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OPTICAL INTER-DOMAIN ROUTING PROTOCOLS WITH WAVELENGTH CONVERTERS

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Abstract

The success of optical technology has introduced a new future for the Internet. With the many advantages of optical technology, multimedia applications which require strict quality of service (QoS) are able to be guaranteed in an optical network. Unfortunately, the optical technology still have some limits in setting up a connection. One of these limits is that a lightpath must use the same wavelength on all the links along its path from source to destination in an optical network without wavelength converters. This limit influents the resource utilization. In an optical network, wavelength converters are used to overcome this limit so they will help to improve the efficiency of the resource utilization. However, because of their expensiveness, a limited number of wavelength converters are usually used at some routers in optical networks.

Many researchers have been working on multi-domain routing protocol for optical networks. In this thesis, we will implement and evaluate the performance of three optical inter-domain protocols in an optical network with wavelength converters. In particular three protocols which are discussed in dept are: Optical Border Gateway Protocol (OBGP), Optical Border Gateway Protocol Plus (OBGP+) and IDRA-based Routing Protocol (IDRA protocol). By building the simulations for each protocol in OPNET, we compare the performance of the three protocols based on two metrics: the blocking ratio of inter-domain lightpath requests and the overall number of routing messages to archive this blocking ratio. Moreover, we also evaluate the efficiency of wavelength converters in an optical network.

Keywords: optical networks, wavelength converters, optical inter-domain routing protocol.

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Chapter 1

Introduction

During the last few years, demand for high bandwidth has been growing at a very rapid rate led by the Internet and multimedia applications. Networks which employ optical fiber for transmission (optical networks) are considered as the future of Internet because of optical fiber's characteristics such as: enormous bandwidth, low loss, very low bit error rate, etc.

1.1 Basic Concepts In Optical Networks

In optical networks, wavelength division multiplexing (WDM) is a technique to utilize the enormous bandwidth of the optical network [2]. Multiple wavelength-division multiplexed channels can be operated in a single fiber simultaneously. With this technique, we can have many channels to transfer data in a fiber. However, a fundamental requirement in fiber optical communication is that these channels operate at different wavelengths so as not to interfere with one another. Nowadays, WDM technique is dominant in all optical networks. Thus, from now on in this thesis, WDM network and optical network are used interchangeably.

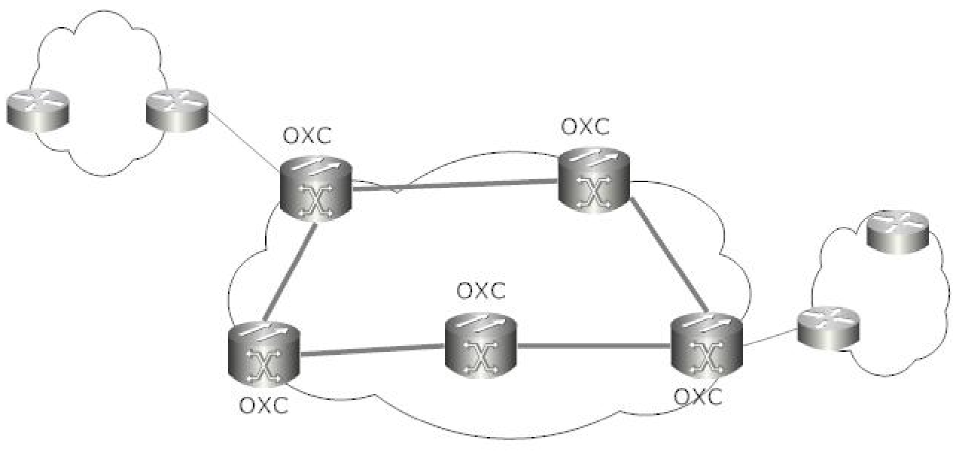


Figure 1.1: WDM network architecture.

In a WDM network, data can be transferred to their respective destinations based on existing wavelengths in the fiber. The use of wavelengths to route data is referred to as wavelength routing and a network which employs this technique is known as a wavelength-routed network [3]. Such a network includes wavelength-routing switches or optical cross-connects (OXCs) which are interconnected by a set of optical fiber links to form an arbitrary topology as shown in the figure 1.1. An OXC is a device which takes an optical signal coming in on a wavelength of an input fiber (input port), and can switch it to the same wavelength in a particular output fiber (output port). The structure of an OXC is shown as in the figure 1.2 [4].

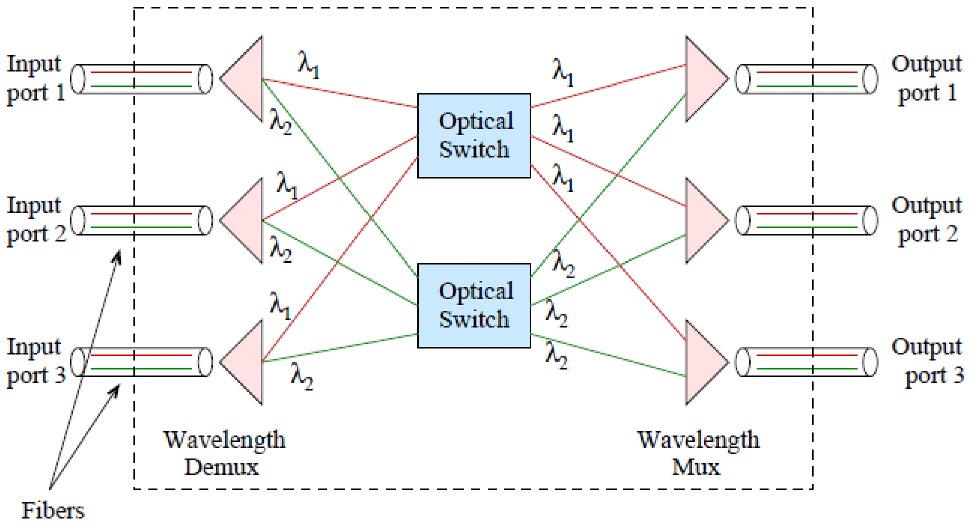


Figure 1.2: 3 x 3 optical cross-connect (OXC) with two wavelengths per fiber.

If an OXC has N input fibers, N output fibers and each fiber is capable of handling W wavelengths, we can consider it as W independent $N \times N$ optical switches. The OXC in the figure 1.2 has 3 input fibers, 3 output fibers and 2 wavelength per fiber. These switches have to be preceded by a wavelength demultiplexer and followed by a wavelength multiplexer. With this structure, an OXC can cross-connect the same wavelength from the input fiber to output fiber without depending on other wavelengths.

Some OXCs can be attached to access normal routers (as in figure 1.1) where data from several end-users could be multiplexed on to a single WDM channel. Normal routers which connect to an OXC usually contain optical-to-electronic (O/E) conversion and vice versa to interface the optical network with a conventional electronic device. A wavelength-routed network which transfers data from source to destination without any intermediate O/E conversion is referred to as an all-optical wavelength-routed network and this path is called a lightpath.

1.2 Two Constraints In Optical Networks

In order to transfer data from one OXC to another OXC, a connection needs to be set up at the optical layer similar to the case in a circuit-switched telephone network. To do this work, we must deal with both routing and wavelength assignment: finding a suitable lightpath (route) to go to the destination and determining a free wavelength on all of the fiber links in this lightpath for the connection. This problem is known as the routing and wavelength assignment (RWA) problem and is significantly more difficult than the routing problem in electronic networks [4]. Moreover, the difficulty of RWA problem arises because it is subject to the following two constraints in a WDM network:

1. *Wavelength continuity constraint:* a lightpath must use the same wavelength on all the links along its path from source to destination. This means a connection is blocked even if there are free wavelengths (but not the same one) on all the links.

2. *Distinct wavelength constraint:* all lightpaths using the same fiber must be allocated distinct wavelengths.

Let's consider an example as shown in the figure 1.3 [5].

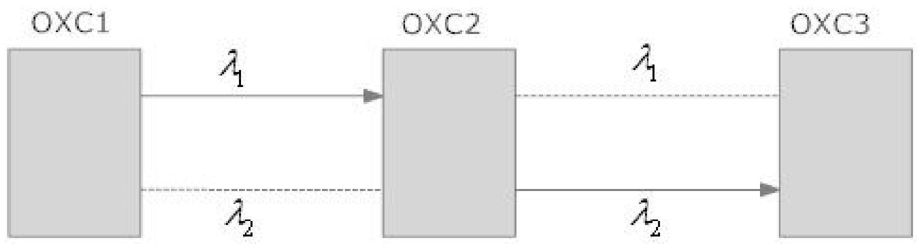


Figure 1.3: Wavelength continuity constraint.

In figure 1.3, we have 3 OXCs and two lightpaths have been established in the network: (i) a lightpath with wavelength λ_1 between OXC1 and OXC2, (ii) a lightpath with wavelength λ_2 between OXC2 and OXC3. Now, assuming that we need to set up a lightpath from OXC1 to OXC3, this is impossible although we still have free wavelengths on each hop from OXC1 to OXC3 but they are different (λ_2 on link from OXC1 to OXC2 and λ_1 from OXC2 to OXC3). Clearly, how to find a suitable ligthpath between a source and a destination is a challenge, especially if this lightpath is long or goes through many OXCs or multi-domains.

We need to notice that the first constraint is only applied to optical networks without wavelength converters. As we will see later, the wavelength continuity constraint can be relaxed with the presence of wavelength converters.

1.3 Optical Multi-domain Routing

The Internet is a very large network connected by many smaller networks known as domains or Autonomous Systems (ASs). Each domain is managed by a different authority and under different administrative control. At the end of 2008, there were already 50.000 ASs registered in the Internet [6]. Finding and selecting an appropriate route to transfer traffic from a source at a domain to a destination at a different domain is known as multi-domain or inter-domain routing. The problems of multi-domain routing in the electronic IP networks have been analyzed for a long time. Currently, the Border Gateway Protocol (BGP) is considered as the standard inter-domain routing protocol in the Internet. BGP was designed as a protocol in which routers only distribute and exchange reachability information [7]. Although BGP has been studied by many researchers and industrial communities, there still remain some unsolved issues which are described in [8].

As optical technology is discovered and applied to computer networks, new features and new requirements will be also applied to routing protocols. This means that we need to redesign these routing protocols to be used for optical networks. During redesigning the new multi-domain protocol, we need to take advantages and avoid disadvantages of the old ones.

The main objective of optical inter-domain routing problems is scalability. Unfortunately, this is not the only problem we need to solve in optical inter-domain routing. There remain several other issues in optical networks and some of them are more difficult than the ones in electronic networks. They will be shown in the following description.

Security: We have two problems in this issue: i) protecting end-points of TCP connection which can easily be attacked by a distant hacker between two OXCs and ii) an OXC only accepts these IP-prefixes which are advertised by authenticated OXCs.

Slow convergence: Convergence time is the time required to reroute traffic when a failure has happened. Currently, BGP convergence is quite slow (hundreds of seconds) and this time can not be acceptable if it happens in optical networks. We need to decrease the convergence time as much as possible due to the fact that optical connections are supposed to transfer a huge volumes of data so if the convergence time is big, the volumes of data loss are tremendous.

Overhead of advertisement messages: In multi-domain networks, a large number of messages are expected to be exchanged between domains whenever a change occurs. These messages will waste a lot of bandwidth in the network, especially in optical networks. Hence, we need to avoid flooding advertisement messages. Some solutions are suggested for BGP but none of them are suitable for an optical scenario. A new strategy should be sought for optical inter-domain routing. From works in [9, 10], we found that information aggregation during advertising indeed limits the number of advertisement messages as well as the bandwidth for signaling.

Routing strategy: The routing problem in an optical network will be more difficult than in an electronic network because we should deal with two problems: finding a route and choosing a wavelength on this route to transport data (RWA). Moreover, this route and wavelength must satisfy the two constraints of optical networks. Besides, a new routing protocol should also support traffic engineering and QoS. These two issues are still weak points in current inter-domain routing protocols, despite being important requirements for a transport network. Finding a good routing strategy which satisfies all requirements will be a difficult work.

Protection and restoration: Any failure that stops transferring data on a lightpath between OXCs without any protection or back-up lightpath is not acceptable due to the fact that we will lose a lot of data on this connection. An optical network should be resilient to failure (survivability) and reroute fast around a failed connection. At the electronic level, some well-defined restoration technologies already exist such as MPLS. Based on MPLS, a GMPLS has been born for optical networks. Unfortunately, GMPLS is not an appropriate solution for optical networks because the time to reroute to avoid a failure is slow. Finding other approaches for a good protection and restoration is a research challenge in a multi-domain scenario.

From these above challenges, a good optical inter-domain routing protocol is not expected to be easy and requires a large effort.

1.4 Wavelength Converters

The wavelength continuity constraint may be relaxed if the OXCs are equipped with wavelength converters. A wavelength converter is a single input/output device that converts the wavelength of an optical signal arriving at its input port to a different wavelength as the signal departs from its output port. In OXCs without any wavelength converters, an incoming signal at port p_i on wavelength λ can be optically switched to any port p_j, but must leave the OXC on the same wavelength λ. With wavelength converters, this signal could be switched to any port p_j on another wavelength γ. Let's return to the previous example but now we have a converter at OXC2 as shown in the figure 1.4 [5].

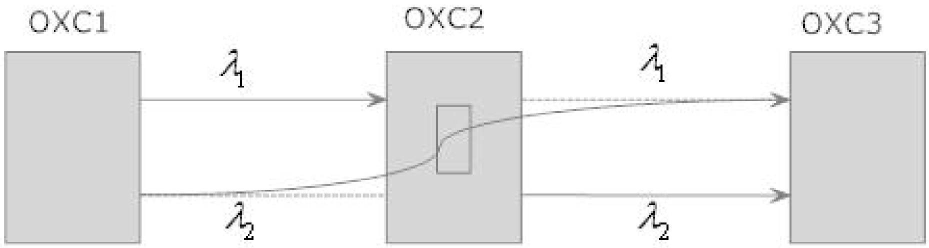


Figure 1.4: Wavelength Converter.

With the presence of a wavelength converter, we can set up a lightpath from OXC1 to OXC3 by using wavelength λ_2 on link from OXC1 to OXC2 and then using λ_1 on the link from OXC2 to OXC3. We notice that one converter is only used to convert one input wavelength to another one at one time. It means that if we have one more free wavelength λ_3 on link (OXC1, OXC2) and a wavelength λ_4 on link (OXC2, OXC3), we can not use this converter to set up one more lightpath with these wavelengths. To set up more lightpaths, we must have more converters on OXC2.

Depending on the levels of wavelength conversion capability, wavelength converters can be divided into 3 groups:

1. *Full wavelength converter:* this is a kind of converter which can convert any input wavelength to any other wavelength.

2. *Limited wavelength converter:* with this converter, each input wavelength may be converted to any of a specific set of wavelengths, which is not the set of all wavelengths for at least one input wavelength.

3. *Fix wavelength converter:* each input wavelength can be converted to exactly one other wavelength.

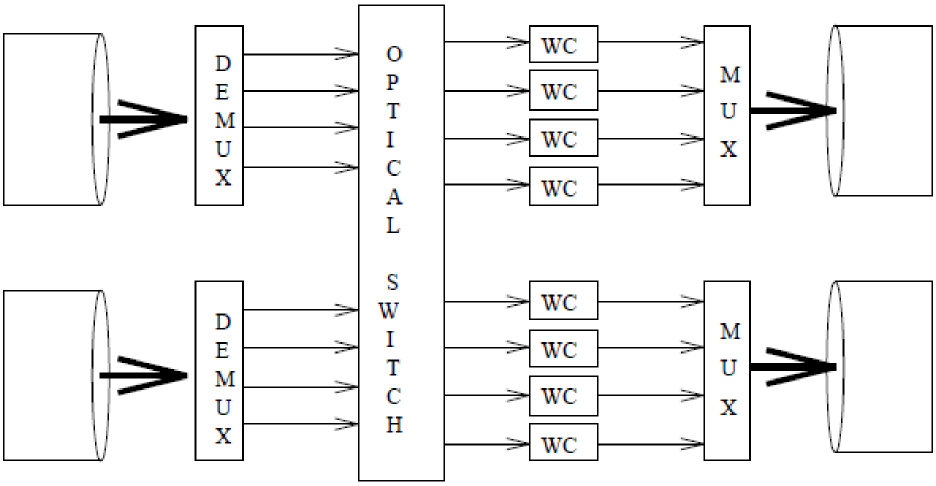


Figure 1.5: Dedicated wavelength-convertible switch architecture (WC: wavelength converter bank).

An OXC which is equipped with wavelength converters is called a wavelength-convertible OXC. The architecture of wavelength-convertible OXCs has been studied in [5, 11]. In general, we have three kinds of architectures of wavelength-convertible OXCs: 1) the dedicated wavelength-convertible switch architecture, 2) the share-per-link switch architecture and 3) the share-per-node switch architecture.

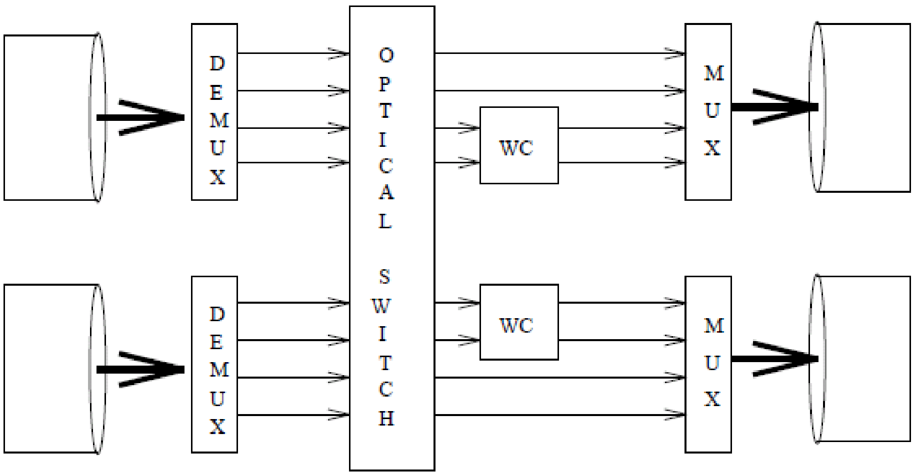


Figure 1.6: Share-per-link wavelength-convertible switch architecture.

The figure 1.5 [5, 11] shows the structure and position of wavelength converters in the dedicated wavelength-convertible switch architecture. In this architecture, each wavelength along each output fiber in an OXC has a dedicated wavelength converter. In other words, if the OXC has N output fibers and each fiber can handle W wavelengths, it will need $W \times N$ converters. Clearly, this architecture is not very cost efficient since we may not require all the wavelength converters at the same time [12]. An effective way to reduce costs is that we will share these converters for incoming lightpaths when needed (We assume that these converters can convert any input wavelength to any output wavelength). The two last architectures of wavelength-convertible OXCs were designed accordingly.

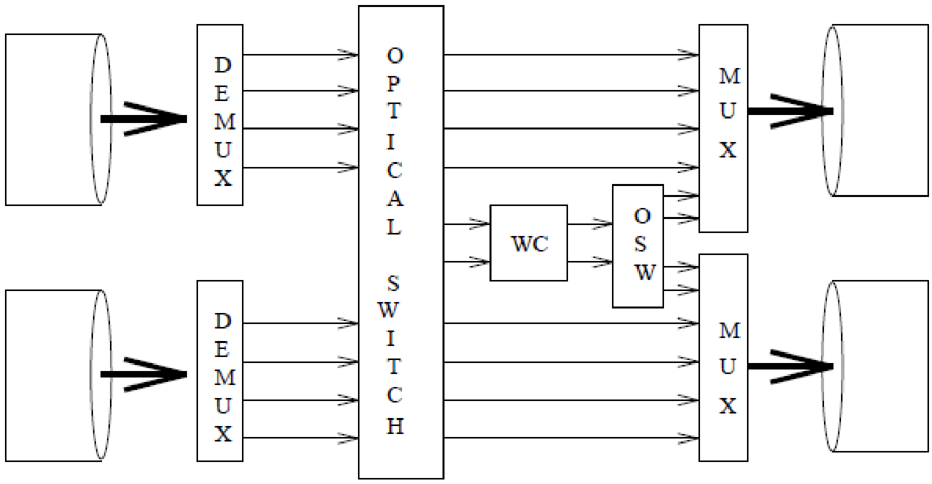


Figure 1.7: Share-per-node wavelength-convertible switch architecture (OSW: optical switch).

Figure 1.6 [5, 11] shows the design of a share-per-link switch architecture. In this architecture, each outgoing fiber link has its own converter bank which can be accessed only by these lightpaths going out of the OXC on this link. All wavelengths along each output fiber link will share its own converter bank.

As shown in the figure 1.7 [5, 11], the share-per-node architecture also has a converter bank, but this converter bank is shared for all outgoing links. A lightpath which needs a conversion will be directed to the converter bank and then be switched to an appropriate outgoing link by a second optical switch.

It is easy to see that wavelength conversion may improve the efficiency in the network by resolving the wavelength conflicts of the lightpaths. If all OXCs in a WDM network have enough wavelength converters whenever they need, this kind of the WDM network is functionally equivalent to a circuit-switched network, i.e., lightpath requests are blocked only when there is no available capacity on the path. Unfortunately, wavelength converters are very expensive and we usually only have a limited number of wavelength converters at some special OXCs, for example at OXCs through which there is a lot of traffic.

1.5 Related Work

With many new features and new challenges, inter-domain routing protocols for multi-domain optical networks is an attractive research area. Researchers have come up with several approaches in order to deal with this problem [1, 9, 10, 13–15].

A hierarchical routing protocol suggested in [15] divided the whole network into routing areas (RAs). Each RAs is represented by a "Logical Routing Area (LRA) Node" in the next hierarchical level. It also introduces a new routing algorithm for Optical Transport Networks (OTN). In this new algorithm, only shortest paths are computed between a source and a destination at the highest level. At the control plane, this protocol uses GMPLS for signaling and setting up a lightpath. Results from [15] shows that the Ligthpath Aggregated Scheme (LAS) is better than the Node Aggregated Scheme (NAS) in blocking reduction, but that NAS produces less signaling overhead than LAS.

The protocol in [13] is also a hierarchical routing with a two-level hierarchical link-state approach: the first level includes OXCs inside a domain and the second level (higher level) includes the border OXCs of domains. The two levels of this protocol run the modified GMPLS OSPF-TE protocol [16] to maintain the full wavelength state of all links. To prevent the flooding of advertisement messages and to increase multi-domain scalability, the protocol only generates link-state advertisement (LSA) messages via a Significance Change Factor (SCF) triggering policy [17]. Besides, this protocol uses RSVP-TE to reserve resources and set up a lightpath at the control plane. From this work, with the presence of wavelength converters in the optical network, the authors in [13] show that a hierarchical routing with full mesh network abstraction at the highest level has a more significant impact on blocking reduction than a simple node at the highest level.

Another approach is to extend the inter-domain routing protocol BGP so that it can be used in multi-domain optical networks [1, 18, 19]. These protocols use basically a set of extended BGP messages to exchange network reachability information between domains. The main advantage of these protocols will be multi-domain scalability as BGP. Because only network reachability information is exchanged, the related state of a network's resource is not considered and hence, finding and setting up a lightpath are similar to BGP-type implementations. As a consequence, none of these protocols are able to provide the routing functionalities and expected performance[1] in multi-domain optical networks.

Protocol OBGP+ in [9] is an improved version of the protocol OBGP [1]. In OBGP+, beside network reachability information, the Effective Number of Available Wavelengths (ENAW) to reach a destination will also be exchanged between OXCs in Path State Information (PSI) messages. To avoid the increase of exchanged messages because of PSI messages, PSI updates could be embedded in Keepalive messages. With the ENAW information, the source has more important information for deciding which lightpath is best to reach a destination. From works in [9], Yannuzzi et al. show that OBGP+ helps to dramatically improve the performance of optical networks and the number of routing messages exchanged.

IDRA-based routing protocol in [10] is also another approach for optical inter-domain routing. This protocol introduces a new control plane for optical networks. The control plane,

[1] The performance metric considered here is the blocking ratio of inter-domain lightpath requests.

which is fully distributed and decoupled from the data plane, is created by the set of Inter-Domain Routing Agents (IDRAs). Each IDRA represents for each domain the basic functions: distributing routing and signaling information between domains; computing and establishing the inter-domain lightpaths. In the IDRA-based protocol, beside network reachability information (as OBGP) and ENAW (as OBGP+), IDRAs also exchange the cost of lightpaths to reach a destination. All information is embedded in Keepalive messages. Results in [10] also show that the performance of the IDRA-based routing protocol is better than that of OBGP as well as the number of routing messages exchanged.

1.6 Objectives

Most of the afore-mentioned related works concentrate only on considering the performance of optical inter-domain routing protocols on optical networks without wavelength converters. This thesis differs from these works in that it evaluates the performance of some protocols in an optical network with wavelength converters which are put at particular OXCs.

The main objectives of the thesis are:

- To implement, evaluate and compare the performance of three protocols: OBGP, OBGP+ and the IDRA-based routing protocol in an optical network with wavelength converters at border OXCs.
- To evaluate the efficiency of wavelength converters in an optical network under three protocols.

The optical network which is considered in this thesis is the *PAN-European Optical Transport Network* [20,21] (see figure 4.1) in which wavelength converters will be put at border OXCs of each domain. Moreover, we also consider the efficiency of wavelength converters through these inter-domain routing protocols on this network. The reason we put wavelength converters at border nodes is that this is a very realistic modeling of emergent optical networks, for example, all-optical "islands" (domains) connected by opto-electronic border nodes [13, 22]. Moreover, traffic load at border OXCs is usually higher than at other OXCs in the same domain. Thus, blocking usually appears there. We also assume that border OXCs in our network use the share-per-node wavelength-convertible switch architecture shown in figure 1.7 and that they can optically switch optical signals from a wavelength to any wavelength (full wavelength converter).

1.7 Thesis Structure

The thesis is divided into six parts. Chapter 2 introduces the three current inter-domain routing protocols: OBGP, OBGP+ and the IDRA-based routing protocol. In this chapter, we also describe in detail the kinds of information OXCs exchange together in each protocol to capture the "state" of a network's resources. Based on this information, each protocol will have a different strategy in choosing the best lightpath from a source to a destination. In chapter 3 we will describe how we calculate and advertise converter lightpaths to a destination when we add wavelength converters at border OXCs of each domain in the optical network. Building the simulation for three protocols in optical network with presence of wavelength converters in chapter 4, we evaluate the performance of each protocol based on two metrics: blocking ratio and the number of routing messages. An improvement for the IDRA-based routing protocol is described in chapter 5. Finally, in chapter 6 we will give a general conclusion on work done and make some recommendations for future work.

Chapter 2

Optical inter-domain routing protocols

2.1 Optical Border Gateway Protocol (OBGP)

Researchers tried to follow the inter-domain routing protocol BGP to have a protocol similar to BGP for optical networks and thus the optical border gateway protocol (OBGP) was born [1, 18]. OBGP is responsible for distributing inter-domain network reachability information and to choose the best AS-path and wavelength to reach a destination. Using the same set of exchanging messages as BGP plus setup messages for the lightpath, OBGP basically proposes two phases: advertising network reachability information and establishing a lightpath.

2.1.1 Advertising Network Reachability Information

The first phase is the exchange of network reachability information (NRI). During this phase, each AS advertises the available optical lightpaths to other ASs using BGP lightpath reachability updates messages. These announcements will contain the following information:

- The IP address of the site egress OXC.
- The reachable IP prefixes.
- A set of wavelengths which can be used to reach this AS.

This first phase will allow border OXCs of each AS to build up a "local RIB" that will be used to determine if a lightpath is feasible across a number of OXC in different ASs. We consider an example as shown in the figure 2.1 [1].

The table 2.1 shows what the OXC A1's local RIB at AS A would look like when update messages from all ASs are received.

The set of wavelengths used here is of the form L(xa) and represents one or a bundle of available wavelengths to reach AS X from neighbor AS A. Each AS is responsible for updating its lightpath availability to its neighbors. If there is no lightpath availability, it must send a withdraw message.

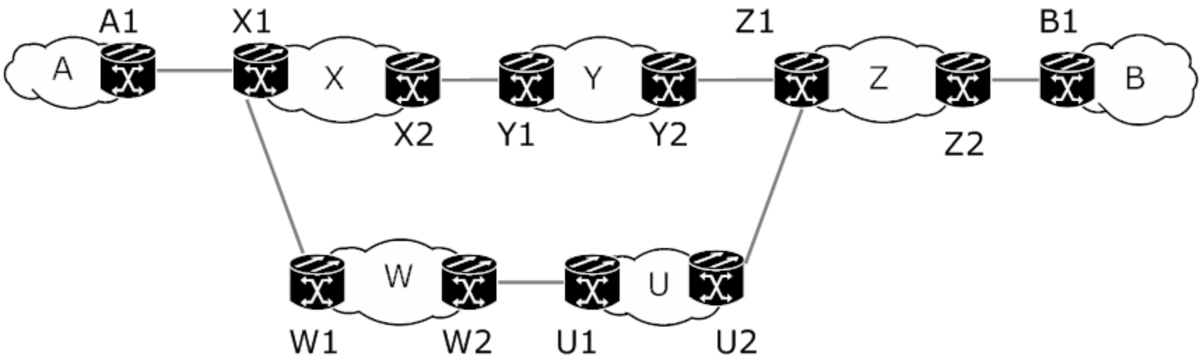


Figure 2.1: An example of a multi-domain WDM network.

Destination	OXC-IP	Next-Hop	Wavelengths	AS-path
Network X	prefix-X	X1	X, L(xa)	X
Network Y	prefix-Y	X1	Y, L(yx)	X, Y
Network Z	prefix-Z	X1	Z, L(zy)	X, Y, Z
Network B	prefix-B	X1	B, L(bz)	X, Y, Z, B
Network W	prefix-W	X1	W, L(wx)	X, W
Network U	prefix-U	X1	U, L(uw)	X, W, U

Table 2.1: Local RIB of OXC A1 [1]

2.1.2 Routing and Wavelength Assignment (RWA) Strategy

The second phase is finding a lightpath and allocating a free wavelength on this lightpath. Using the information from the local RIB, an OXC can determine the lightpath and reachable IP prefix can be used to reach the destination. To illustrate the protocol mechanisms, we reconsider the figure 2.1 and Table 2.1. If OXC A1 wants to establish a lightpath to network Z, the following steps need to be performed by OXC A1:

1. Lookup the local RIB entry for the destination AS.

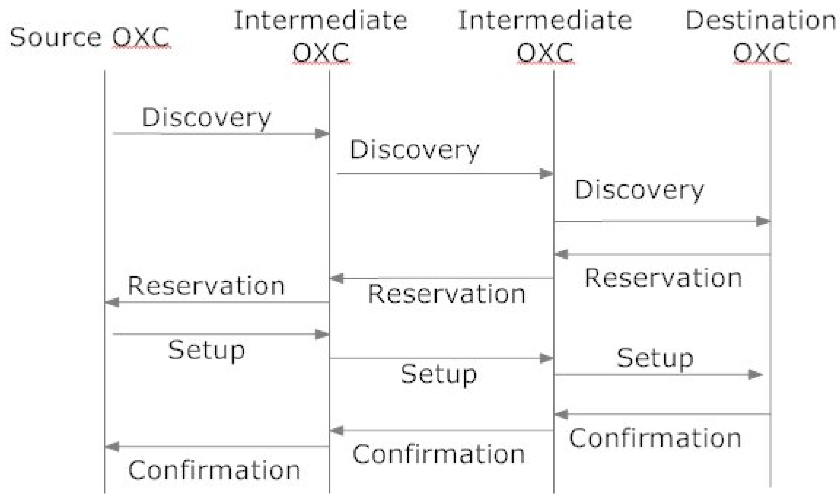
2. Lookup the corresponding entries for the intermediate AS.

3. Send setup messages to destination to set up a lightpath.

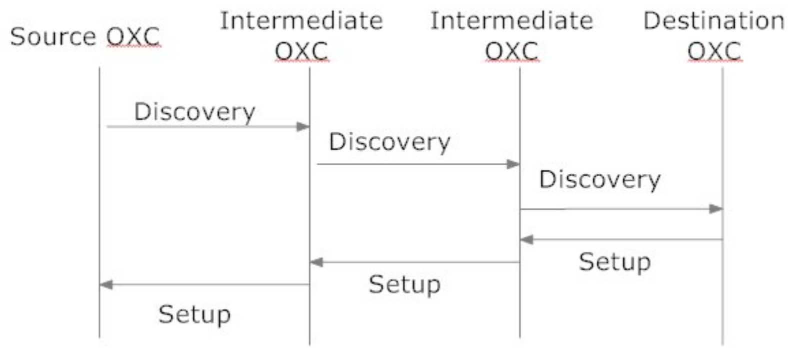
Basing on Table 2.1, after step 1, OXC A1 will know that the AS-path to reach network Z is (X, Y, Z). In step 2, OXC A1 will lookup for the intermediate ASs and it knows that a lightpath can be set up through intermediate ASs X and Y. The reason for looking up the intermediate ASs entries in the local RIB is to make sure that there is a complete path available to the destination AS. Lightpath availability on the optical network may change at any time. For example, if the state of OXC Y1 were to change such that lightpaths were no longer available to go to itself from OXC X2. OXC Y1 must withdraw its lightpath L(yx) by sending a BGP withdraw message. If that were the case, OXC X1 would now advertise to OXC A1 the different path to reach Z (X, W, U, Z) using the standard BGP path selection process.

After determining the AS-path to reach the domain Z with OXC Z1, in step 3, OXC A1 will allocate a free wavelength and set up this lightpath. The two processes happen at the same time in the OBGP so we call them an establishment process.

OBGP can either operate in a two-phase or a four-phase mode in the establishment process. In the four-phase mode of OBGP, the phases include: 1) Discovery, 2) Reservation, 3) Setup and 4) Confirmation. In the two-phase mode, the phases are: 1) Discovery and 2) Setup. The figure 2.2 illustrates the difference between two-phase and four-phase setup. The following part will describe the four phases in more detail.



(a) 4 Phase Setup mode



(b) 2 Phase Setup mode

Figure 2.2: Four-Phase and Two-Phase Setup Mode.

1) *Discovery Phase:* We return to the above example. OXC A1 will initiate the lightpath setup request by sending a Discovery OBGP message to OXC X1. This Discovery message will contain all available wavelengths that can be used to reach X1. When OXC X1 receives the Discovery OBGP message, it checks its local RIB to determine which of the received wavelengths can be used to reach the next hop in the AS-path, which is OXC X2 in this case. In this step, OXC X1 will possibly eliminate a few wavelengths. Only a subset of the original wavelengths will be sent to the next OXC in the AS-path (OXC X2) via a Discovery OBGP

message. All intermediate OXCs will repeat the same elimination process as OXC X1 until the destination OXC Z1 is reached. When the destination receives the Discovery OBGP message, it contains all common wavelengths that can be used from the source for the light path setup and the destination OXC Z1 will decide which wavelength to use for the lightpath.

2) *Reservation Phase:* This phase is only used in the four-phase mode. In this phase, a wavelength will be reserved along the AS-path in order to ensure their availability in the Setup phase.

3) *Setup Phase:* In the case of the two-phase mode the Setup phase takes place immediately after the Discovery phase. During the Setup phase in the two-phase mode, the OXC connections are setup and the wavelength is reserved at the same time to indicate that the specific wavelength is being used. In contrast to the four-mode operation the Setup phase proceeds from the Destination OXC to the Source OXC as shown in the figure 2.2. Since the Setup phase is complete when the Setup OBGP message reaches the source OXC, there is no need to send a separate confirmation message. The Setup message also serves as the confirmation of a successful setup.

In the four-phase mode the Setup phase takes place after resources have been reserved and the Reservation has completed. At this point all nodes along the AS-path have reserved a wavelength for the light path setup, but they have not actually made any hardware connections on the OXC. This is done in the Setup Phase. The OXC source A1 will initiate the Setup Phase by sending a Setup OBGP message to the next OXC in the AS-path (OXC X1). OXC X1 will make the appropriate OXC connection and continue sending this message to the next OXC. This phase is complete when the Setup OBGP message is received at the destination OXC Z1.

4) *Confirmation Phase:* In the four-phase mode after the Setup phase is complete, the source OXC is not aware of this. For this reason, the destination OXC Z1 needs to send a Confirmation OBGP message back to the source along the AS-path. Once the source OXC X1 receives the Confirmation messages, this phase is completed and the source can start using the lightpath.

Beside these main phases, OBGP also has some more phases to end a connection (Teardown Phase) or recover from an error (Error Phase).

On the one hand, the main advantage of this approach is that OBGP will benefit from the well-known advantages of BGP. On the other hand, the main disadvantage of this approach is that OBGP will inherit the well-known issues of BGP [8].

Moreover, OBGP only exchanges the network reachability information (NRI), which will not be sufficient. OBGP also tends to exhaust the available wavelengths along the shortest AS-path before switching to an alternative path [9]. This increases the blocking ratio in WDM networks that employ OBGP drastically. In the following sections, we will describe two new protocols which will calculate and advertise more aggregated information between domains to help find a better path to go to a destination and improve the performance of optical networks.

2.2 Optical Border Gateway Protocol Plus (OBGP+)

This is an improved version of OBGP. In this protocol, beside network reachability information, domains will exchange *path state information* (PSI) to each other. The role of PSI is to capture the “state” of resources along an inter-domain path. In other words, PSI contains the number of available lightpaths which can be set up on a particular wavelength from source to destination. This kind of information will help to drastically reduce the blocking ratio in an optical network and the number of routing messages exchanged to achieve this reduction is also smaller than that of OBGP [9].

2.2.1 Network Reachability Information

As in OBGP, OBGP+ OXCs also exchange network reachability information (NRI). The structure of NRI messages that are distributed between OBGP+ nodes is:

$$\Phi_{NRI}(d) = \Big[\text{AS-path, NH, } (\Lambda_i, M_{\Lambda_i})\Big]_d \tag{2.2.1}$$

With this structure, the information which a source can get from an NRI message consists of:

(i) Destinations d and AS-path to reach this destination.

(ii) The Next-Hop to reach the destination d.

(iii) A set of pairs $(\Lambda_i, M_{\Lambda_i})$ available for this destination d, where Λ_i is a particular wavelength and M_{Λ_i} denotes the maximum multiplicity of Λ_i.

After all OXCs in the network exchange NRI messages, each OBGP+ OXC will build a local table which contains the AS-path, next-hop OXC's IP and a set of wavelengths to reach every destination in the network. This local table is similar to the local RIB table in the OBGP case. Thus, we can assume that both OBGP and OBGP+ handle exactly the same NRI and treat it exactly in the same way.

For each destination in the network, depending on the local policy, a transit domain may filter and advertise a subset Φ_{NRI} to its upstream domains. When a new destination becomes available or unavailable, the NRI messages are triggered immediately by OBGP+. In any other case, the NRI should only change over large timescales.

2.2.2 Path State Information

Besides exchanging network reachability information (NRI), OBGP+ OXCs exchanges *Path State Information* messages (PSI) which contain the *Effective Number of Available Wavelengths* (ENAW) of a wavelength Λ_i to go to a particular OXC. ENAW of a wavelength Λ_i is the number of available lightpaths which can be set up to reach a specific OXC by using wavelength Λ_i. Thus, after the advertising process, each OBGP+ OXC will know how many lightpaths can be set up to reach a destination by using a specific wavelength Λ_i. An OBGP+ OXC advertises PSI messages by aggregating and assembling from three sources of information:

- Intra-domain ENAW (intra-domain PSI).
- ENAW of inter-domain links toward its downstream domains.

- The already aggregated PSI message which was received from downstream domains.

Firstly, we consider how to calculate the intra-domain ENAW (intra-domain PSI) of a wavelength Λ_i between two OXCs r and q inside an AS. In other words, we need to calculate how many lightpaths can be set up between OXC r and OXC q by using Λ_i.

The formula for calculating ENAW of a wavelength Λ_i between OXCs r and q in a transit domain is the following:

$$W_{r,q}(\Lambda_i) = \max_{P(r,q)} \left\{ \min_{l \in P(r,q)} [W_l(\Lambda_i)] \right\} \tag{2.2.2}$$

Wherein:
$P(r,q)$: a path between OXCs r and q.
l: is a link within the path $P(r,q)$.
Λ_i: is a particular wavelength in the path $P(r,q)$.
$W_l(\Lambda_i)$: is effective number of available wavelengths (ENAW) of Λ_i on link l.

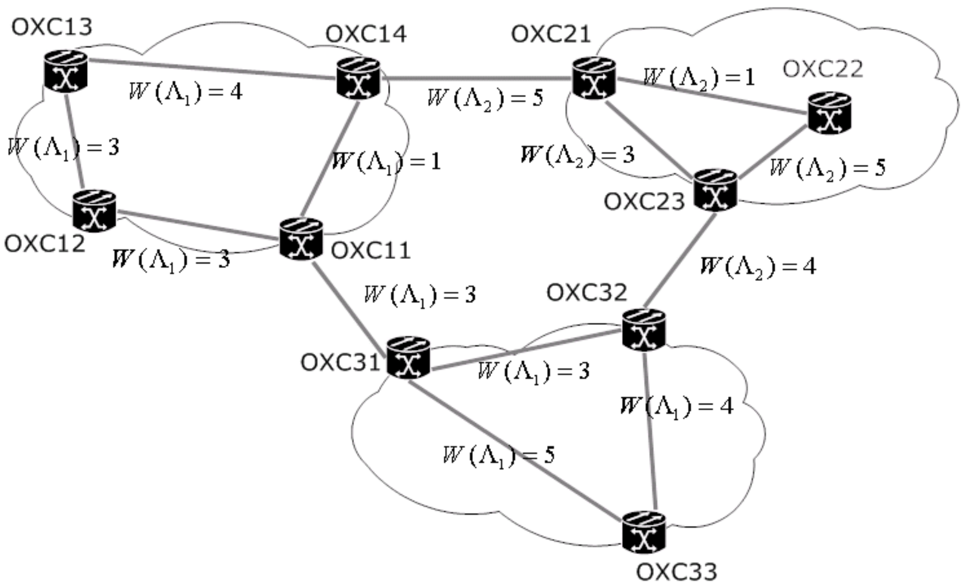


Figure 2.3: Multi-domain WDM network.

The meaning of equation 2.2.2 can be understood more clearly by considering the figure 2.3 [9]. For instance in AS1, we want to calculate the ENAW of wavelength Λ_1 between OXC14 and OXC12. In the figure 2.3, we have the two possible paths between OXC14 and OXC12 in domain AS1: (i) OXC14-OXC13-OXC12 and (ii) OXC14-OXC11-OXC12. The path that goes through OXC11 has a minimum $W_{14,11}(\Lambda_1) = 1$. It means that we can only set up 1 lightpath which uses Λ_1 on this path. Whereas the one that goes through OXC13 has a minimum $W_{13,12}(\Lambda_1) = 3$. It means that we can set up 3 lightpaths which use Λ_1 on this path. The maximum lightpaths which can be set up between both of paths is 3. In other words, ENAW of wavelength Λ_1 between OXC14 and OXC12 in the domain AS1 is $W_{14,12}(\Lambda_1) = 3$.

The ENAW given in equation 2.2.2 is especially important between two border OXCs in a domain since it captures the practical availability of the wavelength Λ_i within the domain. Moreover, it is also a highly aggregated network state information of wavelength Λ_i inside a AS and this information is intra-domain PSI portion in creating and advertising PSI messages to other domains.

Now, we consider the inter-domain portion of PSI messages. Each border OXC is aware of which wavelengths are actually being used on its inter-domain links toward its downstream domains, and when it received PSI messages from neighboring OBGP+ OXCs it would know which wavelengths are effectively available downstream. Let's consider the figure 2.4.

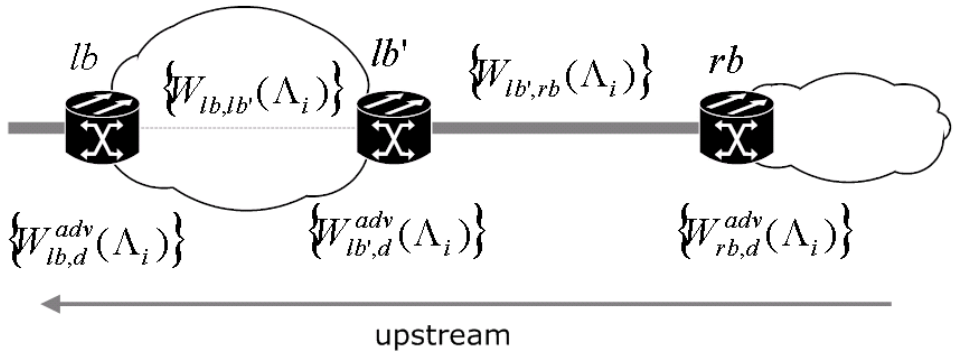


Figure 2.4: An example of aggregating ENAW.

Let $W_{lb',rb}(\Lambda_i)$ denote the ENAW of wavelength Λ_i in the inter-domain link (lb',rb) and $W^{adv}_{lb',d}(\Lambda_i)$ is the ENAW of wavelength Λ_i which will be advertised by OXC lb' to another border on the upstream direction. For instance, in the figure 2.3, the OXC11 is aware that $W_{11,31}(\Lambda_1) = 3$.

Let $W^{adv}_{rb,d}(\Lambda_i)$ denote the number of available wavelengths (ENAW) of wavelength Λ_i contained in PSI message which is advertised by downstream remote OXC rb to OXC lb' for destination d.

Let $W^{adv}_{lb',d}(\Lambda_i)$ denote the ENAW of wavelength Λ_i contained in PSI message which is advertised by OXC lb' for destination d to other OXCs in the domain. We have the formula for calculating $W^{adv}_{lb',d}(\Lambda_i)$, $W^{adv}_{lb,d}(\Lambda_i)$ at border OXC lb' and lb follows:

$$W^{adv}_{lb',d}(\Lambda_i) = \min\Big\{W_{lb',rb}(\Lambda_i), W^{adv}_{rb,d}(\Lambda_i)\Big\} \tag{2.2.3}$$

$$W^{adv}_{lb,d}(\Lambda_i) = \min\Big\{W_{lb,lb'}(\Lambda_i), W^{adv}_{lb',d}(\Lambda_i)\Big\} = \min\Big\{W_{lb,lb'}(\Lambda_i), W_{lb',rb}(\Lambda_i), W^{adv}_{rb,d}(\Lambda_i)\Big\} \tag{2.2.4}$$

We notice that, in formula 2.2.4, $W_{lb,lb'}(\Lambda_i)$ is the ENAW of wavelength Λ_i between OXC lb and lb' and is calculated as in formula 2.2.2

We consider the figure 2.3, for example, the border OXC11 advertises to its neighbor OXC14 in AS1 that the ENAW of wavelength Λ_1 to reach OXC33 is:

$$W_{11,33}^{adv}(\Lambda_1) = \min\left\{W_{11,31}(\Lambda_1), W_{31,33}^{adv}(\Lambda_1)\right\} = \min\left\{3{,}5\right\} = 3$$

And the OXC14 will continue advertising to its neighbor OXC21 that the ENAW of wavelength Λ_1 to reach OXC33 is:

$$W_{14,33}^{adv}(\Lambda_1) = \min\left\{W_{14,11}(\Lambda_1), W_{11,31}(\Lambda_1), W_{31,33}^{adv}(\Lambda_1)\right\} = \min\left\{3{,}3{,}5\right\} = 3$$

Hence, after advertising PSI messages, each OBGP+ OXC will obtain the ENAW of all wavelengths Λ_i which can be used to reach each destination d:

$$\Phi_{PSI}(d) = \left\{W_{rb,d}^{adv}\right\}_{\Lambda_i} \tag{2.2.5}$$

From this information, for each destination, each OBGP+ OXC can build a list of pair (path, wavelength) with ENAW of this wavelength. With this database, each OBGP+ OXC will generally choose the shortest-path and a wavelength with highest ENAW to reach a destination.

To advertise the PSI messages, we take advantage of the *Keepalive* messages exchanged between neighboring OBGP+ OXCs. Similar as in the case of BGP, OBGP+ OXCs exchange Keepalive messages to confirm that neighboring nodes are still alive. In BGP, Keepalive messages have fixed length, consisting only of 19-byte BGP header. In our OBGP+ model, we extend the BGP Keepalive message with the purpose of conveying PSI, when relevant PSI needs to be updated. In other words, the update of PSI is supported by the exchange of Keepalive messages between routing domains. The main advantage of this strategy is that it does not increase the number of routing messages exchanged between domains.

2.2.3 Routing and Wavelength Assignment (RWA) Strategy

As in BGP, OBGP is essentially a shortest AS-path routing algorithm that exchanges NRI messages, but it does not handle PSI. OBGP+, however, handles the highly aggregated PSI and takes ENAW into account to find the best path. The following process shows the OBGP+ decision algorithm [9].

Input:

- $\{P(s,d)\}$ - set of paths between nodes s and d.
- Λ_i - a particular wavelength on the path $P(s,d)$.
- $W(\Lambda_i)$- ENAW of wavelength Λ_i on the path $P(s,d)$.

Output: $(P_{best}, \Lambda_{best})$ - the best lightpath between s and d.

1. Choose (path, wavelength) pair with the highest local preference (LOCAL-PREF) (As in BGP).

2. If the LOCAL-PREFs are equal, choose the shortest AS-path and assign the wavelength with the highest ENAW among the ones available on that path. If more than one wavelength has the same (highest) ENAW along the shortest AS-path, choose the wavelength with the lowest identifier i.

3. If the AS-path lengths are equal choose the (path, wavelength) pair associated with the highest ENAW.

4. If the ENAWs are equal prefer external paths over internal paths.

5. If the paths are still equal prefer the one with the highest ENAW to the next-hop OXC (i.e., to the OXC r_b in the neighboring domain).

6. If more than one path is still available run OBGP tie-breaking rules (As in BGP) [23].

From the above algorithm, it is clear that OBGP+ is essentially a "shortest AS-path highest ENAW" RWA algorithm. In other words, for each destination, it will choose the shortest AS-path (step 2 of the process), but if more than one candidate lightpath exists, then it chooses the wavelength which has highest ENAW (step 3).

2.3 IDRA-based Routing Protocol

This protocol is an alternative approach in controlling and advertising update messages between domains in a WDM network. It introduces a new *route control mode* and new component: *inter-domain routing agents* (IDRAs). These IDRAs are responsible for exchanging all update messages between domains. IDRA also handles NRI and PSI messages to get information of the network, but information contained in these messages is different with ones of OBGP or OBGP+. In this part, we only focus on information which IDRAs exchange to help finding a best path to reach a destination.

2.3.1 Route Control Architecture

In this protocol, we denote a new concept which is the Routing Control Domain (RCD). RCD is a set of OXCs which can reach each other in a same domain. Each domain has one or many RCDs depending on its scale. Each RCD has an inter-domain routing agent (IDRA) which is responsible for all OXCs in this RCD to exchange information with other RCDs. All IDRAs in the WDM network are connected together by different optical links used to transfer data as shown in the figure 2.5 [24]. Such network is called the control plane of an optical network. We can see that the control plane is fully distributed and decoupled from the data plane.

The IDRAs in RCDs are responsible for exchanging inter and intra domain routing information. On the one hand, they are the ones that distribute the routing and signaling information between domains and nodes inside the domain. On the other hand, they are in charge of the computation and establishment of intra and inter domain lightpaths. IDRAs will act as the

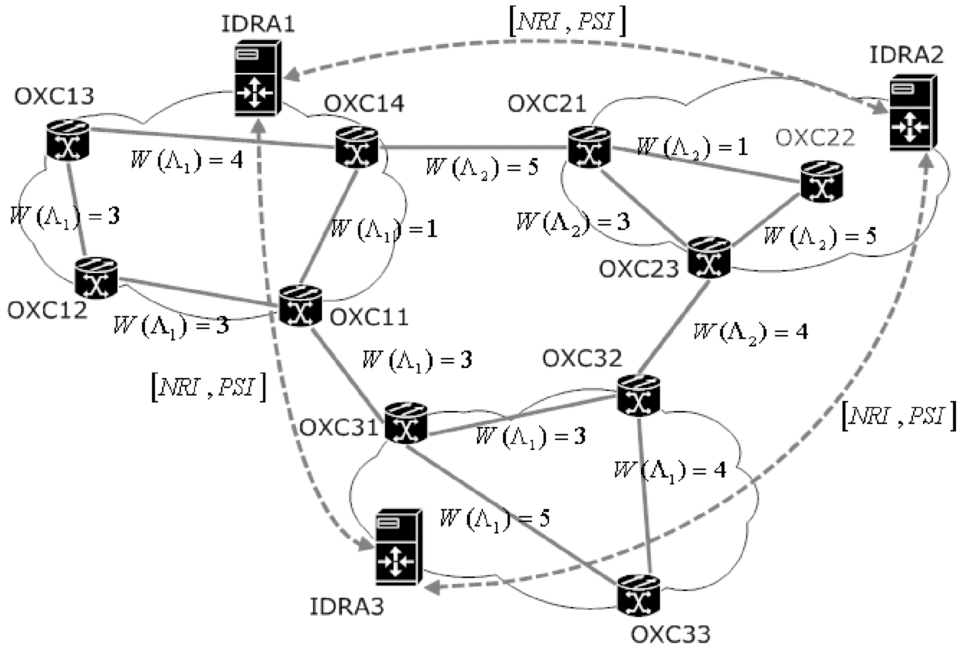


Figure 2.5: Control network and data network in IDRA-based routing protocol.

glue between the intra-domain and inter-domain routing schemes of RCDs. They can compute primary and backup lightpaths subject to performance and/or reliability constraints. Other advantages of such routing control plane have been discussed in [25].

The IDRA-based routing protocol which we will describe runs in the IDRAs. The advertisements distributed by the IDRAs include the usual NRI and PSI, but the information contained in these messages is different. In the following parts, we will describe the kind of information included in these messages.

2.3.2 Network Reachability Information

Depending on the domain's routing policies, each domain will choose a subset of wavelengths that can be used to reach the local networks. The structure of NRI messages which IDRAs exchange together will be:

$$\Phi_{NRI}(d) = \Big[\text{NH},\ (\Lambda_i, M_{\Lambda_i})\Big]_d \tag{2.3.1}$$

With this structure, the information contained in the NRI messages sent by IDRAs consists of:

- The set of destinations.
- The next-hop OXC of a different domain to reach those destinations.

- A set of pair (Λ_i, M_i) for each destination, where Λ_i is a particular wavelength and M_i denotes the maximum multiplicity of Λ_i.

Comparing with equation 2.2.1, we notice that, conversely to OBGP+ and BGP, the NRI exchanged by IDRAs does not contain the AS-path to reach a destination. In this protocol, rather than comparing candidate routes according to the length of the AS-path, the IDRAs use information contained in the PSI messages to compare the routes. As we will see later, this kind of information will actually depend on the length of the AS-path during aggregating along the path. Another important difference between BGP and the IDRA-based routing protocol is that instead of advertising only the best route for any given destination, the IDRAs can advertise multiple routes per destination, even with the same NH address.

2.3.3 Path State Information

Each path advertised by the IDRAs has associated path state information (PSI), which is composed of *aggregated wavelength availability information* (ENAW) and *aggregated cost* of a wavelength on this path. The way to aggregate ENAW for each destination is the same as in OBGP+ so we will not describe it again. Important information we want to describe here is the aggregated cost of a wavelength on a specific path.

The IDRAs advertise the aggregated cost of a wavelength on a path by aggregating and assembling the following three sources of information:

- Intra-domain ENAW.
- ENAW related to the inter-domain link toward its downstream domains.
- The already aggregated cost contained in the inter-domain PSI messages advertised from downstream domains.

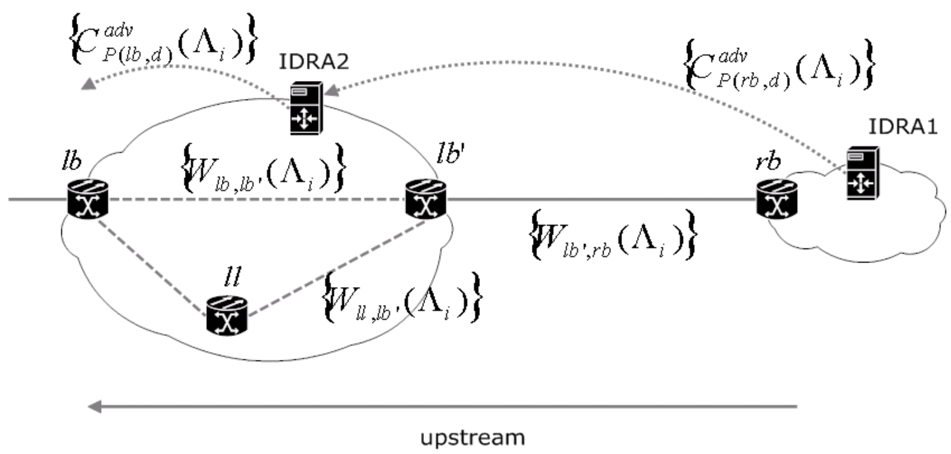


Figure 2.6: An example of aggregating cost.

Let's consider the figure 2.6. We assume that the cost of wavelength Λ_i from OXC rb to destination OXC d advertised by the downstream IDRA1 is $C^{adv}_{P(rb,d)}(\Lambda_i)$. We will have the cost of wavelength Λ_i from OXC lb to destination OXC d advertised by IDRA2 to upstream domain or upstream RCDs as follows:

$$C^{adv}_{P(lb,d)}(\Lambda_i) = \begin{cases} H\left[\frac{1}{\min\left[W_{lb,lb'}(\Lambda_i),M(\Lambda_i)\right]} + \frac{1}{\min\left[W_{lb',rb}(\Lambda_i),M(\Lambda_i)\right]} + \frac{C^{adv}_{P(rb,d)}(\Lambda_i)}{H^{adv}}\right] \\ \propto \text{ if } W_{lb,lb'}(\Lambda_i) = 0 \text{ or } W_{lb',rb}(\Lambda_i) = 0 \end{cases} \tag{2.3.2}$$

Wherein, H is the number of hops from OXC lb to destination d, considering each RCD or domain sub-path as just one hop. H^{adv} is the number of hops between the remote border OXC rb and destination d, advertised by the downstream IDRA1 in the rb's domain. The $\propto$ in formula 2.3.2 reflects the lack of resources to handle a connection between OXC lb and destination d for a particular wavelength Λ_i.

This cost in formula 2.3.2 is also the cost which is associated with an AS-path $P(lb, d)$ from local OXC lb to destination OXC d. OXC ll is one of local OXCs in RCD of IDRA2. From formula 2.3.2, replacing OXC lb by OXC ll, the cost which is associated with a candidate path $P(ll, d)$ is computed by IDRA2 as follows:

$$C_{P(ll,d)}(\Lambda_i) = \begin{cases} H\left[\frac{1}{\min\left[W_{ll,lb'}(\Lambda_i),M(\Lambda_i)\right]} + \frac{1}{\min\left[W_{lb',rb}(\Lambda_i),M(\Lambda_i)\right]} + \frac{C^{adv}_{P(rb,d)}(\Lambda_i)}{H^{adv}}\right] \\ \propto \text{ if } W_{ll,lb'}(\Lambda_i) = 0 \text{ or } W_{lb',rb}(\Lambda_i) = 0 \end{cases} \tag{2.3.3}$$

Wherein, H is the number of hops from OXC ll to destination d.

We notice that the cost which is associated with AS-path $P(lb', d)$ (from OXC lb' to OXC d) is computed by IDRA2 as follows:

$$C_{P(ll,d)}(\Lambda_i) = \begin{cases} H\left[\frac{1}{\min\left[W_{lb',rb}(\Lambda_i),M(\Lambda_i)\right]} + \frac{C^{adv}_{P(rb,d)}(\Lambda_i)}{H^{adv}}\right] \\ \propto \text{ if } W_{lb',rb}(\Lambda_i) = 0 \end{cases} \tag{2.3.4}$$

Wherein, H is the number of hops from OXC lb' to destination d.

In summary, combining with aggregated wavelength availability information (ENAW), the structure of PSI messages received by an IDRA is composed for a destination d as follows:

$$\Phi_{PSI}(d) = \left\{ W^{adv}_{rb,d}, \left(C^{adv}_{P(rb,d)}, H^{adv} \right) \right\}_{\Lambda_i} \tag{2.3.5}$$

With this structure, for each destination, each IDRA will have a list of pairs (path, wavelength) with the cost and ENAW of each pair. From formulas 2.3.2, 2.3.3 and 2.3.4, we found that the cost reflects the current load of a particular wavelength in an inter-domain path, allowing an IDRA to compare routes more accurately than directly using the ENAWs between source and destination. If the load of a wavelength in an inter-domain path is high, the cost of that wavelength on that path will also be high and vice versa. In other words, the cost will increase when the ENAW of Λ_i on each link along an inter-domain path decreases. Moreover, the cost also increases when the length of an inter-domain path (number of hops) increases so an IDRA will generally choose the (path, wavelength) with lowest cost (less load).

For instance, in the figure 2.5, we have two paths to go from OXC14 to OXC32:

- The first path goes through AS1 on wavelength Λ_1: ENAW of Λ_1 is $W_{14,33}(\Lambda_1) = 3$ and number of hops is $H = 3$. Applying formula 2.3.2, the cost of the first path will be: $C_{14,33}(\Lambda_1) = 3[1/3 + 1/3 + 1/3] = 3$.

- The second path goes through AS2 on wavelength Λ_2: ENAW of Λ_2 is also $W_{14,33}(\Lambda_2) = 3$ and number of hops is also $H = 3$. But, applying formula 2.3.2, the cost of the second path will be: $C_{14,33}(\Lambda_2) = 3[1/5 + 1/3 + 1/4] = 2.35$.

It is shown that these two paths have the same ENAW and same number of hops to reach the destination, but IDRA1 will prefer the second path because the cost of the second path is lower than the one of the first path.

As in OBGP+, PSI messages of IDRAs will be embedded in Keepalive messages and be transferred only when relevant PSI needs to be updated. The aim of this approach is to decrease the number and frequency of the routing messages exchanged between domains.

2.3.4 Routing and Wavelength Assignment Strategy

The following process describes steps of the lightpath selection in IDRA-based routing protocol [10].

Input:

- $\{P(s, d)\}$ - set of paths between nodes s and d.
- Λ_i - a particular wavelength on the path $P(s, d)$.
- $C_{P(s,d)}(\Lambda_i)$ - the cost of wavelength Λ_i on the path $P(s, d)$.
- $W(\Lambda_i)$- ENAW of wavelength Λ_i on the path $P(s, d)$.

Output: $(P_{best}, \Lambda_{best})$ - the best lightpath between s and d.

1. Choose (path, wavelength) pair with the highest local preference. (LOCAL-PREF) (As in BGP).
2. If the LOCAL-PREFs are equal, choose the (path, wavelength) pair with the minimum cost.
3. If the costs are equal choose the (path, wavelength) pair associated with the highest ENAW.

4. If the ENAWs are equal choose the path with the shortest number of hops H, and assign the wavelength Λ_i with the lowest identifier i.
5. If the hops H are still equal prefer the one with the highest ENAW to the remote next-hop OXC (i.e., to the OXC rb in the neighboring downstream domain in the figure 2.6).
6. If more than one path is still available run OBGP tie-breaking rules (As in BGP) [23].

This process shows that the IDRAs choose minimum-cost paths (step 1), and if more than one path shows the same (minimum) cost, the IDRAs break the tie first by the highest ENAW along the candidate paths, then by the shortest number of hops H, and after that by following essentially the same steps as BGP.

Chapter 3

Converter lightpaths

To evaluate the efficiency of wavelength converters, we will put a pool of converters at all border OXCs of each domain. With the presence of converters at the border, we realize that the number of lightpaths which go through the border OXCs will increase in both directions (from inside a domain to outside a domain and vice versa), because we can use different wavelengths at two sides of the OXC to set up a lightpath. In this chapter, at a border OXC, we classify two types of lightpaths: converter lightpaths which use converters at the OXC and non-converter lightpaths which have a continuous wavelength across the OXC.

In this chapter we will show how many lightpaths are added due to converters at border OXCs and how to change the set of ENAWs which will be advertised to upstream domains at a border OXC to help a source know that it has more lightpaths to go to a destination.

3.1 Calculating Converter Lightpaths

To calculate the number of lightpaths which have increased due to the presence of wavelength converters in the network, we consider two ASs as in the figure 3.1 under two cases: (i) no converters at border OXC lb, lb', and rb; (ii) some converters at border OXC lb, lb' and rb.

In the figure 3.1, we also assume that:

- The set of ENAWs which are advertised by OXC rb to lb' for destination d is: $\{3, 4, 2, 3\}$.
- The set of ENAWs of all wavelengths on inter-domain link (lb', lb) is $\{2, 3, 5, 6\}$.
- The set of ENAWs of all wavelengths between (lb, lb') is: $\{4, 3, 1, 7\}$.

3.1.1 Case 1: no converter

In this case, we only have one type of lightpaths: non-converter lightpaths. Thus, the number of lightpaths from an OXC to a destination d is also the number of non-converters lightpaths from

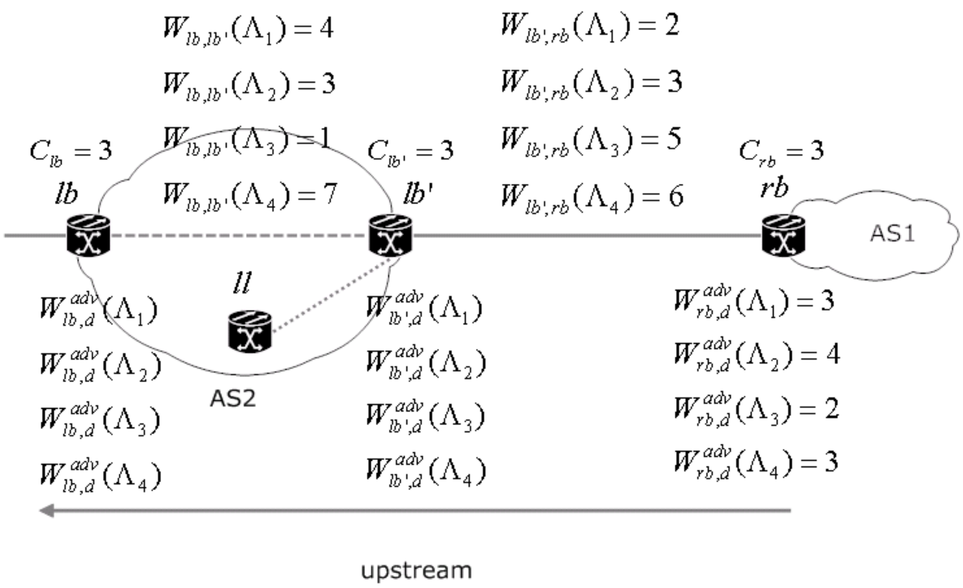


Figure 3.1: An example of calculating the number of lightpaths.

this OXC to reach destination d. The number of non-converter lightpaths $N^{nc}(d)$ will be:

$$N^{nc}(d) = \sum_i W_d^{adv}(\Lambda_i) \tag{3.1.1}$$

For example, from OXC rb we have the number of non-converter lightpaths to reach the destination d is:

$$N_{rb}^{nc}(d) = \sum_i W_{rb,d}^{adv}(\Lambda_i) = 3 + 4 + 2 + 3 = 12 \tag{3.1.2}$$

From OXC lb' we have the number of non-converter lightpaths to reach the destination d is:

$$N_{lb'}^{nc}(d) = \sum_i W_{lb',d}^{adv}(\Lambda_i) \tag{3.1.3}$$

Applying formula 2.2.3, we have a set of ENAWs which are advertised by OXC lb' to lb for destination d is: $\left\{ W_{lb',d}^{adv}(\Lambda_1) = 2,\, W_{lb',d}^{adv}(\Lambda_2) = 3,\, W_{lb',d}^{adv}(\Lambda_3) = 2,\, W_{lb',d}^{adv}(\Lambda_4) = 3 \right\}$ and:

$$N_{lb'}^{nc}(d) = \sum_i \min\left\{ W_{lb',rb}(\Lambda_i),\, W_{rb,d}^{adv}(\Lambda_i) \right\} = 2 + 3 + 2 + 3 = 10 \tag{3.1.4}$$

From OXC lb we have the number of non-converter lightpaths to reach the destination d is:

$$N_{lb}^{nc}(d) = \sum_i W_{lb,d}^{adv}(\Lambda_i) \tag{3.1.5}$$

Applying formula 2.2.4, we have a set of ENAWs which are advertised by OXC lb to upstream domain for destination d is: $\Big\{W^{adv}_{lb,d}(\Lambda_1) = 2, W^{adv}_{lb,d}(\Lambda_2) = 3, W^{adv}_{lb,d}(\Lambda_3) = 1, W^{adv}_{lb,d}(\Lambda_4) = 3\Big\}$ and:

$$N^{nc}_{lb}(d) = \sum_i \min\Big\{W_{lb,lb'}(\Lambda_i), W^{adv}_{lb',d}(\Lambda_i)\Big\} =$$

$$\sum_i \min\Big\{W_{lb,lb'}(\Lambda_i), W_{lb',rb}(\Lambda_i), W^{adv}_{rb,d}(\Lambda_i)\Big\} = 2 + 3 + 1 + 3 = 9 \qquad (3.1.6)$$

3.1.2 Case 2: some converters at border OXCs

In this case, we have two types of lightpaths: non-converter lightpaths and converter lightpaths. Thus, the number of lightpaths which had increased is equal to the number of converter lightpaths. The number of lightpaths to reach a destination d at an OXC will be the sum of non-converter lightpaths and converter lightpaths which can be used to reach that destination. Let's consider border OXC lb', we have the formula:

$$S_{lb'}(d) = N^{nc}_{lb'}(d) + N^{c}_{rb}(d) \qquad (3.1.7)$$

Wherein:

- $S_{lb'}(d)$ denotes the number of lightpaths from OXC lb' to destination d.
- $N^{nc}_{lb'}(d)$ denotes the number of non-converter lightpaths to reach destination d from OXC lb'.
- $N^{c}_{rb}(d)$ denotes the number of converter lightpaths which can be set up across the OXC rb to reach destination d from lb'.

The number of converter lightpaths, $N^{c}_{rb}(d)$, is the minimum of three values: the number of wavelengths (that are not used by non-converter lightpaths) on both sides of the border OXC rb and the number of available converters C_{rb} at OXC rb. We notice that $N^{nc}_{lb'}(d)$ also represents the number of wavelengths which are used by non-converter lightpaths and can be calculated as formula 3.1.4. We call $L_{rb}(d)$, $R_{rb}(d)$ as the number of wavelengths that are not used by non-converter lightpaths on *left side* and *right side* of the border OXC rb. We have formulas for $L_{rb}(d)$ and $R_{rb}(d)$:

$$L_{rb}(d) = \sum_i W_{lb',rb}(\Lambda_i) - N^{nc}_{lb'}(d) \qquad (3.1.8)$$

$$R_{rb}(d) = \sum_i W^{adv}_{rb,d}(\Lambda_i) - N^{nc}_{lb'}(d) \qquad (3.1.9)$$

Applying formula 3.1.4, we have:

$$L_{rb}(d) = \sum_i W_{lb',rb}(\Lambda_i) - \sum_i \min\Big\{W_{lb',rb}(\Lambda_i), W^{adv}_{rb,d}(\Lambda_i)\Big\} \tag{3.1.10}$$

$$R_{rb}(d) = \sum_i W^{adv}_{rb,d}(\Lambda_i) - \sum_i \min\Big\{W_{lb',rb}(\Lambda_i), W^{adv}_{rb,d}(\Lambda_i)\Big\} \tag{3.1.11}$$

Finally, we will have the formula for the number of converter lightpaths to reach destination d from OXC lb':

$$N^c_{rb}(d) = \min\Big\{L_{rb}(d)\ ,\ R_{rb}(d)\ ,\ C_{rb}\Big\} \tag{3.1.12}$$

Wherein, C_{rb} is the number of available converters at OXC rb.

From formulas 3.1.10, 3.1.11, 3.1.12 and 3.1.7, we can calculate the number of converter lightpaths and total number of lightpaths to reach destination d from OXC lb basing on the set of ENAWs of wavelengths on interdomain link (lb', rb) $\{W_{lb',rb}(\Lambda_i)\}$ and the set of ENAWs of wavelengths advertised by OXC rb $\{W^{adv}_{rb,d}(\Lambda_i)\}$

For example in the figure 3.1. Applying formula 3.1.4, we have the number of non-converter lightpaths at OXC lb' will be:

$$N^{nc}_{lb'}(d) = 2 + 3 + 2 + 3 = 10$$

Applying formula 3.1.10 and 3.1.11, we have the number of wavelengths that are not used by non-converter lightpaths on *left side* and *right side* of the border OXC rb are:

$$L_{rb}(d) = (2 + 3 + 5 + 6) - (2 + 3 + 2 + 3) = 6 \tag{3.1.13}$$

$$R_{rb}(d) = (3 + 4 + 2 + 3) - (2 + 3 + 2 + 3) = 2 \tag{3.1.14}$$

We assume that the number of available converters at OXC rb $C_{rb} = 3$. Applying formula 3.1.12, we have the number of non-converter lightpaths from OXC lb' will be:

$$N^c_{rb}(d) = \min\Big\{6\ ,\ 2\ ,\ 3\Big\} = 2 \tag{3.1.15}$$

Applying formula 3.1.7, the total number of lightpaths to reach destination d from OXC lb' will be

$$S_{lb'}(d) = 10 + 2 = 12 \tag{3.1.16}$$

We call OXC ll one of the local OXCs in AS2. Applying formulas 3.1.10, 3.1.11, 3.1.12 for OXC ll, we have the number of converter lightpaths from OXC ll to destination d will be:

$$L_{lb'}(d) = \sum_i W_{ll,lb'}(\Lambda_i) - \sum_i \min\Big\{W_{ll,lb'}(\Lambda_i), W^{adv}_{lb',d}(\Lambda_i)\Big\} \tag{3.1.17}$$

$$R_{lb'}(d) = \sum_i W^{adv}_{lb',d}(\Lambda_i) - \sum_i \min\Big\{W_{ll,lb'}(\Lambda_i),\, W^{adv}_{lb',d}(\Lambda_i)\Big\} \tag{3.1.18}$$

$$N^c_{ll}(d) = \min\left\{L_{lb'}(d)\ ,\ R_{lb'}(d)\ ,\ C_{lb'}\right\} \tag{3.1.19}$$

We notice that if we replace OXC ll by OXC lb, we will have the formula for the number of converter lightpaths from OXC lb.

3.2 Advertising Converter Lightpaths

After having the number of converter lightpaths, we need to advertise these lightpaths to other OXCs. One way to do this work is to assign them specific wavelengths before being advertised to another border OXC. For that purpose, the method we use here is to randomly select from the wavelengths which are not used by non-converter lightpaths.

Let's consider OXC lb' in the figure 3.1. In the case of no converters, from formula 2.2.3, OXC lb' will advertise a set of ENAWs of wavelengths for destination d: $\Big\{W^{adv}_{lb',d}(\Lambda_1) = 2, W^{adv}_{lb',d}(\Lambda_2) = 3, W^{adv}_{lb',d}(\Lambda_3) = 2, W^{adv}_{lb',d}(\Lambda_4) = 3\Big\}$.

In the case of some converters at border OXC, from 3.1, we have 2 converter lightpaths at OXC lb' and wavelengths which are not used by non-converter lightpaths between OXC lb' and OXC rb are: 3 wavelengths Λ_3 and 3 wavelengths Λ_4. We can randomly choose 2 wavelengths of 6 free wavelengths to advertise to other OXCs. For example, we can use 2 wavelengths Λ_3 to advertise for 2 converter lightpaths and OXC lb' will advertise a set of ENAWs of wavelengths for destination d: $\Big\{W^{adv}_{lb',d}(\Lambda_1) = 2, W^{adv}_{lb',d}(\Lambda_2) = 3, W^{adv}_{lb',d}(\Lambda_3) = 4, W^{adv}_{lb',d}(\Lambda_4) = 3\Big\}$. We also can choose 1 wavelength Λ_3 and 1 wavelength Λ_4 to advertise for 2 converter lightpaths and OXC lb' will advertise a set of ENAWs of wavelengths for destination d: $\Big\{W^{adv}_{lb',d}(\Lambda_1) = 2, W^{adv}_{lb',d}(\Lambda_2) = 3, W^{adv}_{lb',d}(\Lambda_3) = 3, W^{adv}_{lb',d}(\Lambda_4) = 4\Big\}$.

We consider OXC lb in the figure 3.1 as another example. We assume that the set of ENAWs of wavelengths which are advertised by OXC lb' will be: $\Big\{W^{adv}_{lb',d}(\Lambda_1) = 2, W^{adv}_{lb',d}(\Lambda_2) = 3, W^{adv}_{lb',d}(\Lambda_3) = 3, W^{adv}_{lb',d}(\Lambda_4) = 4\Big\}$ (case 2).

Applying formulas 3.1.17, 3.1.18 and 3.1.19, we have the number of converter lightpaths from OXC lb to destination d:

$$L_{lb'}(d) = \sum_i W_{lb,lb'}(\Lambda_i) - \sum_i \min\Big\{W_{lb,lb'}(\Lambda_i),\, W^{adv}_{lb',d}(\Lambda_i)\Big\}$$

$$= (4 + 3 + 1 + 7) - (2 + 3 + 1 + 4) = 5 \tag{3.2.1}$$

$$R_{lb'}(d) = \sum_i W^{adv}_{lb',d}(\Lambda_i) - \sum_i \min\Big\{W_{lb,lb'}(\Lambda_i), W^{adv}_{lb',d}(\Lambda_i)\Big\}$$

$$= (2+3+3+4) - (2+3+1+4) = 2 \qquad (3.2.2)$$

$$N^c_{lb}(d) = \min\big\{L_{lb'}(d)\ , R_{lb'}(d)\ , C_{lb'}\big\} = \min\big\{5{,}2{,}3\big\} = 2 \qquad (3.2.3)$$

From OXC lb we also have two converter lightpaths to reach destination d. Moreover, we have 5 free wavelengths which are not used by non-converter lightpaths between OXC lb and OXC lb' including: 2 wavelengths Λ_1 and 3 wavelengths Λ_4. After that we can randomly assign these wavelengths to advertise two converter lightpaths. For instance, we can take two wavelengths Λ_4 and a set of ENAWs of wavelengths advertised by OXC lb to the upstream domain for destination d will be: $\Big\{W^{adv}_{lb,d}(\Lambda_1) = 2, W^{adv}_{lb,d}(\Lambda_2) = 3, W^{adv}_{lb,d}(\Lambda_3) = 1, W^{adv}_{lb,d}(\Lambda_4) = 6\Big\}$.

We notice that from formula 3.1.7, the total number of lightpaths that can be used from OXC lb to reach destination d is 12 lightpaths. While, in the case of no converters, from formula 3.1.6, the total number of lightpaths that can be used from OXC lb to reach destination d is only 9 lightpaths. This means that we have 3 more paths available because of the presence of converters.

Chapter 4

Simulation

In this chapter, we develop our simulations from previous simulations in [9, 10] to evaluate the performance of OBGP, OBGP+ and IDRA-based routing protocol in an optical network with wavelength converters at border OXCs of each domain. The simulations in [9,10] do not support the wavelength converters. The main parts we modified from the previous simulation include:

- Add C/C++ codes to implement wavelength converters at border OXCs of each domain.
- Modify all procedures of ENAW advertising processes to able to support to advertise converter lightpaths.
- Modify all procedures of setting lightpaths to be able to support to set up a converter lightpath.
- Modify all procedures of releasing lightpaths to be able to support to release a converter lightpath.

Our interest in this section is to compare the three protocols with two different performance metrics: the blocking ratio (BR) of inter-domain lightpath requests and the number of routing messages exchanged to achieve this blocking.

4.1 Simulation Environment

The software we use to develop our simulation is OPNET Modeler [26]. OPNET Modeler is a popular simulation software which can be used to simulate many different kinds of network in telecommunication and computer networks. Our multi-domain network for simulation is the PAN European Optical Transport Network topology as shown in the figure 4.1.

This optical network was introduced in [20] as a reference topology suited for a PAN-European Optical Transport Network. The reason we choose this topology is due to the fact that this topology network has been increasingly used as a reference simulation optical network [10].

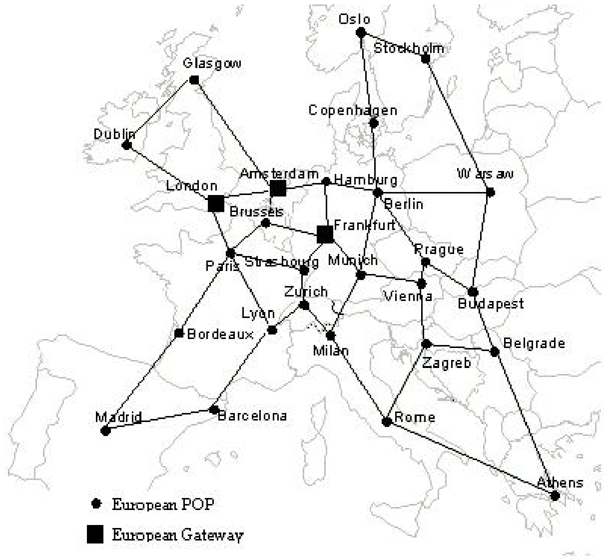


Figure 4.1: PAN-European network topology.

This multi-domain network includes 28 domains and 41 inter-domain links. For the network topology inside each domain in the PAN European network, we have randomly chosen a number of OXCs which is equal or higher than the number of inter-domain links of that domain. In this network, we have randomly placed 18 sources and 10 destinations, covering the entire PAN European network. Each domain of the network has only one source or one destination. In other words, we simulate inter-domain traffic which is transferred between domains. In our simulation, traffic was modeled according to a Poisson distribution with exponentially distributed arrival and departure rates. The blocking ratio and routing messages are collected under different traffic loads, varying from 100 up to 300 Erlangs.

In our network, all links which connect OXCs are the same. Each link has 5 fibers and each fiber has 14 wavelengths. Inside each domain, we reserve two wavelengths for intra-domain traffic and 12 wavelengths for inter-domain traffic on each intra-domain link. But between domains, we still have 14 wavelengths on each inter-domain link. It means that we have two more wavelengths on each fiber of inter-domain links for transferring inter-domain traffic. Totally, we will have 10 more wavelengths on each inter-domain link (each inter-domain link has 5 fibers).

To evaluate the performance of the inter-domain routing protocols with converters, we will simulate three protocols OBGP, OBGP+ and IDRA with 5 converters and 10 converters at each border OXC of domains in our network. It is worth emphasizing that our results shown here are the averages over 20 different PAN European network configurations for each case. Each PAN European network configuration differs each other from the places of sources and destinations or network topology inside each domain. In order to evaluate the impact of the frequency of updates in the PSI message, we have used different *Keepalive Update Intervals* K_T during simulation. K_T corresponds to the time interval between the exchanging of non-dummy Keepalive messages containing PSI messages. In our simulations we have tested three different values of K_T: K_T = 1, K_T = 3 and K_T = 5 units through the simulation run-time. Clearly, the higher the values of K_T, the more time is needed by OXC to detect and react when a neighbor becomes inoperative. Therefore, a major advantage of embedding PSI messages in Keepalive messages is that when we set the value of K_T low to increase the responsiveness between OXC neighbors, PSI messages will update more frequently.

4.2 Performance Evaluation

In this section, we will compare the performance of three protocols in the PAN European network with wavelength converters at border OXCs of each domain under two main metrics: blocking ratio and the number of routing messages.

4.2.1 Blocking Ratio (BR)

Figures 4.2, 4.3 and 4.4 show the average blocking ratio and the standard deviation of the blocking ratios of the three protocols in PAN European network with 5 wavelength converters at border OXCs of each domain, for the different traffic loads, and the different keepalive update intervals K_T: $K_T = 1$, $K_T = 3$ and $K_T = 5$.

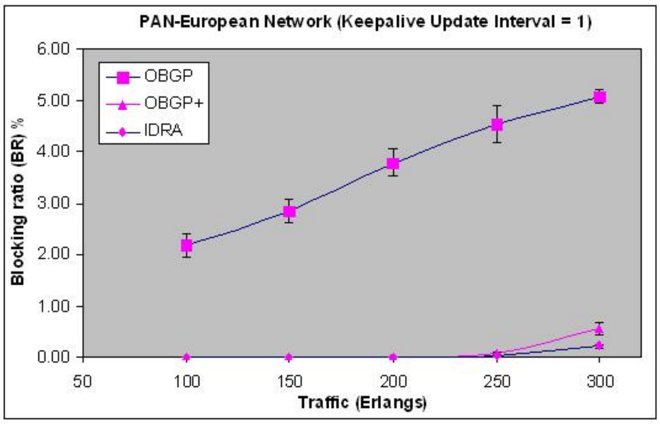


Figure 4.2: Blocking Ratio of three protocols with K_T = 1.

Clearly, IDRA protocol and OBGP+ outperform OBGP in blocking ratio. Moreover, we found that IDRA-based routing protocol is the best protocol among the three protocols. The reason for this is that a source in the IDRA-based routing protocol has more information about a destination than a source has in other protocols. As a result, it can find out the better route and wavelength to reach a destination than other protocols. Figures 4.5, 4.6 and 4.7 contrast the blocking ratio of OBGP+ and IDRA in detail.

These figures also show that the performance of the three protocols decreases when K_T increases. The reason is that when K_T increases, the time which a source node needs to detect the lightpaths or wavelengths which are no longer available to reach a destination is longer (information of resource is updated by Keepalive messages) so the blocking ratio will increase.

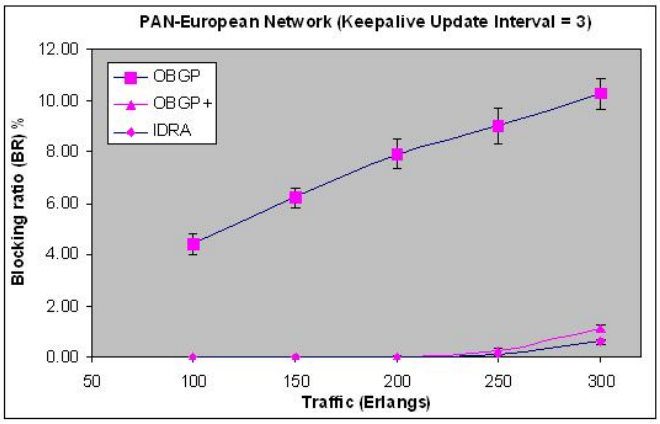


Figure 4.3: Blocking Ratio of three protocols with K_T = 3.

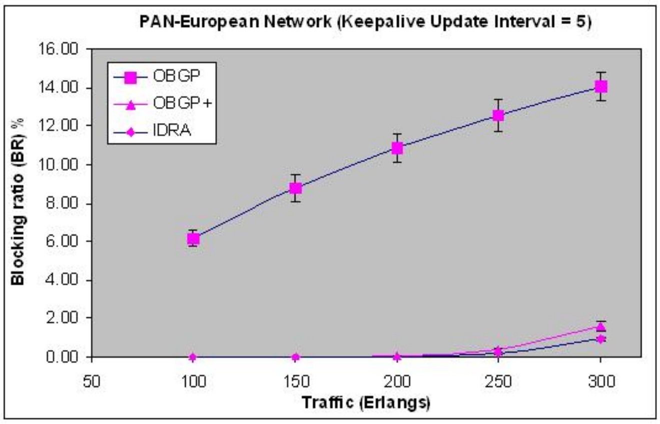


Figure 4.4: Blocking Ratio of three protocols with K_T = 5.

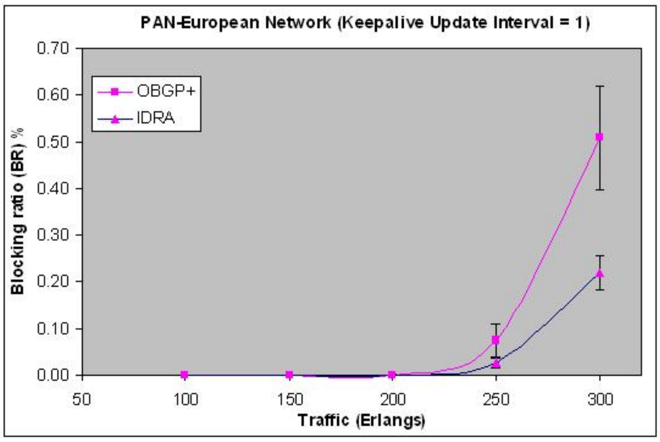


Figure 4.5: Blocking Ratio of OBGP+ and IDRA with K_T = 1.

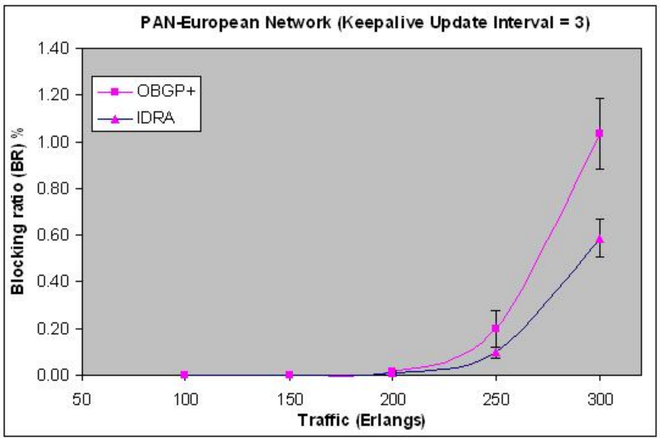


Figure 4.6: Blocking Ratio of OBGP+ and IDRA with K_T = 3.

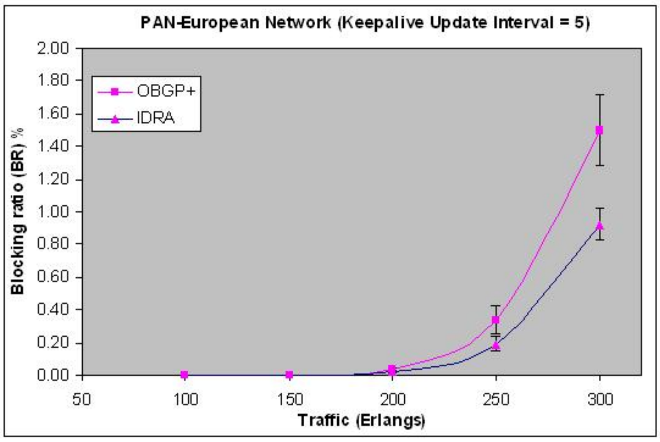


Figure 4.7: Blocking Ratio of OBGP+ and IDRA with K_T = 5.

	Keepalive Update Interval ($K_T = 1$)			Keepalive Update Interval ($K_T = 3$)			Keepalive Update Interval ($K_T = 5$)		
	200 Erlangs	250 Erlangs	300 Erlangs	200 Erlangs	250 Erlangs	300 Erlangs	200 Erlangs	250 Erlangs	300 Erlangs
Improv. Factor (IF)	3651.82	66.58	11.06	542.08	47.81	10.36	314.25	37.63	9.61

Traffic (Erlangs)	Routing Messages OBGP	Routing Messages OBGP+	Routing Messages OBGP	Routing Messages OBGP+	Routing Messages OBGP	Routing Messages OBGP+
100	7336872	4106295	6553396	4045380	5780205	3996540
150	8481770	3999754	7065798	3920216	6137845	3830622
200	9254621	4002240	7634377	3881279	6391353	3775545
250	9384634	4025299	7507066	3916735	6365559	3824549
300	9613223	4783811	7512710	4481222	6304995	4259

Table 4.1: Improvement Factor and overall number of routing messages exchanged of OBGP+ vs OBGP.

4.2.2 Routing Messages and Improvement Factor

In order to quantify the performance between two protocols in terms of blocking, we introduce a new term: *Improvement Factor (IF)*. We assume that the performance of protocol A is better than the performance of protocol B. The IF of protocol A comparing with protocol B is defined as follows:

$$IF(A, B) \triangleq \left(\frac{BR^{(B)}}{BR^{(A)}} \right)_{\text{Traffic (Erlangs)}} \tag{4.2.1}$$

The tables 4.1, 4.2 and 4.3 summarize the improvement factor IF and the number of routing messages exchanged of each pair of protocols (OBGP+ vs OBGP), (IDRA vs OBGP) and (IDRA vs OBGP+) for the different traffic loads and keepalive update intervals to archive these blocking ratios shown in figures 4.2, 4.3 and 4.4.

Tables 4.1 and 4.2 confirm that in the PAN European network with wavelength converters, the IDRA protocol and OBGP+ always need less overall number of routing messages than OBGP. The reason for this is twofold. Firstly, because PSI update messages are embedded in the Keepalive messages used in the three protocols and no extra messages are generated to advertise PSI information. Hence, the number of routing messages in two protocols does not increase although source nodes still have information about resource of network. Secondly, we notice that if a request becomes blocked, this triggers to exchange network reachability messages and path exploration. Because the blocking ratio of OBGP is higher than OBGP+ and the IDRA protocol, the frequency of triggers in OBGP is higher than OBGP+ and IDRA so the number of routing messages in OBGP is larger than OBGP+ and IDRA.

In table 4.3, we also found that the number of routing messages in IDRA is smaller than the ones in OBGP+ in all cases of Keepalive Update Interval K_T. We have this result because in OBGP+ the inter-domain routing messages are exchanged to reach all the OXC nodes in

	Keepalive Update Interval $(K_T = 1)$			**Keepalive Update Interval** $(K_T = 3)$			**Keepalive Update Interval** $(K_T = 5)$		
	200 Erlangs	250 Erlangs	300 Erlangs	200 Erlangs	250 Erlangs	300 Erlangs	200 Erlangs	250 Erlangs	300 Erlangs
Improv. Factor (IF)	5239.75	188.36	25.68	832.31	96.96	18.3	525.59	66.12	15.62

Traffic (Erlangs)	Routing Messages OBGP	Routing Messages IDRA	Routing Messages OBGP	Routing Messages IDRA	Routing Messages OBGP	Routing Messages IDRA
100	7336872	3337685	6553396	3280974	5780205	3226164
150	8481770	3382931	7065798	3297536	6137845	3213501
200	9254621	3402343	7634377	3285279	6391353	3179529
250	9384634	3429541	7507066	3291311	6365559	3160378
300	9613223	3630224	7512710	3409693	6304995	3243739

Table 4.2: Improvement Factor and overall number of routing messages exchanged of IDRA vs OBGP.

	Keepalive Update Interval $(K_T = 1)$			**Keepalive Update Interval** $(K_T = 3)$			**Keepalive Update Interval** $(K_T = 5)$		
	200 Erlangs	250 Erlangs	300 Erlangs	200 Erlangs	250 Erlangs	300 Erlangs	200 Erlangs	250 Erlangs	300 Erlangs
Improv. Factor (IF)	1.44	2.83	2.32	1.54	2.03	1.77	1.67	1.76	1.63

Traffic (Erlangs)	Routing Messages OBGP+	Routing Messages IDRA	Routing Messages OBGP+	Routing Messages IDRA	Routing Messages OBGP+	Routing Messages IDRA
100	4106295	3337685	4045380	3280974	3996540	3226164
150	3999754	3382931	3920216	3297536	3830622	3213501
200	4002240	3402343	3881279	3285279	3775545	3179529
250	4025299	3429541	3916735	3291311	3824549	3160378
300	4783811	3630224	4481222	3409693	4259852	3243739

Table 4.3: Improvement Factor and overall number of routing messages exchanged of IDRA vs OBGP+.

the network while in the IDRA protocol, these messages are exchanged among IDRAs which represent a small fraction of the total number of OBGP+ nodes in the network. Moreover, the blocking ratio of the IDRA protocol is lower than that of OBGP+, thus the number of routing messages which need to exchange in the IDRA protocol is smaller than in OBGP+.

4.3 Efficiency of Wavelength Converters

In this section we will evaluate the efficiency of converters in the three protocols with PAN European Network. We will run the three protocols in PAN European Network under three cases: no converter, 5 converters and 10 converters at border OXCs of each domain.

4.3.1 Efficiency of Wavelength Converters in The IDRA Protocol

To evaluate the efficiency of wavelength converters with the IDRA-based routing protocol, we consider 5 converters and 10 converters at each border OXCs of each domain in the PAN European network under the IDRA-based routing protocol. The figures 4.8, 4.9 and 4.10 show the average blocking ratio of IDRA in the three cases: no converter, 5 converters and 10 converters for different Keepalive Update Intervals K_T. More specifically, we compare their performance in terms of the recommended 0.1 percent blocking ratio of an optical network for supporting real-time and streaming applications [27].

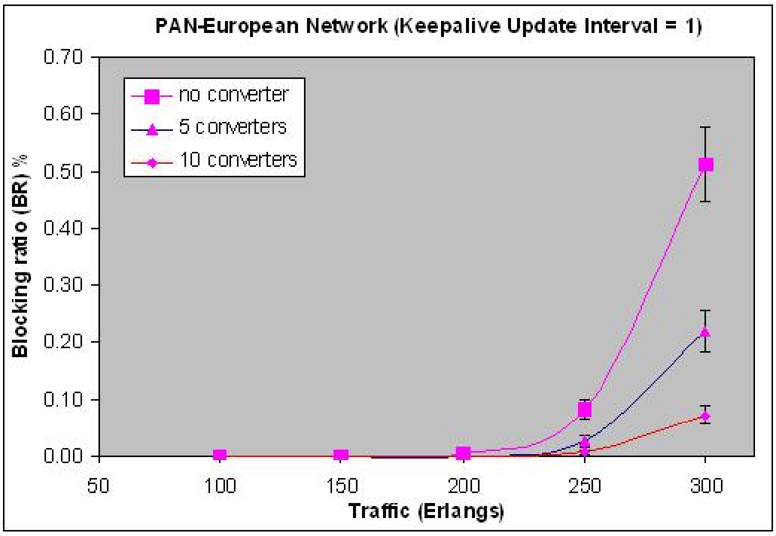


Figure 4.8: Blocking Ratio of the IDRA protocol with wavelength converters at K_T = 1.

From these results, we found that in the PAN European network without wavelength converters, the blocking ratio of IDRA protocol is only smaller or equal to this bound with traffic load smaller than 250 Erlangs for three values of Keepalive Update Intervals K_T. With 250 Erlangs traffic load, the average blocking ratio of the IDRA protocol is only able to reach the 0.1 percent bound if K_T = 1. With highest traffic load (300 Erlangs), the blocking ratio of the IDRA protocol never reach this bound for all cases of K_T.

In the PAN European network with 5 converters at border OXCs of each domain, up to 250 Erlangs traffic load, the average blocking ratio of the IDRA protocol is able to reach the 0.1 percent bound with K_T = 1 and K_T = 3. With highest traffic load (300 Erlangs), the blocking ratio of the IDRA protocol can not reach this bound for all cases of K_T.

In the PAN European network with 10 wavelength converters at border OXCs of each domain, the average blocking ratio of the IDRA protocol reaches 0.1 percent bound up to 250 Erlangs traffic load for all cases of K_T. Moreover, the blocking ratio of IDRA protocol can reach this bound with highest traffic load (300 Erlangs) with K_T = 1.

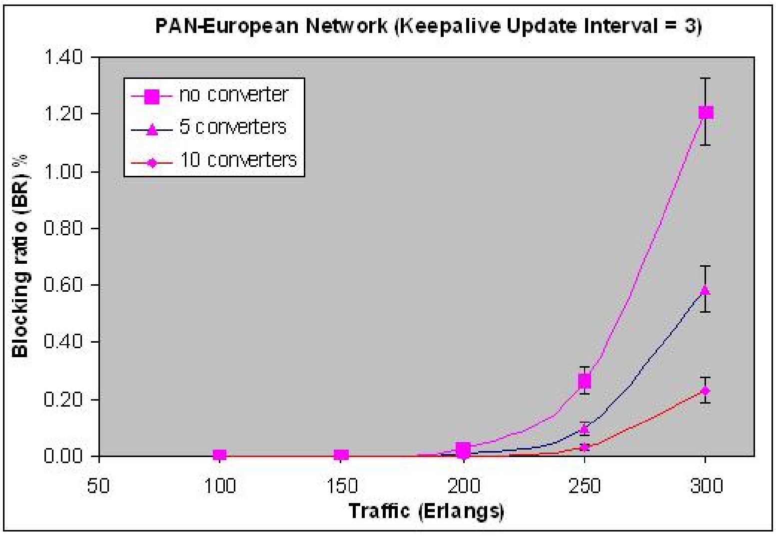


Figure 4.9: Blocking Ratio of the IDRA protocols with wavelength converters at K_T = 3.

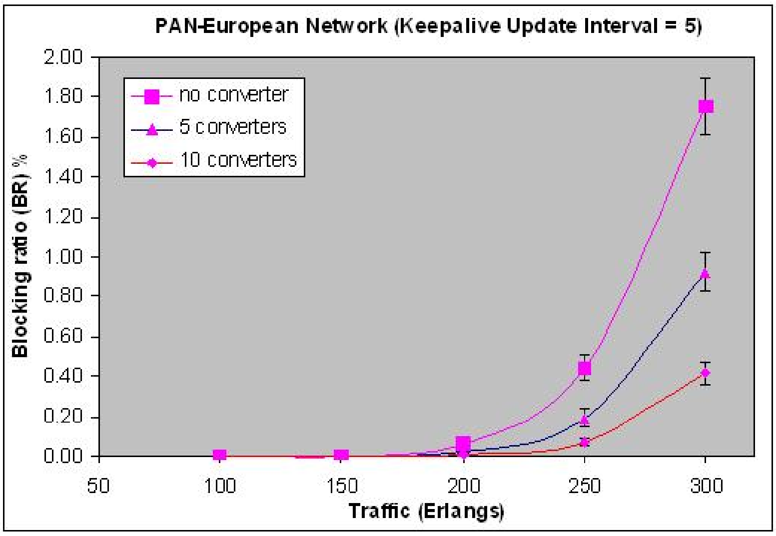


Figure 4.10: Blocking Ratio of the IDRA protocols with wavelength converters at K_T = 5.

4.3.2 Efficiency of Wavelength Converters in OBGP+

The figures 4.11, 4.12 and 4.13 show the average blocking ratio of OBGP+ in the three cases: no converter, 5 converters and 10 converters for different Keepalive Update Intervals K_T and different traffic loads.

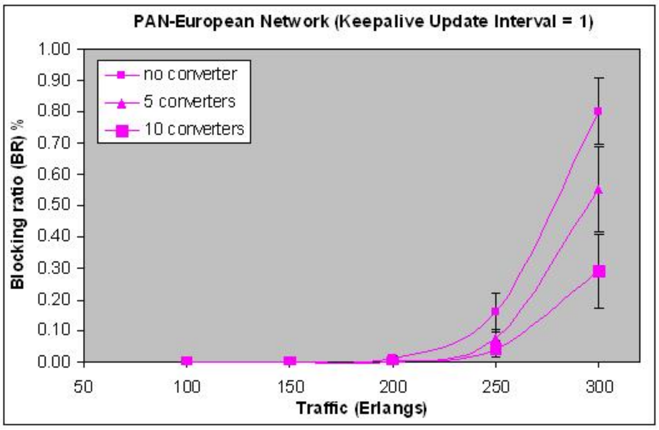


Figure 4.11: Blocking Ratio of OBGP+ with wavelength converters at K_T = 1.

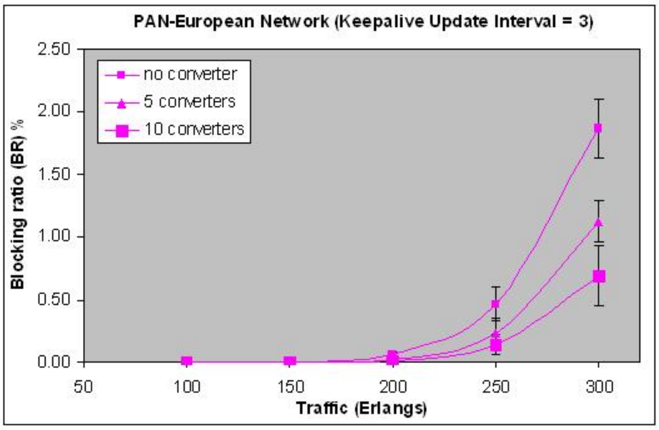


Figure 4.12: Blocking Ratio of OBGP+ with wavelength converters at K_T = 3.

From these results we found that in the PAN European Network without wavelength converters, the blocking ratio of OBGP+ only stay below 0.1 percent bound when the traffic loads is smaller or equal 200 Erlangs. With 250 Erlangs or 300 Erlangs traffic, the blocking ratio of OBGP+ can not reach this bound for all cases of Keepalive Update Interval K_T.

In the PAN European Network with 5 converters or 10 converters at the border OXCs of each domain, the blocking ratio of OBGP+ can reach 0.1 percent bound up to 250 Erlangs traffic only when $K_T = 1$. With $K_T = 3$ and $K_T = 5$, the blocking ratio of OBGP+ only reaches this bound up to 200 Erlangs. With 300 Erlangs traffic, the blocking ratio of OBGP+

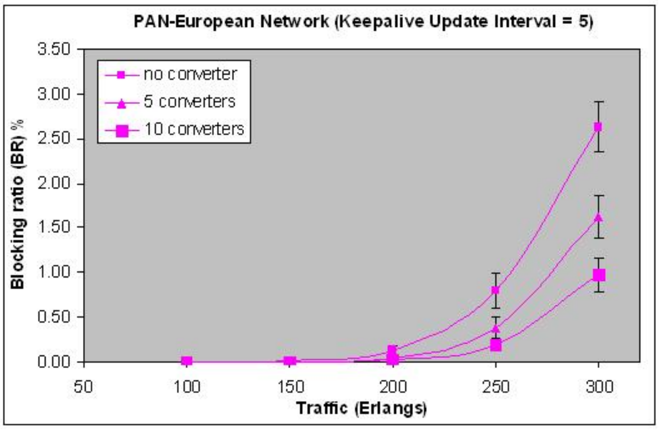


Figure 4.13: Blocking Ratio of OBGP+ with wavelength converters at K_T = 5.

never reaches this bound even with 10 converters and $K_T = 1$. These results show again that the performance of OBGP+ is worse than the one of the IDRA protocol.

4.3.3 Efficiency of Wavelength Converters in OBGP

The figures 4.14, 4.15 and 4.16 show the average blocking ratio of OBGP in the two cases: no converter and 5 converters for different Keepalive Update Intervals K_T and different traffic loads in the PAN European Network.

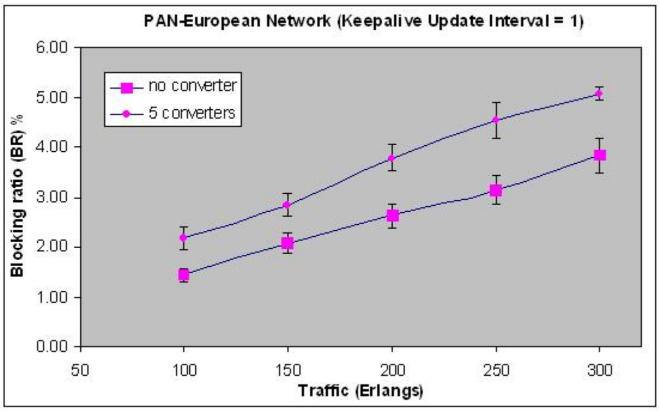


Figure 4.14: Blocking Ratio of OBGP with wavelength converters at K_T = 1.

From these results, we found that the blocking ratio of OBGP increase when we add wavelength converters into the network. These results can be explained as following.

To setup a lightpath to reach to a destination, a source need to choose an AS-path and a free wavelength on this AS-path to go. In OBGP, only network reachability information is exchanged, thus a source only has information about network topology. It does not have any information about the resource of network or the ENAW of wavelengths on a AS-path. Hence,

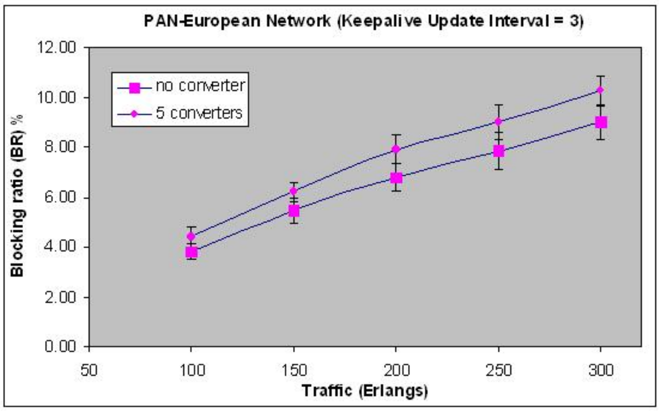


Figure 4.15: Blocking Ratio of OBGP with wavelength converters at K_T = 3.

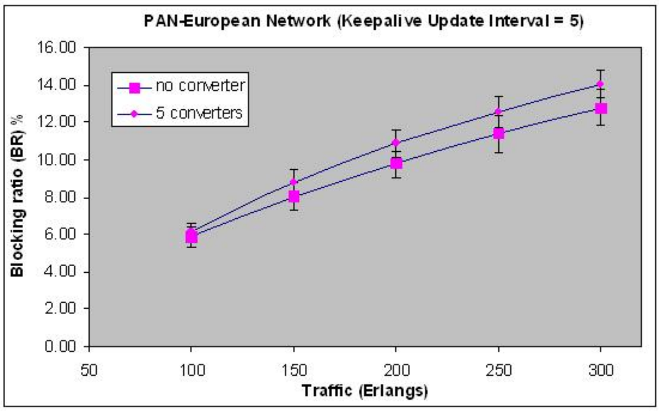


Figure 4.16: Blocking Ratio of OBGP with wavelength converters at K_T = 5.

in the RWA decision process of our OBGP, to reach a destination, a source will choose a shortest AS-path. For the wavelength on this shortest path, a source also choose the available wavelength with the lowest identifier (First Fit). This is the reason which causes these results. We consider the figure 4.17.

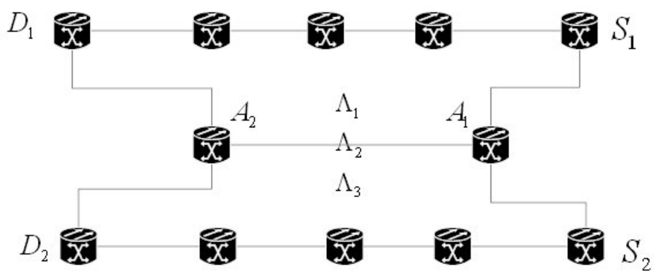


Figure 4.17: An example for blocking request in our OBGP.

In the figure 4.17, we assume that all links in the network are the same and each link have 3 wavelength: Λ_1, Λ_2 and Λ_3. At the beginning, sources S_1 and S_2 always try to choose the shortest path $S_1 - A_1 - A_2 - D_1$ and $S_2 - A_1 - A_2 - D_2$ and use wavelength Λ_1 to reach destinations D_1 and D_2 if it is available. These sources S_1 and S_2 tend to exhaust the available wavelength Λ_1 along the shortest AS-path before switching to an alternative wavelength or an alternative path. Thus, the ENAW of wavelength Λ_1 is usually equal 0 on this link (A_1, A_2) at most of the time. We consider the situation at the time when ENAW of wavelength Λ_1 on the link (A_1, A_2) have just changed from 0 to 1. In other words, on the link (A_1, A_2) we have 1 available wavelength Λ_1. S_1 and S_2 will choose this wavelength to reach destinations D_1 and D_2. The blocking request will happen because we only have 1 available wavelength Λ_1. Thus, the blocking ratio on link (A_1, A_2) will increase if the frequency of changing ENAW of wavelength Λ_1 on link (A_1, A_2) from 0 to 1 increases.

In the optical network without converters, changing ENAW of wavelength Λ_1 from 0 to 1 only happen when a connection on this wavelength is ended and 1 wavelength Λ_1 turn into available. In the optical network with converters, changing ENAW of wavelength Λ_1 from 0 to 1 happens because of two reasons: a connection on this wavelength is ended or converters is available at A_1 and A_2. Hence, frequency of changing ENAW of wavelength Λ_1 from 0 to 1 in the optical network with wavelength converters is much more than the one in the optical network without wavelength converters so the blocking ratio of optical network with wavelength converters is higher than the one in the optical network without wavelength converters.

To make it more clearly, in the following section, we show that by choosing a available wavelengths on the shortest path randomly instead of choosing the wavelength with the lowest identifier, the blocking ratio of OBGP will decrease when we add wavelength converters into the PAN European Network.

4.3.4 Efficiency of Wavelength Converters in OBGP with Randomly Choosing A Wavelength

The figures 4.18, 4.19 and 4.20 show the average blocking ratio of OBGP with choosing available wavelengths randomly on the shortest path in the three cases: no converter, 5 converters and 10 converters for different Keepalive Update Intervals K_T and different traffic loads.

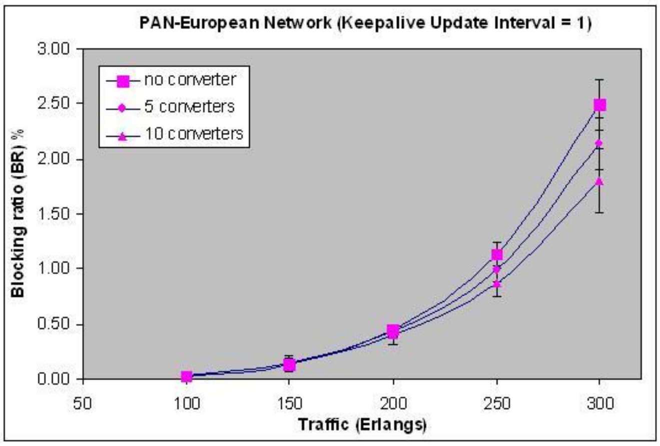


Figure 4.18: Blocking Ratio of OBGP with choosing wavelength randomly at K_T = 1.

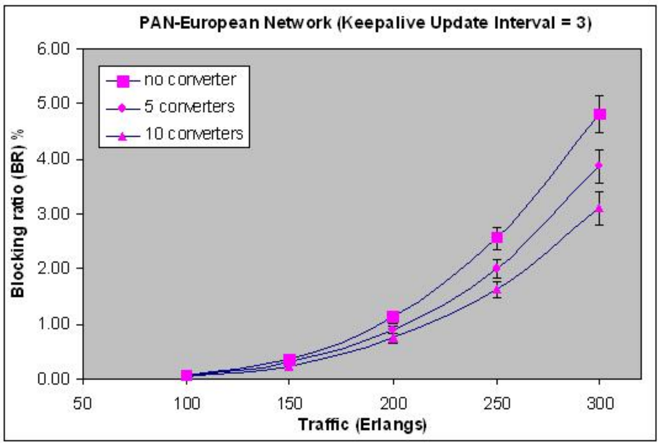


Figure 4.19: Blocking Ratio of OBGP with choosing wavelength randomly at K_T = 3.

Combining with results in the figures 4.14, 4.15, 4.16, these results also show that the blocking ratio of OBGP with choosing the wavelength randomly is always better than the one of OBGP which chooses the wavelength with the lowest identifier for different Keepalive Update Intervals and different traffic loads.

These results also show that the blocking ratio in OBGP with choosing the wavelength randomly will decrease when we add wavelength converters into the network. This proof again

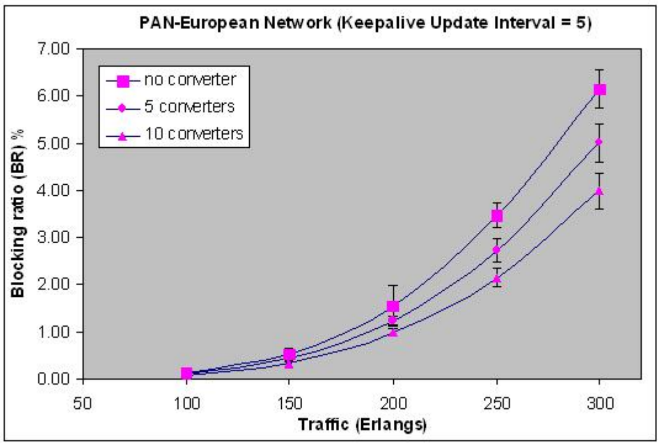


Figure 4.20: Blocking Ratio of OBGP with choosing wavelength randomly at K_T = 5.

that the cause of increasing blocking ratio in our previous OBGP is the way of choosing the wavelength with the lowest identifier on the shortest AS-path.

4.4 Discussion of Simulation Results

In this chapter, we made simulations on the PAN European network with wavelength converters to contrast the performance of the three protocols presented in chapter 2. We simulate the three protocols on the PAN European network under different traffic loads and different keepalive update intervals.

These results show that in the PAN European network with wavelength converters, the performance of IDRA and OBGP+ is always better than OBGP for all cases of Keepalive Update Intervals as well as different traffic loads. The improvement we got from IDRA and OBGP+ is very good and the number of routing messages exchanged between domains also decreased. We have these good results because of two reasons. Firstly, PSI messages which contain information of resources are piggy-backed in the Keepalive messages. Secondly, the blocking ratio of the optical network running IDRA and OBGP+ is smaller than that of the network running OBGP.

These results of simulations also confirm that IDRA is the best protocol among three protocols in blocking ratio as well as the number of routing messages. We have these results because a source node in the IDRA protocol has more information than a source node in OBGP+ so it is able to provide a much better traffic distribution than OBGP+.

In the PAN European network, if traffic in the network is smaller than 200 Erlangs, the blocking ratio of OBGP+ and IDRA is almost the same. Hence, when we want to apply an inter-domain routing protocol for an optical network, we should consider the traffic load on this network. If this traffic is small, we can use OBGP+ instead of the IDRA protocol to decrease the cost of building network. We should notice to apply the IDRA protocol in an optical network, we need to build IDRA for each domain and connect them by different optical links used to transfer data.

In this chapter, we also evaluated the efficiency of wavelength converters in the three protocols with the PAN European network. In the IDRA protocol, with 5 converters at each border OXC of each domain in the PAN European network, the average blocking ratio of IDRA protocol is able to stay below the 0.1 percent bound for Keepalive Update Intervals K_T = 1 and K_T = 3 for up to 250 Erlangs but its blocking ratio can not reach this bound for the highest traffic load (300 Erlangs). If we increase the number of converters at each border to value of 10 converters, the average blocking ratio of the IDRA protocol can reach this bound for all cases of K_T for up to 250 Erlangs and even for highest traffic load (300 Erlangs) its blocking ratio can reach this bound when K_T = 1.

In the OBGP+, adding 5 converters or 10 converters at border OXCs of each domain helps to decrease the blocking ratio of OBGP+. The average blocking ratio of OBGP+ can stay below the 0.1 percent bound when the traffic load is equal or smaller than 200 Erlangs. With 250 Erlangs, the blocking ratio of OBGP+ can reach this bound only if $K_T = 1$. With 300 Erlangs traffic, the blocking ratio of OBGP+ never reaches this bound even when we add 10 converters and $K_T = 1$.

In the OBGP, we found that the blocking ratio of OBGP increases in PAN European Network when we add wavelength converters. We have this result because the way a source in OBGP choose a path and a wavelength on this path to reach a destination. In our OBGP, a source chooses the shortest AS-path and the wavelength with lowest identifier on this AS-path to go to the destination. This is the cause of the increase of blocking ratio when we add wavelength converters into PAN European Network. We also show that instead of choosing the wavelength with the lowest identifier on the shortest path, we choose a wavelength randomly on this path, the blocking ratio of OBGP will decrease when we add converters into the network.

Chapter 5

Improvement

In chapter 2, we presented the IDRA-based routing protocol in detail. By using the cost of each pair (AS-path,wavelength) in choosing a path and wavelength to reach a destination, the performance of the IDRA protocol is better than that of OBGP and OBGP+. The formula of the cost is computed based on the hop count of a AS-path and ENAW of a wavelength on all links of this AS-path.

In previous chapter, the formula of the cost of pair $(P(lb,d),\Lambda_i)$ at the source OXC lb to destination d will be:

$$C^{adv}_{P(lb,d)}(\Lambda_i) = \begin{cases} H\left[\frac{1}{\min\left[W_{lb,lb'}(\Lambda_i),M(\Lambda_i)\right]} + \frac{1}{\min\left[W_{lb',rb}(\Lambda_i),M(\Lambda_i)\right]} + \frac{C^{adv}_{P(rb,d)}(\Lambda_i)}{H^{adv}}\right] \\ \propto \text{ if } W_{lb,lb'}(\Lambda_i) = 0 \text{ or } W_{lb',rb}(\Lambda_i) = 0 \end{cases} \tag{5.0.1}$$

Defining E as:

$$E = \left[\frac{1}{\min\left[W_{lb,lb'}(\Lambda_i),M(\Lambda_i)\right]} + \frac{1}{\min\left[W_{lb',rb}(\Lambda_i),M(\Lambda_i)\right]} + \frac{C^{adv}_{P(rb,d)}(\Lambda_i)}{H^{adv}}\right] \tag{5.0.2}$$

The formula of the cost of pair $(P(lb,d),\Lambda_i)$ will be:

$$C^{adv}_{P(lb,d)}(\Lambda_i) = \begin{cases} H \times E \\ \propto \text{ if } W_{lb,lb'}(\Lambda_i) = 0 \text{ or } W_{lb',rb}(\Lambda_i) = 0 \end{cases} \tag{5.0.3}$$

For example, let's consider the figure 5.1

In the figure 5.1, we assume that all links are the same. Applying the equations 5.0.1, 5.0.2 and 5.0.3, we have formula for the cost of the pair (AS-path and wavelength Λ_i) at node S as shown in the figure 5.1:

$$C^{adv}_{S}(\Lambda_i) = H \times E = 4\left[\frac{1}{W_1(\Lambda_i)} + \frac{1}{W_2(\Lambda_i)} + \frac{1}{W_3(\Lambda_i)} + \frac{1}{W_4(\Lambda_i)} + \frac{1}{W_5(\Lambda_i)}\right] \tag{5.0.4}$$

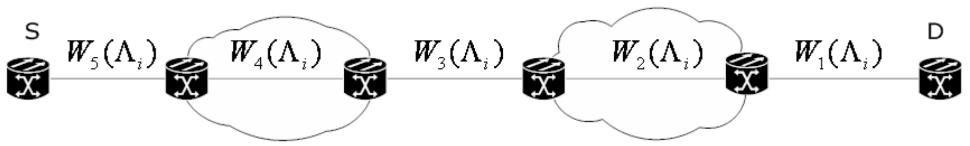


Figure 5.1: An example for formula of the cost.

In the formula 5.0.3, we found that these elements H and E have the same weight in forming the cost $C^{adv}_{P(lb,d)}(\Lambda_i)$. In other words, they are treated as the same way in the formula. Because each element H or E represents for a different quantity, it seems to be better if each element has a different weight in building the cost $C^{adv}_{P(lb,d)}(\Lambda_i)$ of an AS-path. In the following part, we will proof this idea.

We consider a new IDRA-based routing protocol with a new formula in which the weight of elements E and H is different in forming the cost $C^{adv}_{P(lb,d)}(\Lambda_i)$ as following:

$$C^{adv}_{P(lb,d)}(\Lambda_i) = \begin{cases} H\left[\frac{1}{\min\left[W_{lb,lb'}(\Lambda_i),M(\Lambda_i)\right]} + \frac{1}{\min\left[W_{lb',rb}(\Lambda_i),M(\Lambda_i)\right]} + \sqrt{\frac{C^{adv}_{P(rb,d)}(\Lambda_i)}{H^{adv}}}\right]^2 = H \times E^2 \\ \propto \text{ if } W_{lb,lb'}(\Lambda_i) = 0 \text{ or } W_{lb',rb}(\Lambda_i) = 0 \end{cases} \tag{5.0.5}$$

Wherein,

$$E = \left[\frac{1}{\min\left[W_{lb,lb'}(\Lambda_i),M(\Lambda_i)\right]} + \frac{1}{\min\left[W_{lb',rb}(\Lambda_i),M(\Lambda_i)\right]} + \sqrt{\frac{C^{adv}_{P(rb,d)}(\Lambda_i)}{H^{adv}}}\right] \tag{5.0.6}$$

For instance, applying formulas 5.0.5 and 5.0.6, we have a new formula for the cost of the pair (AS-path and wavelength Λ_i) at node S as shown in the figure 5.1:

$$C^{adv}_{S}(\Lambda_i) = H \times E^2 = 4\left[\frac{1}{W_1(\Lambda_i)} + \frac{1}{W_2(\Lambda_i)} + \frac{1}{W_3(\Lambda_i)} + \frac{1}{W_4(\Lambda_i)} + \frac{1}{W_5(\Lambda_i)}\right]^2 \tag{5.0.7}$$

In the equation 5.0.5, the weight of element E is bigger than the one of element H in forming the cost $C^{adv}_{P(lb,d)}(\Lambda_i)$. In other words, the sum of inverse ENAWs of a wavelength on all links of an AS-path is more important than the hop count of this AS-path.

The figures 5.2, 5.3 and 5.4 sumarize the blocking ratio of the new IDRA protocol and the old IDRA protocol in the PAN European Network for different Keepalive Update Intervals and different traffic loads. Clearly, the blocking ratio of the new IDRA protocol with new formula is better than the blocking ratio of the old IDRA protocol.

The table 5.1 show the number of routing messages in new IDRA protocol is very slightly higher than the one in old IDRA protocol and even some traffic loads (100 Erlangs and 150

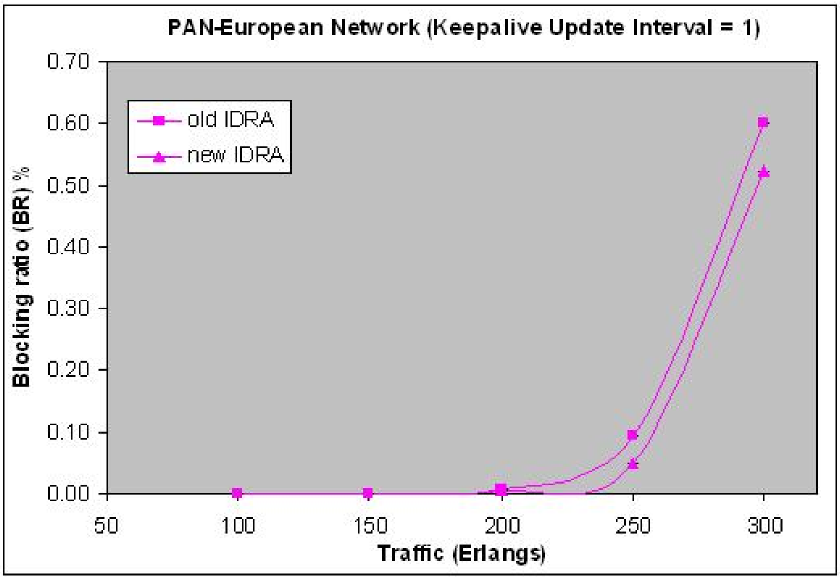


Figure 5.2: The blocking ratio of old and new IDRA protocol with $K_T = 1$.

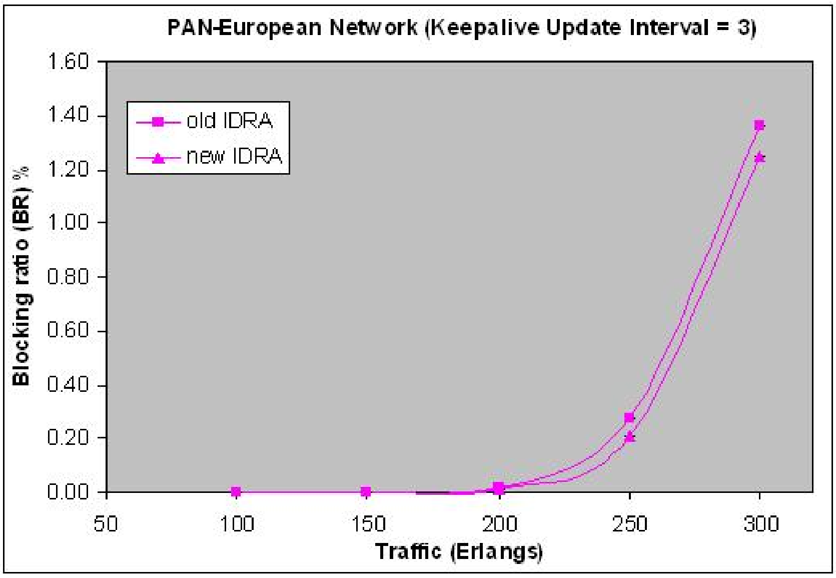


Figure 5.3: The blocking ratio of old and new IDRA protocol with $K_T = 3$.

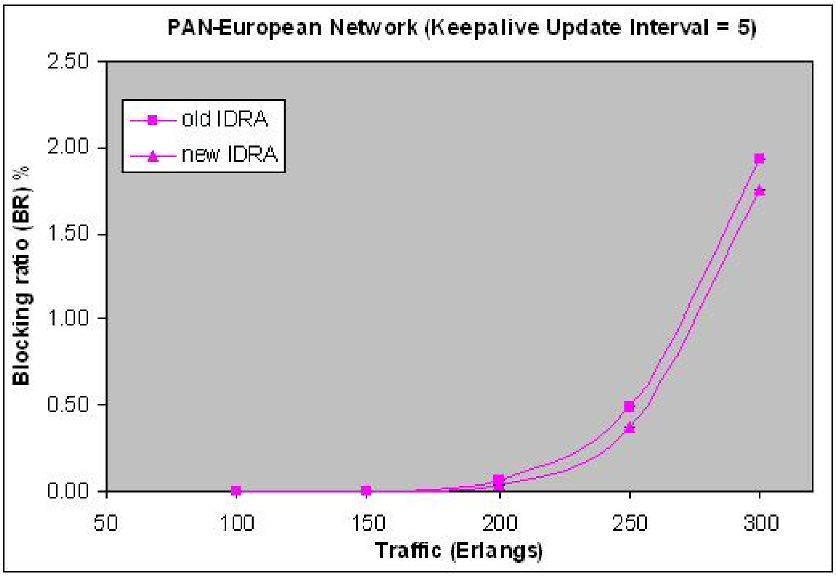


Figure 5.4: The blocking ratio of old and new IDRA protocol with $K_T = 5$.

Traffic (Erlangs)	Routing Messages old IDRA	Routing Messages new IDRA	Routing Messages old IDRA	Routing Messages new IDRA	Routing Messages old IDRA	Routing Messages new IDRA
100	3457902	3385280	3400257	3320048	3340310	3263443
150	3472600	3465395	3384130	3359368	3299721	3273881
200	3520048	3530855	3410401	3406950	3266974	3282647
250	3675541	3695550	3504612	3525313	3320843	3386358
300	4109397	4170458	3805888	3815500	3559075	3565069

Table 5.1: The number of routing messages exchanged of old and new IDRA protocol.

Erlangs), the number of routing messages in new IDRA protocol is smaller than the one in old IDRA protocol.

From these results, we can see that the formula of the cost in old IDRA protocol is not a good formula. The new formula gave us the better results and the performance of the new IDRA protocol is better than the one of the old IDRA protocol.

Maybe our new formula is not a optimal formula. Finding good weight of each element E or H to form a best formula for the cost $C^{adv}_{P(lb,d)}(\Lambda_i)$ is not expected a easy work and it will be studied in the future.

Chapter 6

Discussion and Conclusion

In this thesis, we developed some simulations to evaluate the performance of some optical inter-domain routing protocols. This work differs from other related works in that:

- Compare the performance of optical inter-domain routing protocols in an optical multi-domain network with wavelength converters based on two metrics: blocking ratio and the number of routing messages exchanged to archive this blocking ratio.
- Evaluate the efficiency of wavelength converters in an optical multi-domain network.
- Wavelength converters are put at the border OXCs of each domain in an optical multi-domain network.

In chapter 2, we introduced three protocols. For each protocol, we described the kinds of information which OXCs exchange together and RWA decision process in which a source will find out which lightpath is best lightpath to reach a destination. Whereas in chapter 3, we proposed a method to calculate and advertise converter lightpaths by changing the set of ENAWs which are advertised by border OXCs. These converter lightpaths is created by the presence of wavelength converters at border OXCs of each domain. In chapter 4, we build simulations to evaluate the performance of the three protocols in PAN European Optical Transport Network with wavelength converters for different traffic loads and different Keepalive Update Intervals K_T. An improved version of the IDRA protocol is given in chapter 5.

6.1 Conclusion

In the thesis, we considered the three optical inter-domain routing protocols in detail: OBGP, OBGP+ and IDRA-based routing protocol. In OBGP, OXCs only exchange network reachability information together as in BGP. Whereas in OBGP+, OXCs exchange two kinds of information: network reachability information and effective number of available wavelengths (ENAW) of wavelengths on an AS-path. With these information, a source in OBGP+ will choose the shortest AS-path and a wavelength which has a biggest ENAW to reach a destination. In the IDRA-based routing protocol, OXCs advertise three kinds of information: network reachability information, ENAW and the cost of an AS-path. With these information, a source in the IDRA protocol will choose the AS-path which has smallest cost to reach a destination.

Our simulations showed that the blocking ratio of inter-domain lightpath requests of IDRA and OBGP+ is always extremely lower than the one of OBGP for different traffic loads and different Keepalive Update Intervals K_T in the PAN European network with wavelength converters at the border OXC of each domain. This is because a source in IDRA and OBGP+ have more information about the resource of the network than a source in OBGP so it is able to distribute the traffic better than OBGP. Moreover, IDRA is the best protocol among the three protocols because a source OXC in IDRA have most information than other sources in other protocols.

Another performance comparison we used is the number of routing messages. Although in OBGP+ and IDRA-based routing protocol, OXCs exchange more information than in OBGP but the total number of routing messages of OBGP+ and the IDRA protocol is smaller than the total number of routing messages of OBGP. We have this result because of two reasons. The first reason is that PSI messages which contain the information exchanged are piggy-backed in the Keepalive messages so exchanging more information does not increase the number of routing messages. The second reason is that the blocking ratio of IDRA and OBGP+ is smaller than the one of OBGP. We notice that if a request become blocked, this triggers network reachability messages. Hence, fewer network reachability messages need be exchanged in OBGP+ and the IDRA-based routing protocol.

By changing the number of wavelength converters at border OXC of each domain, we considered the efficiency of wavelength converters in the PAN European network under the three protocols: OBGP, OBGP+ and the IDRA protocol. In the IDRA protocol, the simulation results show that with 5 converters at border OXCs, the blocking ratio of the IDRA protocol is able to stay below the 0.1 percent bound for all cases of Keepalive Update Intervals K_T for up to 200 Erlangs traffic. For 250 Erlangs traffic, it is can reach this bound if $K_T = 1$ and $K_T = 3$. With 10 converters at the border OXCs, the blocking ratio of the IDRA protocol is smaller than 0.1 percent bound for up to 250 Erlangs and for all cases of K_T. Moreover, the blocking ratio of the IDRA protocol still stays below this bound for 300 Erlangs with $K_T = 1$.

In OBGP+, adding wavelength converters (5 converters or 10 converters) helped the blocking ratio of OBGP+ stay below 0.1 percent bound up to 250 Erlangs if $K_T = 1$. When $K_T = 3$ or $K_T = 5$, the blocking ratio of OBGP+ only reach this bound up to 200 Erlangs. The blocking ratio of the OBGP+ never reaches this bound with 300 Erlangs traffic even with 10 converters and $K_T = 1$. These results show again that the performance of the OBGP+ is worse than the one of the IDRA protocol.

In OBGP, adding wavelength converters made the blocking ratio of OBGP increase. This is because a source in OBGP always choose the wavelength with the lowest identifier on the shortest AS-path to reach a destination. By choosing the wavelength randomly on the shortest AS-path, the simulation results showed that the blocking ratio of OBGP decrease when we add converters into the network.

In chapter 5, we considered the formula of the cost for a pair (AS-path, wavelength) in the IDRA protocol. In the old formula, elements which form the cost of an AS-path are treated as the same way. We introduced a new formula to calculate the cost. In this new formula, the sum of inverse ENAWs E on all links of an AS-path is considered more important than the hop count H of this AS-path so the weight of E is bigger than the one of H. Our simulations show that the blocking ratio of new IDRA protocol with new formula is smaller than the blocking ratio of the old IDRA protocol. This proofs that our formula is better than the old one.

6.2 Future Works

Here we suggest possible directions of future works.

- In all our simulations, the traffic which we simulate transfers between domains or only inter-domain traffic is simulated in our network. In the real world, there are two kinds of traffic running in an optical network: inter-domain traffic and intra-domain traffic. Thus, combining two kinds of traffic into the simulation could be an extension for our work.
- My conclusions is only applied to the PAN European Network (small multi-domain optical network), so further studies are needed to analyze the performance of the three protocols in a large multi-domain optical network with thousands of ASs.
- Although the IDRA-based routing protocol is the best protocol among the three protocols, it does not have a protection or restoration mechanism when a failure happens. This is not acceptable in an optical network. Hence, further work is to build a protection and restoration algorithm for the IDRA protocol and improve its survivability.

Appendix A

A guide to run our simulations

To able to run our simulations which are presented in chapter 4, a computer need to be installed Microsoft Visual C++ 6.0 and Opnet Modeler 11.5 [26]. In this section, we will describe how to run our simulations and collect these simulation results in detail.

A.1 Running simulations of OBGP and OBGP+

To run the OBGP or OBGP+ simulations, the steps should be followed:

1. Run the Opnet Modeler and set the model directory to the folder containing OBGP or OBGP+ simulation.
2. Open the PAN-european-obgp- project. After that, an optical network will appear as shown in the figure A.1.
3. Open the process model gfg-process-OxcControl-obgp. In this process, we can change the number of wavelength converters at border OXC of each domain by set the value we want to simulate to variable CONVERTERS in header block of process. After changing, we need to compile the process again to make our change effect.
4. To run the simulation, we use Configure/Run Discrete Even Simulation (Advance) function from main menu . A new window is opened as the figure A.2. In this window, there are 15 scenarios which represent for three cases of Keepalive Update Intervals: $K_T = 1$, $K_T = 3$, $K_T = 5$ and five cases of traffic in the network: 300 Erlangs, 250 Erlangs, 200 Erlangs, 150 Erlangs, 100 Erlang. Now you can run our simulation. Depending on your computer's power, it will take from 1 to 2 days to finish these 15 scenarios.

A.2 Running simulations of IDRA protocol

1. Run the Opnet Modeler and set the model directory to the folder containing IDRA protocol simulation.

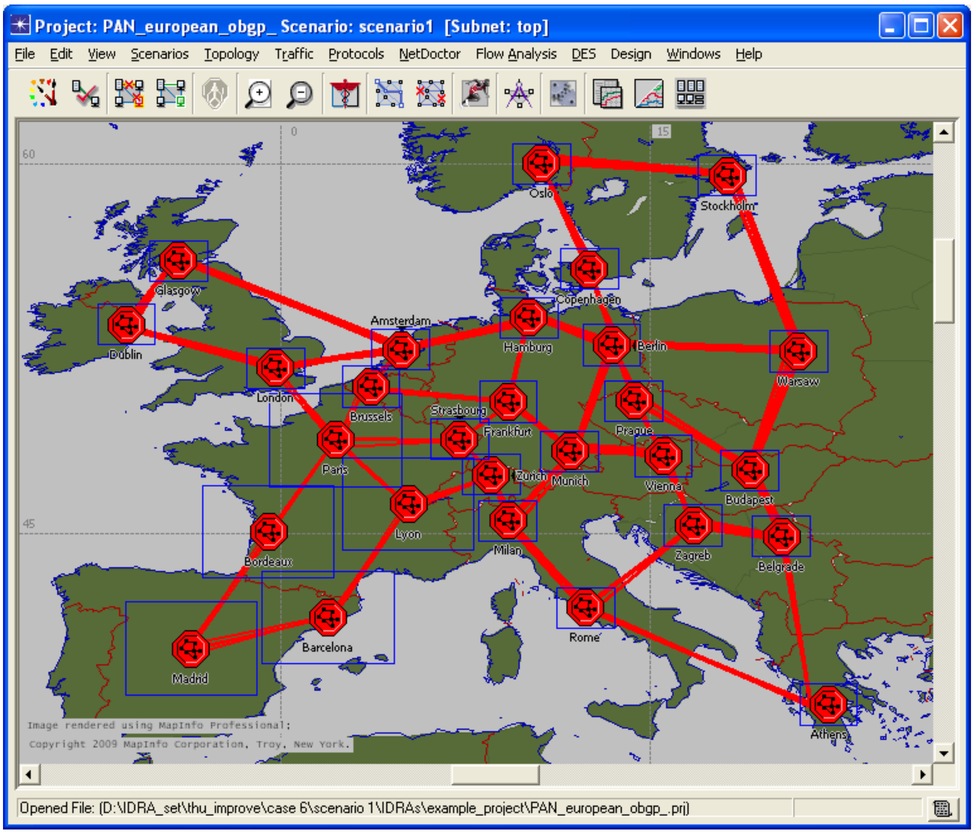


Figure A.1: Network topology of OBGP+ in the simulation.

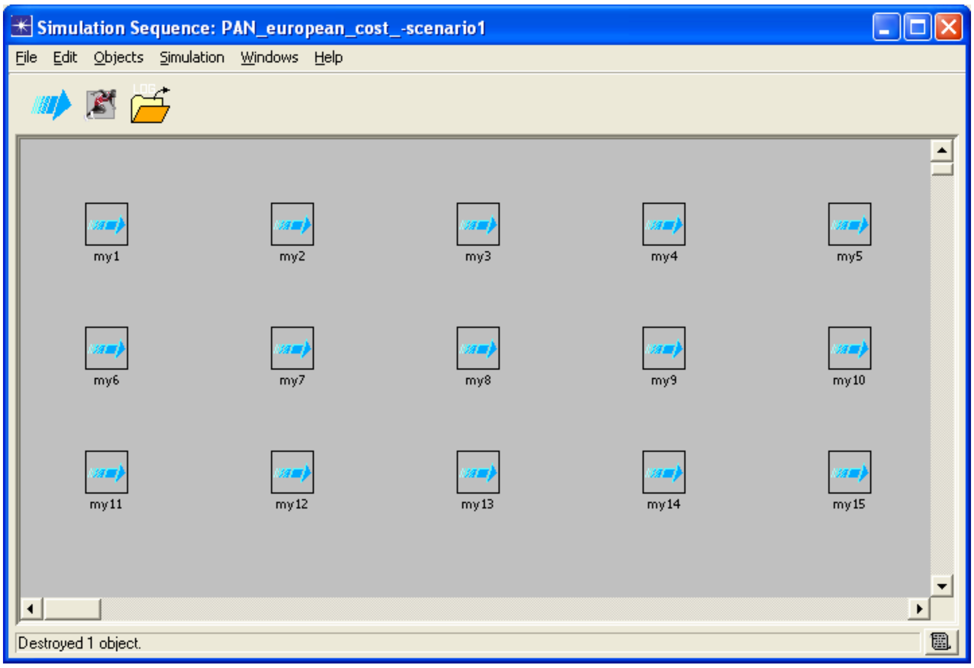


Figure A.2: Simulation sequence.

2. Open the PAN-european-cost- project and an optical network will appear as shown in the figure A.3.

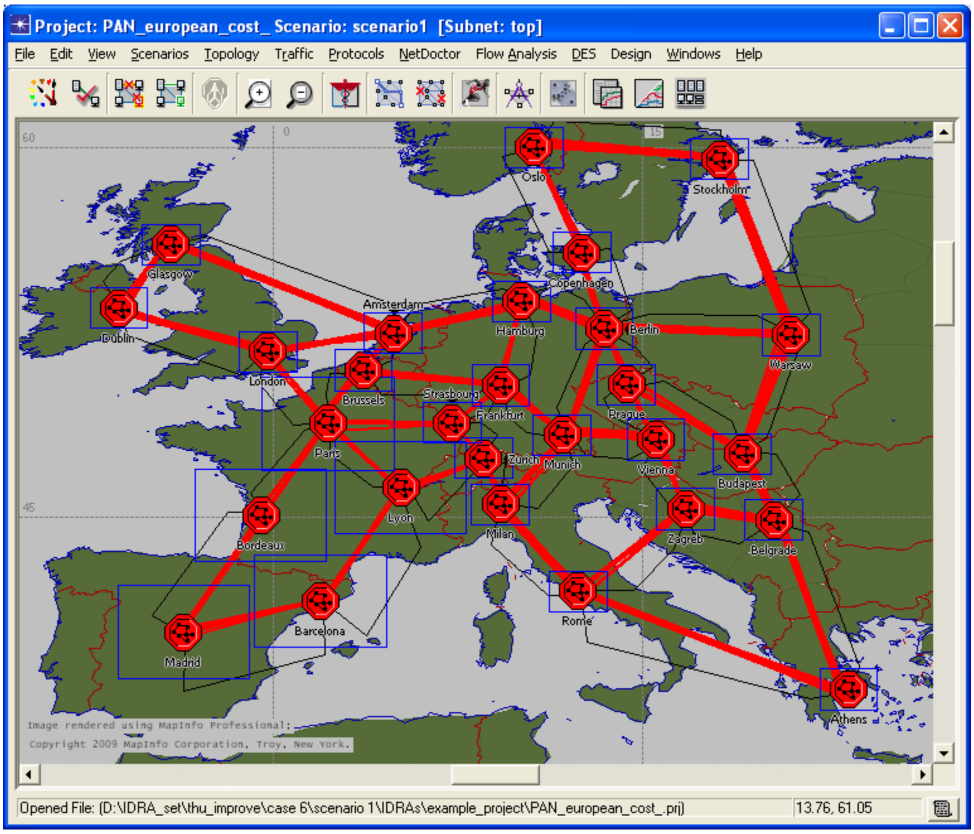


Figure A.3: Network topology of the IDRA protocol in the simulation.

3. Open two process models: gfg-process-OxcControl-cost and gfg-process-Idra-cost. In these processes, we can change the number of wavelength converters at border OXC of each domain by set the value we want to simulate to variable CONVERTERS in header block of each process. After changing, we need to compile two processes again to make our change effect.

4. To run the simulation, we follow the same instructions as the case of OBGP+.

A.3 Collecting the simulation results

After we finish running the simulation, we can collect simulation results as following:

1. Return the main menu of Opnet Modeler.

2. Create a new Analysis Configuration. A new window will be opened as in figure A.4.

Figure A.4: Analysis Configuration.

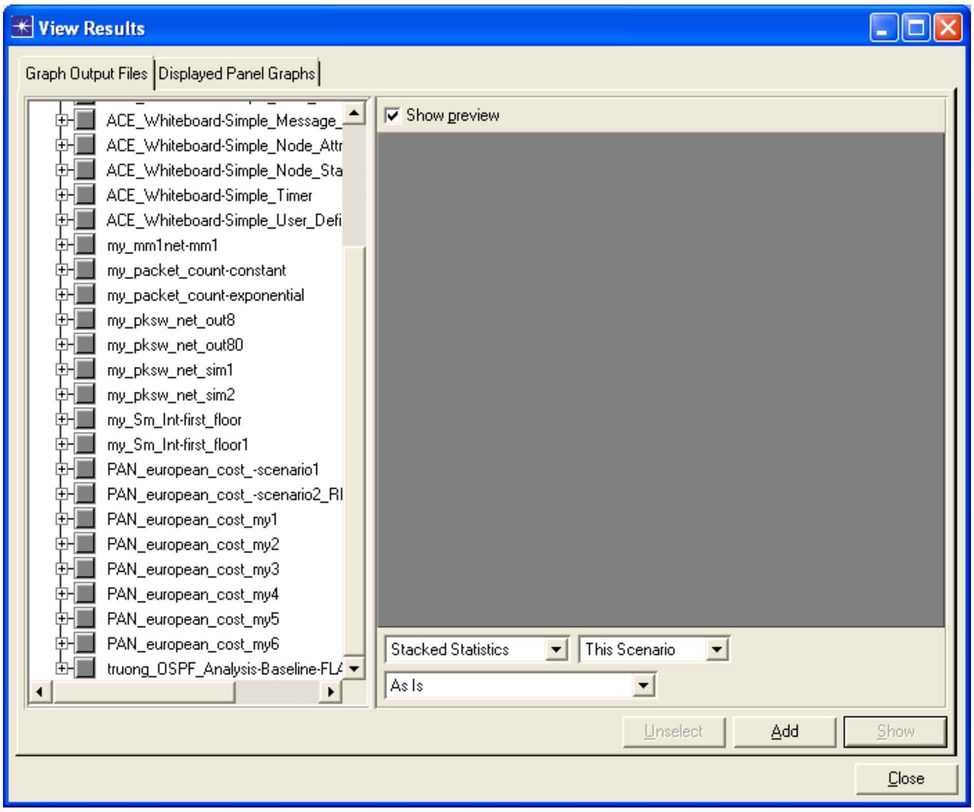


Figure A.5: View Results.

3. Click on the button which has function “Create a Graph of a Statistic” (the first button from left). A new window appears as in the figure A.5. Expending this window, we can see the blocking ratio, total advertisements, traffic of 15 scenarios which we have run before by choosing the name of each scenarios.

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