Robust Design of Virtual Topology for WDM Networks under Bandwidth Demand Uncertainties

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Abstract In this paper, a novel method is proposed to address the problem of designing virtual topology over wavelength division multiplexing (WDM) networks under bandwidth demand uncertainties. And a bandwidth demand model under uncertainties is presented. The optimization goal of virtual topology design is defined as minimizing the maximum value among \( p \) percentiles of the bandwidth demand distribution on all light-paths. Correspondingly, we propose a heuristic algorithm called an improved decreasing multi-hop logical topology design algorithm (ID-MLTDA) that involves with a degree of uncertainties to design virtual topology. The proposed algorithm yields better performance than previous algorithms. Additionally, the simplicity and efficiency of the proposed algorithm can be in favor of the feasibility for topology design of large networks.

Keywords bandwidth demand uncertainties; robust; virtual topology; wavelength division multiplexing networks

1 Introduction

Currently, Internet protocol (IP) over wavelength division multiplexing (WDM) networks is expected to offer an infrastructure for the next generation Internet. One reason for the expectation is that IP services have dominated in the field of date communication since Internet has been spreading in the world. Another reason lies in several important advantages of the WDM networks, such as increased usable bandwidth, reduced electronic processing cost, protocol transparency, and efficient failure handing for network component, which have made the WDM optical networks become a typical standard for high-speed backbone transport networks. The WDM optical network can be divided into two parts by the switching mode: one is the wavelength routed optical networks (WRON), which is circuit switching mode; another is optical burst switching (OBS) or optical packet switching (OPS), which is on the basis of packet switching. No doubt, the OBS/OPS optical networks can more sufficiently support the IP packet than the WRON. However, compared to the equipments for OBS/OPS optical networks, the WRON is more suitable for realization, such as optical cross connect (OXC) and optical add/drop multiplexing (OADM). Additionally, a great progress has been made in the control and management for the WRON.

WRON consists of wavelength routing nodes interconnected by point-to-point fiber links. A physical topology of WRON is the physical set of wavelength routed nodes and the fiber links upon which one sets up light-paths between node pairs. A light-path is a route on the continuous wavelengths between a node pair, if wavelength converter is not provided in the network. The light-paths can be set up by configuring these routing nodes in the WRON. Any two working light-paths sharing the common fiber link should use different wavelengths. The set of all light-paths that have been set up between node pairs constitutes the virtual topology. To design the virtual topology for a given physical network, we need to determine the light-paths in the virtual topology, assign the routings and wavelengths for the light-paths, and develop a method for routing traffic, such as IP packets, over the virtual topology.

Traditionally, the traffic arriving of WDM networks could be characterized by Poisson distribution or Self-similar processes. The long-term average traffic and corresponding bandwidth requirement (bandwidth demand) between each node pair of WDM networks can be calculated and would not fluctuate frequently. Thus, the long-term average traffic and bandwidth demand of WDM networks were...
considered to be certain and stable. Most of previous studies about virtual topology design are based on the static traffic matrix, whose each element is the long-term traffic between each node pair of WDM networks. Such problem has been widely and intensively studied. Variants of the related problems have been addressed such as comprehensive description and analysis, different heuristic algorithms with performance comparisons, and investigation based on a linear formulation\cite{1-3}.

However, in competitive market, uncountable and diverse services are provided for the insatiable needs of modern society. The long-term average traffic and bandwidth demand of WDM networks is not still certain. In IP network, one of the challenges for the network planners is to predict the bandwidth demand in the future. One possible solution is to predict the future bandwidth demand by measuring the traffic in the past. However, such method is not perfect and the inaccuracy of prediction can reach to 20\%\cite{4}. Hence, it is very difficult to obtain the long-term traffic and to exactly predict the bandwidth demand where the network would be in five or more years in terms of technology available to deploy. Due to the significant fluctuations and an unstable behavior exhibited by bandwidth demand between nodes pair, planning networks under the certain bandwidth demand may lead to disadvantageous network performance, e.g. high congestion and long message delay. Generally, there are two possible methods to overcome these problems. The first is the reconfiguration of virtual topology under dynamic network traffic\cite{5}. The virtual topology will be adjusted timely according to the change of traffic in network, but the effectiveness of the reconfiguration is still not sure due to the uncertainties of the traffic matrix. In addition, the cost of this method is very high when the reconfiguration often occurs. Over-provisioning is the other approach, which provided more resources than the average to deal with potential change of the long-term traffic and bandwidth demand. No doubt, this approach will lead to the waste of resources and it is difficult to calculate how many resources to be over-provided.

Thus several studies have proceeded under uncertainties of the long-term average traffic and bandwidth demand. For example, the planning and dimensioning of circuit-switched networks have been investigated in Ref.\cite{6}; the capacity planning of survivable mesh-based transport network has been studied in Ref.\cite{7}; the logical topology design over WDM optical network has been first taken into consideration under uncertainties in Ref.\cite{8}. Nevertheless, the uncertainty model has not been explicitly analyzed\cite{6-8}. Additionally, the proposed algorithm in Ref.\cite{8} based on Taboo Search requires extreme computation time to adequately explore the all state places, because for all topologies generated, the corresponding routing algorithm must be employed to evaluate the congestion in the whole network, and thus extreme computation time should be needed.

In this study, we will explicitly explain how to design virtual topology under uncertainties of bandwidth demand and propose an efficient heuristic algorithm to determine light-paths of virtual topology. The rest of study is formed as follows: Section 2 presents the uncertainties model of bandwidth demand. Section 3 shows the optimization goal of determining virtual topology. A heuristic algorithm is proposed in Section 4. Section 5 gives the simulation results with the corresponding discussions.

## 2 Uncertainties Model of Bandwidth Demand

Currently, the most fundamental and important aspect of planning network under uncertainties of bandwidth demand is to determine the scope of uncertainties, because it is helpful to decide what mathematical information is to be applied to solve the planning problem. In Ref.\cite{9}, the aggregated bandwidth demand between network nodes is assumed to follow Gaussian distribution in real networks, when bandwidth demand between a node pair comes from many independent individual sources. Similarly, in the WRON, we characterize the bandwidth demand between each node pair as a random variable, which is specified by Gaussian distribution. Consider the node pair from Chengdu to Beijing (both Chengdu and Beijing are nodes of backbone network in China) in WDM backbone network for example. There are thousands of users, such as companies, colleges, governments and individuals, having bandwidth demand from Chengdu to Beijing. For each user, the bandwidth demand can be described as a random variable that is specified by certain probability distribution under bandwidth demand uncertainties. We assume that each user’s bandwidth demand is independent and identically distributed. Thus, according to Central Limited Theorem, the aggregated bandwidth demand from Chengdu to Beijing can be
represented as Gaussian distribution, for it is the combination of countless random variables that are independent and identically distributed. So do other node pairs in WDM backbone network. Thus, the bandwidth demand under uncertainties between each node pair in WDM network is a random variable that follows Gaussian distribution. In addition, the means $\mu_{ij}$ and standard deviation $\sigma_{ij}$ need to be provided for random variable that characterizes the bandwidth demand from source node $i$ to destination node $d$.

Since the bandwidth demand cannot be negative value in practice, the Gaussian distribution, whose random variable $x$ can be negative theoretically, can be implemented with adjustment as follows:

$$f(x) = \begin{cases} \frac{1}{\sqrt{2\pi} \sigma_{ij}} \exp \left( \frac{- (x - \mu_{ij})^2}{2\sigma_{ij}^2} \right), & 0 \leq x \\ 0, & x < 0 \end{cases}$$

where $f(x)$ is the probability density function (PDF) of adjusted Gaussian distribution, and

$$\phi(\mu_{ij}) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\mu_{ij}} \exp \left( -\frac{x^2}{2} \right) dx$$

This aims to ensure the fact that

$$\int_{-\infty}^{\infty} f(x)dx = 1$$

### 3 Optimization Goal

Generally, minimizing the congestion, defined as the maximum offered traffic on any light-path in the WMD networks, is chosen to be the function goal for the virtual topology design, in that it often dominates significant network performance metric, such as average weighted number of hops, message delay. Similarly, our optimization goal is to minimize the maximum bandwidth demand on the light-paths, which can reduce the congestion. These two goals are strongly correlated.

Presently the aggregated bandwidth demand on each light-path can also be described as a random variable that is specified by Gaussian distribution, since it is combination of traffic flows among several node pairs whose bandwidth demands are characterized as Gaussian distribution. Let $\mu_{ij}$ and $\sigma_{ij}$ respectively to represent the average bandwidth demand and standard deviation of bandwidth demand on light-path from node $i$ to node $j$, and let $r_{ij}$ to be light-path indicator that adopts value 1 if the traffic flow from node $s$ to node $d$ traverses the light-path from node $i$ to node $j$, and 0 otherwise. Therefore,

$$\mu_{ij} = \sum \mu_{ij}^p \mu_{ij}^d, \quad \sigma_{ij}^2 = \sum \mu_{ij}^p \sigma_{ij}^d$$

Let $\lambda_{ij}$ denote the maximum bandwidth demand value among $p$ percentile on the light-path from node $i$ to node $j$, and it can be defined as follows:

$$P[X_{ij} \leq \lambda_{ij}] = p$$

where, $X_{ij}$ is the random variable describing the bandwidth demand on the light-path from node $i$ to node $j$. Since $X_{ij}$ is specified by Gaussian distribution, we can obtain

$$P\left( \frac{X_{ij} - \mu_{ij}}{\sigma_{ij}} \leq \frac{\lambda_{ij} - \mu_{ij}}{\sigma_{ij}} \right) = \phi\left( \frac{\lambda_{ij} - \mu_{ij}}{\sigma_{ij}} \right) = p$$

We can find $\lambda_{ij}$ through Eq. (6). The maximum value among all light-paths can be defined as

$$\lambda = \max\{\lambda_{ij}\}, \quad \text{for all } i \text{ and } j$$

The optimization goal is minimizing the value of $\lambda$.

### 4 Proposed Algorithm

It has been proved that virtual topology design is a NP-hard problem[2]. Finding the optimal virtual topology is almost impractical when the network size becomes larger. Fortunately, we can use heuristic solutions to generate relatively optimum one. There are a lot of heuristic algorithms for virtual topology under static bandwidth demand pattern[1-2]. In this section we propose an improved heuristic algorithm, which is called ID-MLTDA that is based on D-MLTDA (Decreasing Multi-hop Logical Topology Design Algorithm) presented in Ref.[2], to deal with the virtual topology design under uncertainties of bandwidth demand.

In this paper, the bandwidth demand between each node pairs is not static value, but it can be described as a random variable that is specified by Gaussian distribution. The transformation from random variable to concrete value $x_{ad}$, which should be the synthesis of average value $\mu_{ad}$, standard deviation $\sigma_{ad}$ and uncertainties parameter $\eta_{ad}$, can be accomplished for each node pair. The relationship of these values can be expressed with the following equation:

$$\phi\left( \frac{x_{ad} - \mu_{ad}}{\sigma_{ad}} \right) = \eta_{ad}$$

Through Eq.(8), random variable that follows
Gaussian distribution in bandwidth demand matrix can be transformed into concrete bandwidth demand \( t_{sd} \) for node pair between \( s \) and \( d \). When \( \eta_{sd} \) equals to 0.5, \( t_{sd} \) will be the average bandwidth demand \( \mu_{sd} \). To be consistent with optimization goal in section III, we often set \( \eta_{sd} \) equally to 0 (see Eq.(5)).

The procedures of ID-MLTDA are listed below:

Step 1: For each node pair, according to Eq.(8) calculate \( t_{sd} \) under the average bandwidth demand value \( \mu_{sd} \), standard deviation \( \sigma_{sd} \) and uncertainties parameter \( \eta_{sd} \).

Step 2: Mapping the current virtual topology into a bipartite graph. Two vertices \( o_s \) and \( i_d \) in the bipartite graph corresponds to each node \( n \) in the virtual topology. The value of \( t_{sd} \) between node \( s \) and node \( d \) is used to initialize the edge from \( o_s \) to \( i_d \) in the bipartite graph. Additionally, a Boolean variable \( b_{sd} \), which is associated with each edge from node \( s \) to node \( d \) in the virtual topology, is assumed to have the values DELETABLE or UNDELETABLE.

Step 3: Select the fully connected virtual topology and mark all light-paths as DELETABLE.

Step 4: Solve the routing problem on the current topology (using Dijkstra shortest-path algorithm) and compute the traffic on light-paths (using Eq. (6)).

Step 5: Update the weights of the edges in the graph using computed traffic on light-paths.

Step 6: Find a set of edges that can be removed from the graph by solving a 1-Minimal Weight Matching (1-MWM) on the bipartite graph. Only the edges that are marked as DELETABLE can be chosen in the matching.

Step 7: Removed edges in the 1-Minimal Weight Matching, together with the corresponding light-path in the virtual topology, only if the resulting virtual topology remains connected. If the removal of a matched light-path would disconnect the logical topology, mark the light-path as UNDELETABLE.

Step 8: If all the in/out degree constraints are satisfied then STOP, otherwise GOTO back to Step 4.

Compared to D-MLTDA, the bandwidth demand \( t_{sd} \) applied in ID-MLTDA involves not just with the average bandwidth demand \( \mu_{sd} \) but also with standard deviation \( \sigma_{sd} \) and uncertainties parameter \( \eta_{sd} \). In addition, the bandwidth demand calculation on light-paths is on the basis of Eq.(6), not the simple addition of average bandwidth demand traversing light-paths. All the improvements are supposed to deal with the bandwidth demand uncertainties in WDM optical network. The computational complexity of this algorithm is upper-bounded by \( O(N-\delta)N^4 \log N \), since the 1-MWM algorithm has complexity \( N^3 \log N \), and at most \( N(N-\delta) \) light-paths must be removed from the initial logical topology, if the in/out degree is \( \delta \).

5 Simulation and Discussion

In this section, several performance results will be reported through simulation. A network of twenty nodes has been considered in simulation. The in/out degree is constrained to 5. The number of wavelengths is not limited. Both \( p \) and \( \eta_{sd} \) are set to be 0.99.

We firstly generate ten different bandwidth demand scenarios whose average bandwidth demand \( \mu_{sd} \) and standard deviation \( \sigma_{sd} \) varies from 500 to 650 Mega bytes and from 0 to 100 Mega bytes respectively.

For each scenario, the \( \lambda \) (see Section 3) of each virtual topology that is respectively generated by ID-MLTDA and D-MLTDA is obtained under optimization goal in Section 3. Let \( \lambda^k_1 \) and \( \lambda^k_0 \) represent maximum bandwidth demand of virtual topology generated by ID-MLTDA and D-MLTDA, respectively, under bandwidth demand scenario \( k \). The gain of applying ID-MLTDA for bandwidth demand scenario \( k \) is defined as

\[
\frac{\lambda^k_0 - \lambda^k_1}{\lambda^k_0} \times 100\% \tag{9}
\]

If \( m \) different bandwidth demand scenarios are generated, the average gain of applying ID-MLTDA for all the bandwidth demand scenarios is defined as

\[
\frac{\sum_{k=1}^{m} \lambda^k_0 - \sum_{k=1}^{m} \lambda^k_1}{\sum_{k=1}^{m} \lambda^k_0} \times 100\% \tag{10}
\]

As we see in Fig.1, the \( \lambda \) of virtual topology constituted by ID-MLTDA is less than that by D-MLTDA under same bandwidth demand scenario. An average gain about 6.57% is obtained by applying ID-MLTDA for all ten bandwidth demand scenarios. This result can be explained by the simple example: Assume that node pairs (0, 1) and (0, 2) cannot set up light-path at same time, \( \mu_{01} \) is little more than \( \mu_{02} \) and \( \sigma_{01} \) is much little than \( \sigma_{02} \). If we apply D-MLTDA, light-path should be set up between node pair (0, 1) based on \( \mu_{01} \) while the traffic flows between node pair (0, 2) will cross several light-paths and lead the
maximum value $\lambda_{ij}$ to be greater on these light-paths, because of large uncertainties of the bandwidth demand between node pair $(0, 2)$. By applying ID-MLTDA, we should establish light-path between node pair $(0, 2)$ and $\lambda_{ij}$ will be smaller due to the stability of the bandwidth demand of node pair $(0, 1)$ although its average bandwidth demand is little bigger.

Then, ten simulation scenarios will be finished. For each simulation scenario, ten traffic scenarios will be randomly generated based on the given range of $\mu_{sd}$ and $\sigma_{sd}$. Then, by applying ID-MLTDA and D-LMTDA, we can obtain corresponding virtual topology and calculate $\lambda$ (see Section 3) and gain (see Eq. (9)) for each bandwidth demand scenario. Further, we get the average gain of the ten bandwidth demand scenarios that belong to the same simulation scenario.

Tab.2 shows the average gain of applying ID-MLTDA under the change of the average bandwidth demand $\mu_{sd}$. As we can see in Tab.2, the gain by applying ID-MLTDA becomes higher as the average bandwidth demand $\mu_{sd}$ gradually decreases, which leads to the decrease of the rate of $\mu_{sd}$ to $\sigma_{sd}$. It illustrates that ID-MLTDA provides better performance under higher degree of uncertainties.

Tab.3 shows the average gain of applying ID-MLTDA under the change of the standard deviation $\sigma_{sd}$. We can find in Tab.3 that the gain becomes lower as the standard deviation decreases. It also demonstrates that the better performance is offered by ID-MLTDA under higher degree of uncertainties.

Thus, we can deduce from the above simulations that ID-MLTDA is suitable for designing virtual...
topology under bandwidth demand uncertainties. When the degree of uncertainties is higher, ID-MLTDA is much more advantageous to minimizing the maximum bandwidth demand of the networks.

6 Conclusions

In this paper, the problem of designing virtual topology under the bandwidth demand uncertainties is studied. The bandwidth demand model under uncertainties is presented. Based on such bandwidth demand model, optimization goal concerning with uncertainties is proposed. Correspondingly, we offer a heuristic algorithm called ID-MLTDA. The algorithm shows good performance under the bandwidth demand uncertainties. The novel method, including definition of bandwidth demand model, optimization goal, and a heuristic algorithm, is reasonable and efficient.

References


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