.049

Table 3-1 Test results for $\rho = 0.8$

In Table 3-1, ρ is traffic load in Erlang and $\rho = 0.8$ is calculated by setting λ to 0.8 and μ to 1 and using formula $\rho = \frac{\lambda}{\mu}$. Using (B.1) and (B.2), the theoretical value of mean queue length and mean waiting time can be calculated. The theoretical value of mean queue length is 3.2 and the theoretical value of mean waiting time is 16.0.

In this test, 50,000 requests were inputted into the network simulator and the mean queue length and the mean waiting time were calculated every 10,000 requests. To measure the queuing performance of the network simulator, blocking was ignored and every request was accepted and served by the network simulator.

In Table 3-1, it is clear that when the number of requests increases, the simulated mean queue length reflects closely the theoretical value 3.2, and the simulated mean waiting time

reflects closely the theoretical value 16.0. Table 3-1 proves that the proposed simulator works well and can be used to measure the performances of the proposed inter-domain routing algorithm, intra-domain routing algorithm, topology aggregation scheme and signalling protocol.