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IP over WDM 網路中具服務品質保證及群播技術之研究
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行政院國家科學委員會專題研究計劃成果報告

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一、摘要

本年度計畫主要研究分波長多工全光網路(WDM all-optical networks)中群播樹之路由演算法的設計。我們所針對的環境是網路中僅有部分的光交換機具有分光器(power splitter)，因此只有部分的網路節點可作為群播樹的分叉點。目前相關研究大都是結合史坦爾樹(Steiner tree)演算法以及重新路由(rerouting)機制，這類作法的主要缺點是其所產生的群播樹會使用較多的網路連結(link)，因而較浪費網路資源。在本年計畫中我們提出演算法改進此缺點，藉由模擬驗證，我們所提出的演算法使用較少網路資源。此外，我們亦分析所提出的演算法在壞情況下之效能，並討論延申此演算法以支援動態群組的可能性。

關鍵詞：分波長多工光纖網路、全光網路，群播

Abstract

In this project, we formulate an optimization problem for the design of light-tree based logical topology in Wavelength Division Multiplexing (WDM) networks. The problem is comprised of two parts: (1) multicast routing and wavelength assignment of light-trees, and (2) the design of light-tree based logical topology for multicast streams. In the first part, we use Mixed Integer Linear Programming (MILP) to solve the optimal routing and wavelength assignment problem of light-trees with an end-to-end delay bound,

and obtain the optimal placement of power splitters and wavelength converters. The numerical results show that networks with just a few power splitters and wavelength converters can efficiently carry multicast data. In the second part, we extend the above formulation to design the logical topology based on light-trees for multicast streams. In our approach, a light-tree can carry data of multiple multicast streams, and data of a multicast stream may traverse multiple light-trees to reach a receiver. The numerical results show that our approach use network resources more efficiently, as compared to the approach with a separate light-tree for a multicast stream and to the approach of transporting multicast streams over logical networks.

Keywords : Mixed Integer linear programming (MILP); WDM; multicas; light tree; logical topology

二、研究動機與目的

Optical networks based on Wavelength Division Multiplexing (WDM) are the most promising candidates for the next generation backbone networks. In a wavelength-routed network, data are transported in all-optical WDM channels referred to as lightpaths. The set of lightpaths forms the logical topology of a WDM network. Data are processed electronically only at each node of a logical topology (i.e., at the endpoints

of the lightpath), and switched optically at intermediate nodes of the underlying physical network. Design of logical topologies has been studied in recent years [1-4], and the goal is to minimize the congestion (i.e., the load on each channel), or the resources used in physical networks.

Multicast is an efficient way to transport the data of one-to-many and many-to-many applications. Supporting multicast in higher layers is inefficient due to the lack of topological information of the physical networks [5-10]. To support multicast in the WDM layer, [6] introduced the concept of the light-tree, which is a point-to-multipoint extension of a lightpath. Branching nodes of a light-tree are equipped with *power splitters*. It is widely believed and desired that only a portion of the network nodes are required to be equipped with power splitters due to their expensive cost. This kind of networks is called a *sparse-splitting* network. Compared with multicasting in higher layers, transporting multicast streams on light-trees uses less number of wavelength channels¹, optical transmitters and receivers [6]. However, transporting each multicast stream on a different light-tree is also inefficient if the data rate of a stream is much lower than the data rate provided by a wavelength channel. In this case, it is more efficient to carry multiple multicast streams on a light-tree. Since the senders and receivers of different streams may be different, a multicast stream may need to be transmitted on multiple light-trees to reach all the receivers. In other words, data of a multicast stream may need to traverse multiple light-trees to reach each

receiver. To provide such service efficiently, the following three issues need to be addressed: (1) to determine the destinations of each light-tree, (2) to determine the routing and wavelength assignment of each light tree, and (3) to determine the set of light-trees used by a multicast stream, provided that the set of multicast streams to be transmitted is given. Interestingly, this problem is just equivalent to designing a light-tree based logical topology for multicast streams. The light-tree based logical topology is a *hypergraph* [10], in which each link of the logical topology is a *hyperedge*. Here a hyperedge is a link by which more than two nodes can be connected. Each hyperedge represents a light-tree in WDM networks.

Light-tree based logical topologies have been studied in [19,20] using heuristics. The authors assume that each node is capable of both wavelength conversion and power splitting. However, their heuristics do not give optimal solutions.

In this paper, we study the design of optimal light-trees for multicast streams in WDM networks. The problem is comprised of two parts: (1) multicast routing and wavelength assignment of light-trees and (2) the design of light-tree based logical topology for multicast streams. In the first part, we use MILP to solve the multicast routing and wavelength assignment of light-trees. The number of nodes capable of power splitting or wavelength conversion is given as a parameter (i.e., known *a priori*). Our formulation has the following characteristics:

- End-to-end delay of a light-tree is bounded.
- Optimal placement of wavelength converters and power splitters are obtained.

¹ A wavelength channel means an edge on a light-tree.

- In the second part, we extend the above formulation to design the logical topology based on light-trees for multicast streams.

A common problem of MILP formulation is the difficulty in requiring some constraints to hold only under a certain condition. For example, the flow conservation rule states that the amount of flows incoming to a node is the same as the amount of flows outgoing from the node. This rule holds for a node only if the node is not capable of power splitting. It is hard to make the constraint *linear* if the capability of a node is to be decided (e.g., whether a node should be equipped with power splitters or wavelength converters). To solve this problem, we incorporate a large number, say, M into the formulation. In our approach, for the node which does not follow the flow conservation rule, M will force the constraint to always hold. This technique enables MILP to formulate more complicated scenarios for WDM networks, while the number of variables and constraints only increases slightly. We will demonstrate how to use this technique in the next section.

三、問題描述及演算法

The problem to be studied is comprised of two parts: routing and wavelength assignment of light-trees, and logical topology design. We assume the physical topology, the number of power splitters and wavelength converters in the network, and the number of optical transmitters and receivers at each node are given as parameters. We assume that the power loss of power splitting can be neglected because optical amplifiers are used. We also assume that each wavelength converter is a *full range wavelength converter* [16], i.e., each wavelength on a channel can be converted to any other wavelength.

The notation is defined as follows.

V	the set of all nodes in a network;
E	the set of all links in a network;
Γ	the set of light-trees to be created;
Λ	the set of wavelengths supported in a fiber;
$In(n)$	the set of links incident to node n , i.e., n is the sink of the links, $n \in V$;
$Out(n)$	the set of links incident from node n , i.e., n is the source of the links, $n \in V$;
T_n	the set of light-trees rooted at node n , $n \in V$;
$UP(e)$	the source node of link e , $e \in E$;
$DN(e)$	the destination node of link e , $e \in E$;
k	a wavelength in a fiber;
t	a light tree

Multiple fibers on a link are supported in our formulation. We assume that the set of wavelengths that a fiber can support is the same for all fibers. There is one *source* and multiple *destinations* on a light-tree. We define an *incoming channel* of a node n as a wavelength channel of a fiber on a link which belongs to $In(n)$. Similarly, an *outgoing channel* of n is a wavelength channel of a fiber on a link belonging to $Out(n)$. We also define the *outgoing wavelengths* of n used by light-tree t as the wavelengths assigned to outgoing channels of n which are used by t . For a light-tree, we call m an *upstream node* of n if there is a path from m to n on the light-tree. In the above case, we can also call n a *downstream node* of m .

i) Routing and Wavelength Assignment of Light-trees

We use MILP to find (1) the optimal routing and wavelength assignment of light-trees with an end-to-end delay bound, and (2) the optimal placement of power splitters and wavelength

converters in a WDM network. The given parameters for this problem are denoted as follows.

- N_S the number of power splitters in a network;
- N_C the number of wavelength converters in a network;
- Rx_n the number of optical receivers at node n ;
- Tx_n the number of optical transmitters at node n ;
- F_e the number of fibers on link e ;
- P_e the propagation delay of link e ; we assume $P_e > 0$ for $\forall e \in E$;
- PT_t the end-to-end delay bound of light-tree t ;
- $D_n^{(t)}$ if node n is a destination of light-tree t , $D_n^{(t)} = 1$; otherwise, $D_n^{(t)} = 0$;
- M used to enforce conditional rules to the constraints; the value of M is set as follows.

$$M = \max \left(\sum_{t \in \Gamma} PT_t, |E| \times |\Lambda| \times F_e, \sum_{e \in E} P_e \right) \quad (1)$$

We note that the number of light-trees in which a node n participates must be equal to or less than the number of optical receivers at n .

The variables are defined as follows.

- $I_{e,k}^{(t)}$ the number of fibers of link e in which wavelength k is used by light-tree t . $I_{e,k}^{(t)}$ must be a positive integer or 0;
- $J_e^{(t)}$ if any wavelength of a fiber on link e is used by light-tree t , $J_e^{(t)} = 1$; otherwise, $J_e^{(t)} = 0$;
- $Q_n^{(t)}$ the end-to-end delay from the source of light-tree t to node n ;
- Φ_n if node n is capable of power splitting, $\Phi_n = 1$; otherwise, $\Phi_n = 0$;
- Θ_n if node n is capable of wavelength conversion, $\Theta_n = 1$; otherwise, $\Theta_n = 0$;
- $G_k^{(t)}$ if light-tree t uses wavelength k of any fiber incident from the source of

$$t, G_k^{(t)} = 1; \text{ otherwise, } G_k^{(t)} = 0$$

The objective function is formulated as follows.

$$\text{minimize } \sum_{t \in \Gamma} \sum_{e \in E} \sum_{k \in \Lambda} I_{e,k}^{(t)} \quad (2)$$

Similar to [14], this objective function is to minimize the resource, i.e. the number of incoming channels of all nodes, used by all light-trees in a WDM networks. The goal of most existing work [5-9] is to maximize the number of light-trees which can be created in the network. Note that our objective function is highly correlated with this goal because more light-trees can be created as the resource used by all light-trees decreases. Moreover, our formulation can include some other objective functions proposed by existing work. For example, with some minor modification to our formulation, the following two objective functions can be achieved: (1) to minimize the number of optical transmitters and receivers in a network, i.e., the objective function in [6] and (2) to minimize the overall profit of creating light-trees, i.e., the objective function in [12,13].

The set of constraints is shown as follows..

(a) Routing and wavelength assignment constraints:

$$\sum_{t \in \Gamma} I_{e,k}^{(t)} \leq F_e, \quad \forall e \in E, \forall k \in \Lambda \quad (3)$$

$$\frac{\sum_{k \in \Lambda} I_{e,k}^{(t)}}{M} \leq J_e^{(t)}, \quad \forall e \in E, \forall t \in \Gamma \quad (4)$$

$$\frac{D_n^{(t)} + \sum_{e \in Ou(n)} \sum_{k \in \Lambda} I_{e,k}^{(t)}}{M} \leq \sum_{e \in In(n)} \sum_{k \in \Lambda} I_{e,k}^{(t)}, \quad \forall n \in V, \forall t \in \Gamma, t \notin T_n \quad (5)$$

In the conventional multi-commodity flow

assignment problem, a *flow conservation constraint* is required to ensure that the amount of outgoing flows of a node must be equal to the amount of incoming flows if the node is neither the source nor a destination. In optical multicast networks, this constraint does not hold because the flow, i.e., optical signal, can be duplicated. We use eqs. (3)-(5) to make sure that there is a path from the source to each destination on the light-tree. Eq. (3) ensures that each wavelength of a link is used by at most light-trees. Eq. (4) guarantees that $J_e^{(t)}$ equals one if at least one wavelength of a fiber on link e is used by light-tree t . If node n is not the source of t and at least one of the following conditions holds,

- n is a destination of light-tree t
- at least one outgoing channel of n is used by t

then eq. (5) guarantees that t uses at least one incoming channel of n . Since the incoming channel of n must be an outgoing channel of another node, say, m , eq. (5) also ensures that at least one incoming channel of m is used by t if m is not the source of t . Therefore, there must exist a path from the source of t to n , or n and m are in a loop, i.e., n is also an upstream node of m . The delay constraints specified later will guarantee that there is no loop in any feasible solution.

(b) Node constraints:

$$\sum_{e \in \text{Out}(n)} \sum_{k \in \Lambda} I_{e,k}^{(t)} + D_n^{(t)} \leq (\Phi_n) \times M + \sum_{e \in \text{In}(n)} \sum_{k \in \Lambda} I_{e,k}^{(t)}, \quad \forall n \in V, \forall t \in \Gamma, t \notin T_n$$

$$\sum_{e \in \text{Out}(n)} I_{e,k}^{(t)} \leq (\Phi_n + \Theta_n) \times M + \sum_{e \in \text{In}(n)} I_{e,k}^{(t)}, \quad \forall n \in V, \forall t \in \Gamma, t \notin T_n, \forall k \in \Lambda$$

$$\sum_{e \in \text{In}(n)} I_{e,k}^{(t)} \geq \frac{\sum_{e \in \text{Out}(n)} I_{e,k}^{(t)}}{M} - \Theta_n, \quad \forall n \in V, \forall t \in T_n, t \notin T_n, \forall k \in \Lambda$$

$$\sum_{n \in V} \Phi_n \leq N_S \quad (9)$$

$$\sum_{n \in V} \Theta_n \leq N_C \quad (10)$$

- Eqs. (6)-(10) ensure that the result will not contradict with the capability of a node.

Eqs. (9) and (10) ensures that the number of nodes equipped with power splitters or wavelength converters must be less than or equal to N_S or N_C , both of which can be given according to the budget of a network provider.

(c) Delay constraints:

$$Q_n^{(t)} = 0, \quad \forall n \in V, \forall t \in T_n \quad (11)$$

$$1 - J_e^{(t)} - \frac{Q_{UP(e)}^{(t)} + P_e - Q_{DN(e)}^{(t)}}{M} \geq 0, \quad \forall e \in E, \forall t \in \Gamma \quad (12)$$

$$D_n^{(t)} + \frac{Q_n^{(t)} - PT_t}{M} \leq 1, \quad \forall n \in V, \forall t \in \Gamma \quad (13)$$

Eqs. (11)-(13) ensure that the delay of the path from the source of a light-tree to each destination must be equal to or less than the delay bound. Eq. (11) states that the delay from the source of a light-tree t to a node n equals zero if n is the source of t . Eq. (12) ensures that if link e from node m to n is used by t , then the delay from the source of t to n is equal to or larger than the delay from the source of t to m plus the propagation delay of e . If e is not used by t , i.e., $J_e^{(t)} = 0$, M makes eq. (12) always hold. Eq. (13) guarantees that the delay from the source of t to n must be equal to or less than the delay bound if n is a destination of t .

(d) Optical transceiver constraints:

$$\sum_{e \in \text{Out}(n)} \sum_{t \in T_n} \sum_{k \in \Lambda} I_{e,k}^{(t)} \leq Tx_n + \Phi_n \times M, \quad \forall n \in V \quad (14)$$

$$\frac{\sum_{e \in \text{Out}(n)} I_{e,k}^{(t)}}{M} \leq G_k^{(t)}, \forall n \in V, \forall t \in T_n, \forall k \in \Lambda$$

$$\sum_{t \in T_n} \sum_{k \in \Lambda} G_k^{(t)} \leq Tx_n + \Theta_n \times M, \forall n \in V$$

$$\sum_{t \in \Gamma} D_n^{(t)} \leq Rx_n, \forall n \in V \quad (17)$$

Eq. (17) states that the number of light-trees in which a node n participates must be equal to or less than the number of optical receivers at n . Since both $D_n^{(t)}$ and Rx_n are given parameters, here we assume this constraint always holds. Later in the next section, we will need this constraint when $D_n^{(t)}$ becomes a variable.

(e) Design of Light-Tree Based Logical Topologies

In this section, we extend the formulation described above to solve the logical topology design problem. A logical topology is a hypergraph, in which each node represents a switch capable with electronic processing. Each hyperedge represents a light-tree in the physical network. We use the formulation of light-trees described in the last section to find the hyperedges for the logical topology. The traffic over the logical topology is composed of multiple *multicast streams* to which an end-to-end delay bound is guaranteed. Each multicast stream has a *sender* and several *receivers*. We assume that the propagation delay dominates the end-to-end delay because the link can be maintained relatively lightly utilized by setting λ_{\max} properly, leading to negligible queueing delays. The goal of this section is to find the optimal design of logical topologies and the optimal routing of multicast streams using MILP. Some new parameters are defined as follows.

- j a multicast stream;
- $\lambda_{(15)}$ data rate of multicast stream j ;
- λ_{\max} the data rate supported on a wavelength channel;
- $R_n^{(j)}$ if n is a receiver of stream j , $R_n^{(j)} = 1$; otherwise, $R_n^{(j)} = 0$;
- $S_n^{(j)}$ if n is the sender of stream j , $S_n^{(j)} = 1$; otherwise, $S_n^{(j)} = 0$;
- PS_j the end-to-end delay bound of stream j ;

Some new variables are defined as follows.

- $B^{(t,j)}$ if data of multicast stream j are carried on light-tree t , $B^{(t,j)} = 1$; otherwise, $B^{(t,j)} = 0$;
- $Z_n^{(t,j)}$ if node n is a destination of light-tree t , and the data of multicast stream j are carried on light-tree t , $Z_n^{(t,j)} = 1$; otherwise, $Z_n^{(t,j)} = 0$;
- $Y_n^{(j)}$ the delay from the sender of stream j to node n ;

$D_n^{(t)}$, a given parameter in the last section, becomes a variable in this section. Moreover, variable PT_t and the constraint in eq. (12) are of no use in this section. Here the value of M should be set as follows.

$$M = \max \left(\sum_{j \in H} PS_j, |E| \times |\Lambda| \times |\Gamma| \times |H| \times F_e, \sum_{e \in E} P_e \right) \quad (18)$$

The objective function may either be to minimize the congestion [1,3] or to minimize the average packet hop distance [2]. For the former case, λ_{\max} is set as a variable. For the latter case, additional variables representing the data rate of each stream carried on light-tree t transmitted on each link are required. In this paper, we use the same objective function as in the previous section (i.e., eq. (2)) in order to compare the following three design scenarios fairly.

- Each multicast stream is carried on a different light-tree. The problem is just the routing and wavelength assignment of light-trees as discussed in [5-9,12-14].

- Multicasting is only available on logical networks. Each node of a logical network is capable of multicasting. Each edge of a logical network is a lightpath. It is the problem as discussed in [15].
- Multicasting is available both on physical networks and logical networks. A light-tree can carry data from multiple multicast streams. It is the focus of this section.

The set of constraints is listed as follows.

Multicast routing constraints:

$$R_n^{(j)} \times \sum_{t \in \Gamma, t \notin T_n} Z_n^{(t,j)} \geq R_n^{(j)}, \forall n \in V, \forall j \in H$$

$$B^{(t,j)} + D_n^{(t)} \geq 2 \times Z_n^{(t,j)}, \forall n \in V, \forall t \in \Gamma, t \notin T_n, \forall j \in H$$

$$(1 - S_n^{(j)}) \times \frac{\sum_{t \in T_n} B^{(t,j)}}{M} \leq (1 - S_n^{(j)}) \times \sum_{t \in \Gamma, t \notin T_n} Z_n^{(t,j)}, \forall n \in V, \forall j \in H \quad (21)$$

Eqs. (19) to (21) ensure that data of each multicast stream will pass through one or several light-trees to each receiver. Eqs. (19) to (20) guarantee that each receiver of stream j must be a destination of a light-tree which carries the data of j . Eq. (21) ensures that the source of the light-tree must be a destination of another light-tree which carries the data of stream j , or the source must be the sender of stream j . Similar to the routing and wavelength assignment constraints in the last section, there must exist a path from the sender of j to each receiver, or a loop will exist. The delay constraints specified in the next paragraph will ensure that there is no loop in any feasible solution.

Delay constraints:

$$S_n^{(j)} \times Y_n^{(j)} = 0, \forall n \in V, \forall j \in H$$

$$Y_n^{(j)} \geq Y_m^{(j)} + Q_n^{(t)} - (1 - Z_n^{(t,j)}) \times M, \forall m, n \in V, m \neq n, \forall t \in T_m, \forall j \in H \quad (23)$$

$$R_n^{(j)} \times (PS_j - Y_n^{(j)}) \geq 0, \forall n \in V, \forall j \in H \quad (24)$$

Eqs. (22) to (24) ensure that the delay of the path from the sender of a multicast stream to each receiver must be equal to or less than the end-to-end delay bound of the stream. Eq. (22) states that the delay from the sender of stream j to a node n equals zero if n is the sender of stream j . Eq. (23) ensures that if node n is a destination of light-tree t rooted at m , and t carries the data of stream j , then the delay from the sender of stream j to n must be equal to or larger than the delay to node m plus the delay of the path from m to n . Eq. (24) guarantees that the delay from the sender of stream j to each receiver must satisfy the end-to-end delay bound.

Rate constraints:

$$\sum_{j \in H} \lambda_j \times B^{(t,j)} \leq \lambda_{\max}, \forall t \in \Gamma \quad (25)$$

Eq. (25) ensures that the data rate carried on each light-tree must be equal to or less than the maximum data rate which a wavelength channel can support

四、效能分析

In our experiments, the CPLEX optimization package [21] is used to obtain optimal solutions. We use a 14-node NSFNET backbone network [1] as the topology of our numerical examples. The number beside each node indicates the ID of the node. The number beside each link shows the propagation delay of the link. We add some auxiliary constraints to improve the speed of finding optimal solutions.

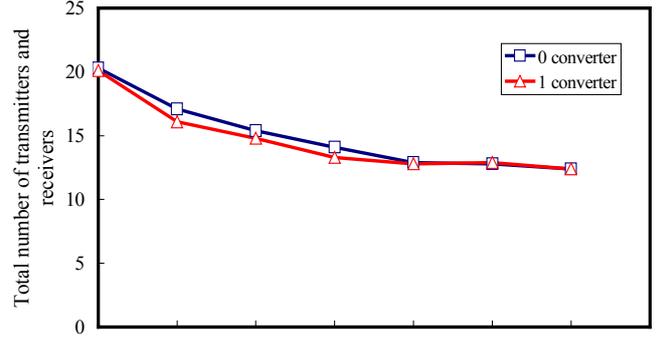
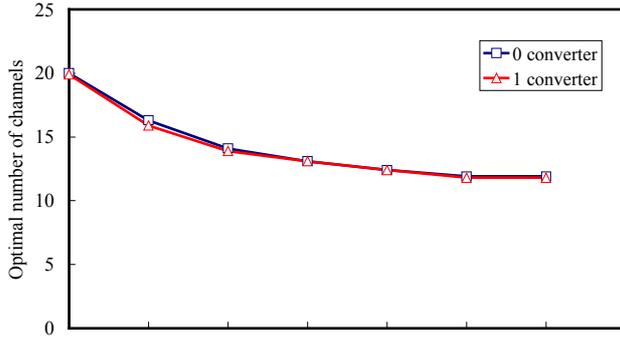


Figure 2. Comparisons of the resources used by two light-trees with different number of power splitters and wavelength converters

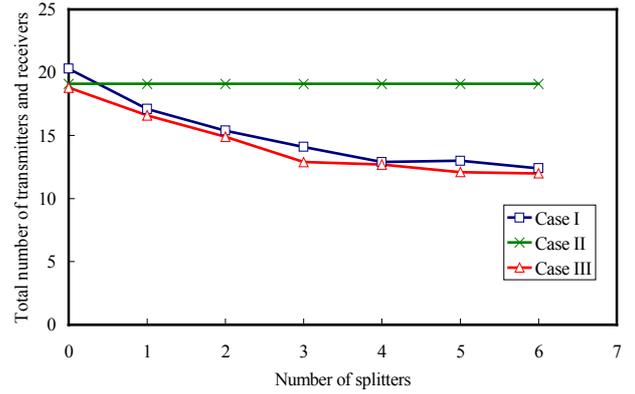
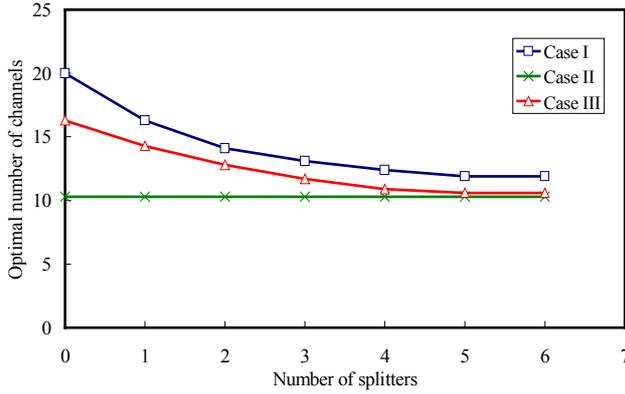


Figure 3. Comparisons of the resources used by two multicast streams with different deployments

The numbers of optical transmitters and receivers of all nodes are both set to 10 for the above three cases. The end-to-end delay bound of all light-trees is set to 100. We note that the results for the cases with more than one converter in the network and two wavelengths in a fiber are the same as case II. The results for the cases with more than zero converter in the network and three wavelengths in a fiber are the same as case III. Tables I and II show the number of wavelength channels and the total number of optical transmitters and receivers used by the two light-trees versus different number of power splitters in a network for the three cases. The results show that a small number of power splitters (e.g., 5 splitters) can reduce the number of wavelength channels and the total number of optical transmitters and receivers used by the two light-trees. Without power splitters, a separate

lightpath has to be created for each pair of source and destination. With more power splitters, a shorter lightpath can be created by splitting another lightpath from a nearby power splitter. Thus, the average number of wavelength channels and the total number of optical transmitters and receivers used by a light-tree can be reduced. Table III shows the optimal placement of power splitters and wavelength converters versus a different number of power splitters in a network for the three cases. In this example, we find that wavelength converters are needed only when the number of wavelength channels is insufficient. Due to space limitations, the results of routing and wavelength assignment are not included in this paper.

Fig. 2 is the result averaged over 10 cases. The sender and destinations of each light-tree in all cases are chosen randomly. The average number

of destinations on a light-tree is set to 6. The number of wavelengths that a fiber supports is set to 4. The number of optical transmitters and receivers of each node are both set to 10 for the above three cases. Here the objective function is modified to find the minimal number of optical transmitters and receivers used by light-trees when the optimal number of wavelength channels is found. As expected, both the number of wavelength channels and the total number of optical transmitters and receivers are reduced when more power splitters and wavelength converters are used.

The second part of our results is to compare the three approaches to supporting multicast streams in section II-B. We consider the following three cases:

- Case I: two multicast streams are transmitted on two separate light-trees.
- Case II: two multicast streams are multicast in a logical network. All nodes are capable of electronic processing. Hence, the logical topology is the same as the physical topology. Light-trees are not supported in the physical network.
- Case III: multicast is supported in both logical and physical networks.

The data rate of each multicast stream is set as half of the maximal data rate that a wavelength channel can support. The results are averaged over 10 samples. The parameters are the same as in Fig. 2.

Fig. 3 shows the optimal number of wavelength channels and the total number of optical transmitters and receivers versus different number of power splitters in a network. Case II uses the least number of wavelength channels because we assume all nodes are capable of multicasting. In real networks, however, only part of the nodes in WDM networks is capable of electronic processing. Since multicast is achieved

TABLE I.
NUMBER OF OPTICAL CHANNELS VERSUS DIFFERENT NUMBER OF POWER SPLITTERS

	Number of power splitters					
	0	1	2	3	4	5
Case I	24	18	16	15	14	13
Case II	23	18	16	15	14	13
Case III	23	18	16	15	14	13

TABLE II.
TOTAL NUMBER OF OPTICAL TRANSMITTERS AND RECEIVERS VERSUS DIFFERENT NUMBER OF POWER SPLITTERS

	Number of power splitters					
	0	1	2	3	4	5
All cases	22	18	16	14	14	14

TABLE III.
PLACEMENT OF POWER SPLITTERS AND WAVELENGTH CONVERTERS VERSUS TOTAL NUMBER OF OPTICAL TRANSMITTERS AND RECEIVERS VERSUS DIFFERENT NUMBER OF POWER SPLITTERS

	N_s	Splitter	Converter
Case I	0	N/A	N/A
	1	9	Needless
	2	9,13	Needless
	3	4,9,13	Needless
	4	4,9,10,13	Needless
	5	1,4,9,13,14	Needless
Case II	0	N/A	6
	1	9	Needless
	2	9,13	Needless
	3	4,9,13	Needless
	4	4,9,10,13	Needless
	5	1,4,9,12,14	Needless
Case III	0	N/A	N/A
	1	9	Needless
	2	9,12	Needless
	3	4,9,13	Needless
	4	4,9,12,14	Needless
	5	1,4,9,10,13	Needless

over logical networks in case II, more optical transmitters and receivers are used. Compared to case I, case III uses less number of wavelength channels, optical transmitters and receivers because a light-tree can carry data from both streams. With a few power splitters, the number of wavelength channels used in case III is close to that in case II. However, case III requires far fewer optical transmitters and receivers. Since the cost of power splitters is less expensive than that of optical transmitters and receivers [6], case III

outperforms the other two cases.

五、結論

In this paper, we have presented an Mixed Integer Linear Programming (MILP) formulation to solve the optimal routing and wavelength assignment problem of light-trees with an end-to-end delay bound, and obtain the optimal placement of power splitters and wavelength converters in the network. The results show that networks with just a few power splitters and wavelength converters can efficiently carry multicast data. We have also extended the above formulation to design a light-tree based topology for multicast streams with an end-to-end delay bound, and obtain the optimal routing of multicast streams. We have demonstrated that this approach can use the network resources more efficiently, as compared to the approach in which each multicast stream is transmitted on a different light-tree, and the approach in which all streams are multicast in logical networks.

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