A Capacity Allocation Algorithm for Optical Virtual Private Networks

Bin ZENG¹ and Rui WANG²,*

¹Department of Management, Naval University of Engineering, Wuhan, Hubei, China
²Library of Naval University of Engineering, Wuhan, Hubei, China
*Corresponding author

Keywords: Optical virtual private networks, Wavelength-Division Multiplexing, Quality of services, Capacity allocation.

Abstract. As the development of optical communication technologies such as Wavelength-Division Multiplexing (WDM), it is important to support virtual private networks (VPN) over WDM networks. In order to overcome the limits of WDM network capacity and achieving more revenue new VPNS, an optimal model supporting both optical VPN and IP VPN on WDM networks is proposed to admit the maximum number of new VPNS without influencing the QoS guarantee for the existing VPNs. Furthermore, three heuristic algorithms are designed to simplify the computation process of getting optimal solution. The simulation results over MESH WDM networks show the algorithm can takes advantage of the reliable transmission capability of WDM networks and provides diverse QoS for different traffic streams by different quality of optical transmission.

Introduction

Wavelength-Division Multiplexing (WDM) has emerged as a promising technique for opening up the Terahertz transmission bandwidth of the single-mode optical fiber [18]. A virtual private network (VPN) is provisioned over public or third party network infrastructure, for example a frame relay carrier network or the Internet, to provide dedicated connectivity to a closed group of users. For most users, VPNs are more economic than deploying and maintaining physical cables and equipment themselves [10]. A private network can be built through tunneling, encryption and authentication mechanisms. To the users, a VPN looks like a private network, even though it is sharing a web of cables with the traffic of other users at the same time.

As the technology of WDM progresses, we can build VPNs over WDM networks, which takes advantage of the reliable transmission capability of WDM networks and provides diverse QoS for different traffic streams by different quality of optical transmission. In [9], the authors propose a virtual topology design and lightpath routing algorithm based on the concept of loose virtual topologies, it pluses lightpaths generated by MaxSingleHop [4] algorithm for unsatisfied traffic in the ring. In [6], the authors split the virtual topology problems into several subproblems: virtual topology design, routing for lightpaths, wavelength assignment. Although these papers focus right on the IP over WDM traffic engineering problems, but all of their algorithms are based on heuristic approaches and can’t be analyzed mathematically. In this paper, we propose a VPN over WDM traffic engineering mathematical formulation and optimization algorithm for solving the problem.

Problem Description

In this paper, we want to provide a capacity allocation algorithm for the operators who have their own optical networks. This model is used for the decision making of admitting the maximum number of new VPNs without influencing the QoS guarantee for the existing VPNs and our objective is to maximize our total revenue.

The given parameters are as follows:
1. The optical layer topology.
2. The maximum number of wavelengths per fiber link.
3. The topologies for existing VPNs.
4. The set new VPNs of which each admittance is to be determined.
5. The average traffic of each O-D pair in each VPN.

The objective is to maximize the total revenue.

Subject to:
1. The QoS constraint guaranteed by limiting the end-to-end mean delay, delay jitter and the maximum hop distance for each O-D pair in the network.
2. The number of lightpaths routing on a fiber link shouldn’t exceed the number of wavelengths of the fiber link.
3. The wavelength continuity constraint for each lightpath.
4. The ratio of lightpath reassignment cost and the total revenue should less than a given value.

The results to determine are as follows:
1. The maximum total revenue.
2. The topologies of the VPNs in the network.
3. The route of each O-D pair of each VPN in the network.

The notations of the parameters are given below.
- \( V' \) is denoted as the set of existing VPNs.
- \( V'' \) is denoted as the set of new requesting VPNs.
- \( V \) is denoted as the total VPNs, i.e., the union of \( V' \) and \( V'' \).
- \( K \) is denoted as the set of WDM links.
- \( J \) is denoted as the set of candidate wavelength in WDM network.
- \( B \) is denoted as per wavelength capacity. (e.g. 10Gbps).
- \( \sigma_{qk} \) is denoted as 1 if lightpath \( q \) uses WDM link \( k \); otherwise 0.
- \( Q_l \) is denoted as Candidate lightpaths to support IP link \( l \).
- \( L_i \) is denoted as the set of all candidate IP links.
- \( \delta_{pl} \) is denoted as 1 if directed path \( p \) uses link \( l \); otherwise 0.
- \( P_w \) is denoted as the set of candidate directed IP paths connecting O is denoted as D pair \( w \).
- \( \phi_{vw} \) is denoted as an artificial path for the O is denoted as D pair \( w \) of the rejected VPNs.
- \( P'_w \) is denoted as the union of \( P_w \) and \( \phi_{vw} \).
- \( W_v \) is denoted as the set of O is denoted as D pairs of VPN \( v \).
- \( a_v \) is denoted as the revenue for admitting VPN \( v \).
- \( r_{vw} \) is denoted as the mean traffic rate of O is denoted as D pair \( w \) of VPN \( v \).
- \( k_{vw} \) is denoted as a given hop distance in terms of IP links for O is denoted as D pair \( w \) of VPN \( v \).
- \( \omega_{vw} \) is denoted as a given packet overdue probability for O is denoted as D pair \( w \) of VPN \( v \).
- \( \Phi(D_{vw}, E_{vw}, T) \) is denoted as the probability under the threshold \( T \) on link \( l \in L \), which is a function of \( D_{vw} \) and \( E_{vw} \).

The notations of the decision variables are given below.
- \( x_{vp} \) = 1 if VPN \( v \) uses IP path \( p \); otherwise 0.
- \( y_{qj} \) = 1 if lightpath \( q \) uses wavelength \( j \); otherwise 0.
- \( z_v \) = 1 if VPN \( v \) is admitted; otherwise 0.
- \( r_{vw} \) is the estimated aggregation flow on IP link \( l \).
- \( b_{vw} \) = 1 if link \( l \) is selected for O-D pair \( w \) of VPN \( v \), and 0 otherwise.
- \( D_{vw} \) denotes end-to-end mean delay requirement for each O-D pair \( w \) in VPN \( v \).
- \( E_{vw} \) denotes end-to-end delay jitter requirement for each O-D pair \( w \) in VPN \( v \).

Objective function is as below:

\[
F_{ob} = \max \sum_{vw} a_v z_v . \quad (1)
\]

Subject to:

\[
\sum_{v \in V} \sum_{w \in W} \sum_{p \in P_w} x_{vp} r_{vw} \delta_{pl} \leq g_l, \quad \forall l \in L \quad (2)
\]
Constraint (1) is the aggregated flow constraint. Constraint (2) is to ensure the aggregated flow on each IP link won’t exceed the capacity of the IP link. Constraint (3) is to ensure all each O-D pairs
will have an IP path to transmit traffic. Constraint (4) is to ensure all each O-D pairs will be admitted
or rejected jointly if the VPN is admitted or rejected. Constraint (5) represents the integer property
constraint. Constraint (6) is to ensure the hop distance of each O-D pair is within a given value.
Constraint (7) is to ensure the ratio of the lightpath reassignment cost and the total revenue should
less than a given value. Constraint (8) is ro enforce the integer property. Constraint (9) is to ensure a
specific wavelength in a specific WDM link will be used at most one time. Constraint (10) is to
enforce the integer property. Constraint (11) is to ensure the number of each wavelength used by
outgoing IP links of each router must not exceed the number of add ports of the corresponding OXC.
Constraint (12) is to ensure the number of each wavelength used by incoming IP links of each router
must not exceed the number of drop ports of the corresponding OXC. Constraint (13) is to ensure the
capacity of each IP link must not exceed the aggregated capacity provided by the lightpaths.
Constraint (14) is to ensure the capacity of all IP links must be a multiple of the capacity of a
wavelength. Constraint (15) is to ensure the end-to-end mean delay of each O-D pair is within a given
value. Constraint (16) is to ensure the end-to-end delay jitter of each O-D pair is within a given value.
Constraint (17) is to ensure every IP link will be used by one IP path at most one time. Constraint (18)
means the integer property constraint. Constraint (19) is ro guarantee the overdue probability caused
by a specific set of delay and delay jitter should be restricted within a given value.

Algorithm Design

Due to the complexity of our primal problem and the purpose of simplifying the process of getting
primal feasible solutions, we divide the primal problem into three parts: (1) VPN admission control
subproblems, (2) IP layer routing subproblems, (3) WDM layer routing subproblems. We’ll derive
some heuristics for solving these subproblems in the following sections.

VPN Admission Control Subproblems

As an admission control problem, we intuitively apply drop-and-add heuristics in this subproblem.
While applying drop-and-add heuristics, we must decide the priority of each requesting VPN, which
are used to determine the drop sequence. Similarly, some add criteria are used to decide the priority to
construct the add sequence of the previously dropped VPNs. In our formulation, the set of decision
variables $z_v$ are used to determine which requesting VPN can be admitted into our physical network.
While solving the subproblem 1 of the Lagrangean relaxation dual problem, we decide $z_v$ to be 1 if
$f(z) = (1 + u3\beta)av + \sum_{uv\in F} u2vw \geq 0$, otherwise 0. So using $f(z)$ as the criteria of dropping or adding is
quite intuitively reasonable. We also provide some other criteria for drop-and-add heuristics, which
demonstrates the multiple combinations of four criteria of drop and add by $f(z)$, $Traffic(z)$, $Revenue(z)$
and $Ratio(z)$, where $Traffic(z) =$ total traffic of VPN $z$, $Revenue(z) =$ the revenue brought by VPN $z$, $Ratio(z) =$ $Revenue(z) / Traffic(z)$.

The algorithm is shown as follow:

Step 1. Choose a combination of criteria of drop-and-add heuristics.
Step 2. Sort the requesting VPNs by the chosen drop criterion. The ranking rule is as
following:
   If drop criterion = $Traffic(z)$
       VPN $j$ ranks higher than VPN $j'$ if $Traffic(j) < Traffic(j')$
   If drop criterion = $Revenue(z)$
       VPN $j$ ranks higher than VPN $j'$ if $Revenue(j) > Revenue(j')$
   If drop criterion = $Ratio(z)$
       VPN $j$ ranks higher than VPN $j'$ if $Ratio(j) > Ratio(j')$
   If drop criterion = $f(z)$
       VPN $j$ ranks higher than VPN $j'$ if $f(j) > f(j')$.  

204
Step 3. According to the ranks given by Step 2, drop VPN \( j \) with the smallest rank one by one until all the constraints of the primal problem are satisfied.

Step 4. Sort the dropped VPNs given in Step 3 by the chosen add criterion. The ranking rule is as following:
- If add criterion = \( Traffic(z) \)
  - VPN \( j \) ranks higher than VPN \( j' \) if \( Traffic(j) < Traffic(j') \)
- If add criterion = \( Revenue(z) \)
  - VPN \( j \) ranks higher than VPN \( j' \) if \( Revenue(j) > Revenue(j') \)
- If add criterion = \( Ratio(z) \)
  - VPN \( j \) ranks higher than VPN \( j' \) if \( Ratio(j) > Ratio(j') \).

Step 5. According to the ranks given by Step 4, add the VPN with largest rank one by one until some constraints of the primal problem are violated.

**IP Layer Routing Subproblems**

The set of decision variables \( x_{vp} \) are used to decide the routing of each OD pair of each VPN in the IP layer. Solving each routing problem of one specific OD pair is a typical shortest path problem. We apply Bellman-Ford algorithm in our implementation.

**WDM Layer Routing Subproblems**

Lightpaths, which are constructed from the WDM layer, are used to provide the capacity of physical transmission to each IP link. Consequently, the order of construction of each lightpath is highly related with the loading of the IP link the lightpath supports. In our implementation, \( K \)-shortest path algorithm is adopted to decide the \( K \) shortest lightpaths supporting one specific IP link. Similarly, the choices of arc weights can be made to determine the shortest paths. Like the previous section, there’re also some multipliers related with each lambda in a specific WDM link. The algorithm is shown as follow:

Step 1. Sort the IP links by the traffic on each IP link.
Step 2. Assign the arc weight of each link in the \( K \)-shortest path algorithm to be 1.
Step 3. According to the order obtained from Step 1, run \( K \)-shortest path algorithm to decide the WDM layer routing of each IP link, and assign the arc weight of the links used by the IP link to be infinite, which can avoid the links to be used again by the following IP links.
Simulation Results

In order to show the difference between the results from our optimal algorithm (OA) and other primal heuristics (CA), we would like to do some experiments for the purpose of showing the effectiveness of results. Input parameters are configured as below. The number of existing VPNs is 4. The number of OD pairs per VPN is 3. The traffic of each OD pair is between 100 and 600. The capacity of each lambda is 1000. The ratio of lightpath modification cost and the total revenue is 0.8. The Rerouting cost per WDM link is 50. The revenue of each VPN is between 1000 and 10000. The End-to-end delay threshold is 0.5 sec. The number of supporting lightpaths per IP link is 2. The stop criteria are 500 iterations.

We have tested MESH topology in our simulation with the number of requesting VPNs equal to 60, 70, 80, 90, and 100. Compared with the results of algorithm SA, our Lagrangean-based algorithm LA has achieved improvements from 8.42% to 89.65% in the above three topologies, which can show the effectiveness of our approach.

Summary

In this paper, we try to develop an admission control algorithm jointly considering VPN admission control and the routing assignments of IP and WDM layers. The simulation results prove that the algorithm can efficiently solve the design problem of these three layers over WDM networks, which makes the problem more complicated then considering any single layer only.

Additionally, there exists an easier extension of our primal problem, that is, given an OD pair of IP layer, we just need to construct a lightpath for this OD pair without considering the routing assignments of IP layer, i.e. the traffic of this OD pair is directly switched between the OXCs, which can not only speed up the transmission, but also achieves better security.
References


