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Optical-Drop Wavelength Assignment Problem for Wavelength Reuse in WDM Ring Metropolitan Area Networks

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Abstract

This paper presents a formulation of the optical-drop wavelength assignment problem (ODWAP) *and its heuristic algorithm for WDM ring networks. The wavelength-division multiplexing (WDM) technology has been popular in communication societies for providing very large communication bands by multiple lightpaths with different wavelengths on a single optical fiber. Particularly, a double-ring optical network architecture based on the packet-over-WDM technology such as the HORNET architecture, has been studied as a next generation platform for metropolitan area networks (MANs). Each node in this architecture is equipped with a wavelength-fixed optical-drop and a tunable transmitter so that a lightpath can be established between any pair of nodes without wavelength conversions. In this paper, we formulate ODWAP for efficient wavelength reuse under heterogeneous traffic in this network. Then, we propose a simple heuristic algorithm for ODWAP. Through extensive simulations, we demonstrate the effectiveness of our approach in reducing waiting times for packet transmissions when a small number of wavelengths are available to retain the network cost for MANs.*

1. Introduction

Optical communication networks based on the *wavelength-division multiplexing (WDM)* technology has extensively been studied in academics and industries as a promising approach to meeting highly-demanded huge-bandwidth communication networks to support the ongoing information society [8]. The WDM technology provides very large communication bands through multiple communication paths with different wavelengths on a single optical fiber.

A connection in a WDM network is established by selecting a routing path from the source node to the destination, and then allocating a free wavelength to every link along the path, which is called a *lightpath*. The lightpath configuration with the routing and wavelength assignment plays an important role in determining the transmission efficiency of a WDM network. Thus, a lot of efforts have been conducted in literatures. As summarized in [10], they may be categorized by difference in assumptions on the traffic pattern (static or dynamic), the availability of wavelength conversions, and the desired objective. This paper is concerned with dynamic traffic (instead of static one), no wavelength conversion, and the minimization of waiting times or blocking probabilities under given network resources including the number of wavelengths (instead of the minimization of the number of required wavelengths for given requests). These assumptions intend to consider a practical implementation of a WDM ring network for metropolitan area networks (MANs). The ring network has not only been the predominant topology for MANs and interoffice networks, but also is expected to be the first topology for the WDM network used in real worlds [7]. The evaluation with dynamic traffic is more productive in empirical studies with simulations, because it can investigate dynamic behaviors of the network. The use of wavelength conversions is costly for MANs.

Recently, a WDM ring network architecture called *HORNET* (a hybrid optoelectronic ring network), has been proposed as a next generation platform for MANs by a research

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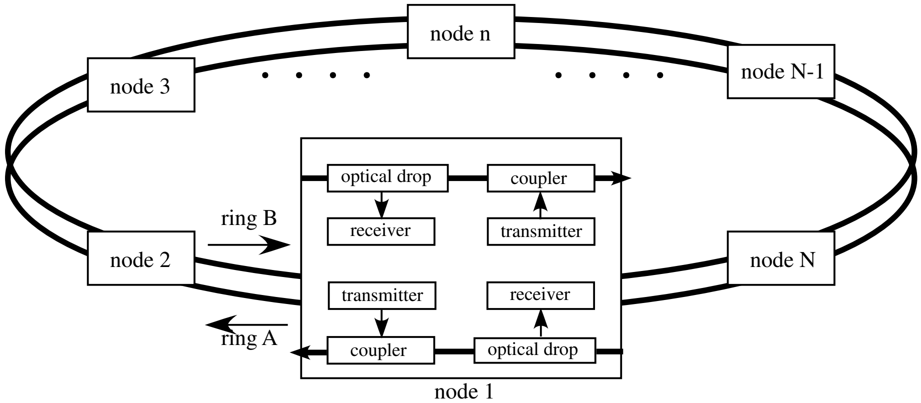

Figure 1. A HORNET architecture.

group at Stanford University, in order to afford the rapid increase of incoming traffic into MANs [14][3][15][16]. This WDM-based MAN architecture employs wavelength-fixed optical-drops and wavelength-tunable transmitters at every node, so that it does not require wavelength conversions. A lightpath can be established between any pair of nodes by tuning the wavelength for the transmitter at the source node to the one for the optical-drop at the destination node. Due to the popularization of broadband Internet access services by ADSL, cable TV, and FTTH, MANs have been highly demanded to handle very large traffic between local are networks (LANs). HORNET adopts the packet-over-WDM technology to cost-effectively scale beyond $1Tbps$ transmissions with high survivability from node/link failures using double optical fiber rings.

Figure 1 illustrates an overview of the HORNET architecture. It employs two optical fiber rings for wide-band communications between nodes that are access points to backbone networks and LANs. Like the DQDB (distributed-queue dual bus) network (IEEE 802.6 standard protocol for MANs) [11][13][12][5], each ring handles unidirectional packet transmissions between nodes. Ring A transmits packets from source nodes to destinations in the clockwise direction, whereas ring B does in the anticlockwise direction. This two-fiber-ring architecture also provides the survivability from failures of nodes and/or links, which is critical for MANs. Each node is equipped with two sets of a wavelength-fixed optical-drop and a wavelength-tunable transmitter as interface to two optical fibers.

Each wavelength in this architecture can be reused by plural lightpaths simultaneously, if they are not spatially overlapped or intersected with each other, as in DQDB networks [13][12][5] and other WDM-based networks [1][17][2][6]. This wavelength reuse becomes more critical if the number of available wavelengths is smaller than the number of network nodes, where optical-drops at several nodes must share the same wavelength, which can often be true for large-scale MANs [1]. The use of a large number of wavelengths on a single fiber needs expensive hardware, because the wavelength clearance between two adjacent channels becomes small.

With the wavelength sharing among optical-drops at plural nodes, their wavelength assignments determine the degree of interference between connection requests in lightpath establishments. When the traffic is homogenous among nodes in the network, each wavelength should be reused by optical-drops at nodes in a cyclic fashion with the regular interval, so that the distribution of the expected blocking probability of connection requests becomes even at any node. However, if the traffic is heterogeneous depending on nodes, the wavelength assignment should be differentiated among nodes so that the blocking probability of requests connecting highly-demanded nodes can be reduced as much as possible. As a result, the wavelength reassignment from the cyclic one is of great interest for the heterogeneous traffic that may often happen in MANs.

In this paper, we formulate the *optical-drop wavelength assignment problem (ODWAP)* in a WDM ring network for a given traffic arriving probability as a combinatorial optimization problem. Then, we propose a simple heuristic algorithm for ODWAP. Through dynamic traffic simulations complying with the Poisson process, we demonstrate the effectiveness of our approach in reducing waiting times for requests in their lightpath establishments. Here, we note that most of existing studies for wavelength assignment problems in WDM networks assume that all the connection requests are given beforehand, and the goal is to assign a feasible wavelength to the lightpath for every request, with various objectives such as the minimization of the number of wavelengths [7][4] and the minimization of the number of add/drop multiplexers [17]. Our ODWAP formulation with a given traffic probability is more realistic than the formulation where every connection request is known beforehand.

This paper is organized as follows: Sect. 2 defines ODWRP in the WDM network and discusses its computational complexity. Section 3 presents the heuristic algorithm for ODWAP. Section 4 shows the performance evaluation by simulations. Section 5 provides the conclusion of this paper.

2. Optical-Drop Wavelength Assignment Problem

2.1. Traffic Matrix

The goal of the optical-drop wavelength assignment problem (ODWAP) is to find a proper wavelength assignment to optical-drops at nodes from available W wavelengths in the network, such that the total blocking probability of lightpath establishments should be minimized for a given traffic arriving probability between node pairs. The traffic probability for node pairs in an N-node network is described by an $N \times N$ traffic matrix T. The ijth element t_{ij} (row i, column j) in T for $i = 1, \ldots, N$ and $j = 1, \ldots, N$ represents the arrival rate of connection requests with source node i and destination node j to the network.

2.2. Intersection Matrix

The blocking of a lightpath establishment for a connection request occurs when a lightpath of its intersecting request has already been established in the network. Two lightpaths intersect with each other, when optical-drops at their destination nodes are assigned the same wavelength and their intervals between sources and destinations are overlapped. Here, we discuss this intersection condition mathematically. In a double-ring WDM network, each ring deals with packet transmissions in the opposite direction. Thus, the intersection depends on the used ring and the positional relationship between the source node and the destination of the connection. Let us consider the intersection condition between two lightpaths, $p_i = (s_i, d_i)$ and $p_j = (s_j, d_j)$ on ring A, as in Figure 2, when optical-drops at destination nodes d_i and d_j are assigned the same wavelength. Actually, they intersect with each other when the following condition is satisfied:

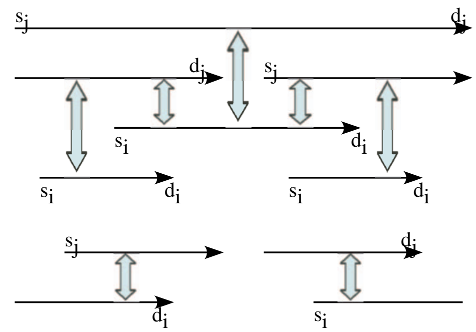

Figure 2. Intersections between lightpaths.

$$\begin{array}{l} (s_i = s_j) \text{ or} \\ \left(\begin{array}{l} s_i < s_j < d_i \text{ or} \\ s_i < d_j < d_i \text{ or} \\ s_j < s_i < d_i < d_j \text{ or} \\ s_i < d_i < d_j < s_j \text{ or} \\ d_j < s_j < s_i < d_i \end{array} \right) \text{ or} \\ \left(d_i < s_i \text{ and} \left(\begin{array}{l} s_j < d_i \text{ or} \\ s_i < d_j \end{array} \right) \right) \end{array} \quad (1)$$

Since the intersection condition on ring B is symmetric to that on ring A, we omit it. Then, the intersection matrix M_A (M_B) is introduced to concisely describe the intersection on ring A (B) between any pair of lightpaths. The $ijpq$th element m^A_{ijpq} (m^B_{ijpq}) represents whether on ring A (B), a lightpath from node i to node j and another one from p to q intersects with each other ($= 1$) if optical-drops at j and q are assigned the same wavelength, or not ($= 0$).

2.3. Total Blocking Probability

The total blocking probability of lightpath establishments is given by the sum of traffic arriving probabilities of intersecting requests. The probability of simultaneous arrivals of a request from node i to node j and another one from p to q is given by the multiplication of their traffic probabilities: $t_{ij} \times t_{pq}$. Besides, only the traffic on the *preferred ring* is considered here, because it provides a shorter lightpath than the opposite ring. The preferred ring is preliminarily found to reduce intersections with other requests and the propagation delay as best as possible, although a lightpath between any pair of nodes can be established on either ring. Then, the total blocking probabilities E^A for ring A and E^B for ring B are given by:

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$$E^A = \sum_{i=1}^{N}\sum_{j=1}^{N}\sum_{\substack{p=1\\(p,q)\neq(i,j)}}^{N}\sum_{q=1}^{N} m_{ijpq}^{A} \cdot t_{ij}^{A} \cdot t_{pq}^{A} \cdot I\left(x_j, x_q\right) \tag{2}$$

$$E^B = \sum_{i=1}^{N}\sum_{j=1}^{N}\sum_{\substack{p=1\\(p,q)\neq(i,j)}}^{N}\sum_{q=1}^{N} m_{ijpq}^{B} \cdot t_{ij}^{B} \cdot t_{pq}^{B} \cdot I\left(y_j, y_q\right) \tag{3}$$

where x_j represents the assigned wavelength at node j on ring A, and y_j does that at node j on ring B respectively. These variables are outputs of ODWAP. The modified traffic matrix element $t_{ij}^A = t_{ij}$ ($t_{ij}^B = t_{ij}$) if ring A (ring B) is preferred for the lightpath from node i to node j, and $t_{ij}^A = 0$ ($t_{ij}^B = 0$) otherwise. The function $I(a, b)$ returns 1 if $a = b$, and does 0 otherwise. From now, the total blocking probability is called the *cost function* for convenience in this paper.

2.4. Definition of ODWAP

We give the definition of ODWAP in this paper mathematically.

Optical-drop wavelength assignment problem (ODWAP)

- **Input:** a traffic matrix T, and the number of available wavelengths W in the N-node network.
- **Output:** wavelength assignments to optical-drops at nodes on ring A: $(x_1, \ldots, x_N)$, and on ring B: $(y_1, \ldots, y_N)$.
- **Objective:** to minimize the cost functions for both rings: $E^A \rightarrow$ min, and $E^B \rightarrow$ min.
- **Constraint:** to assign an available wavelength to every node on both rings: $1 \leq x_i \leq W$, and $1 \leq y_i \leq W$ for $i = 1, \ldots, N$.

3. Heuristic Algorithm for ODWAP

In this section, we present a simple heuristic algorithm for ODWAP. It first assigns wavelengths in a cyclic fashion to optical-drops at nodes, where each of W wavelengths is reused at N/W nodes in the N-node network. The node span with the wavelength reuse is always W for any wavelength. This cyclic wavelength assignment is optimum under homogenous traffic in the network. Then, it iteratively improves the wavelength assignment to meet heterogeneous traffic, by repeating either a *move* operation or a *swap* operation with the equal probability. In the move operation, the wavelength of a randomly selected node is changed to a randomly selected new one. In the swap operation, the wavelength of a randomly selected node and that of its randomly selected neighbor node is swapped. This swap operation aims to gradually differentiate node spans for the wavelength reuse. In either operation, only if the cost function is not increased after the operation, the new assignment is accepted. Otherwise, it is discarded. The procedure of this ODWAP algorithm is described as follows:

Procedure ODWAP_algorithm

1) Calculate a preferred ring for every lightpath between a pair of nodes.
2) Set the modified traffic matrix element t_{ij}^A and t_{ij}^B for cost functions.
3) Calculate edge weights w_{jq}^A and w_{jq}^B.
4) Cyclically assign wavelength $((j-1) \bmod W + 1)$ to the optical-drop at node j ($j = 1, \ldots, N$), so that every wavelength is reused with the same node span.
5) Compute the cost functions E^A and E^B.
6) Repeat the following steps for both rings sequentially in $K \times N$ times.

(a) Randomly select either the move operation or the swap operation with the equal probability.

(b) Apply the selected operation.

(c) If the new cost function is not larger than the current one, accept the new assignment. Otherwise, discard it.

Here, the time complexity of each step in this procedure is discussed: 1) and 2) are $O(N^2)$, 3) is $O(N^4)$, 4) is $O(N)$, 5) is $O(N^2)$, and 6) is $O(N^2)$ because each update of the cost function requires $O(N)$ computations. Thus, the total time complexity of this algorithm is $O(N^4)$.

4. Performance Evaluation by Simulations

4.1. Simulated Instances

In order to evaluate the effect of our ODWAP approach in the performance improvement of the WDM ring network, we have implemented the procedure in Section 3 by C with a dynamic traffic simulation program that follows the Poisson process. In this simulation program, we assume that connection requests arrive at nodes by following the Poisson distribution, and they terminate by the exponential distribution [9]. To produce the heterogeneous traffic, nodes are categorized into two classes, namely "normal nodes" and "busy nodes". The rate of busy nodes among all nodes is set 5% in our simulations, where these busy nodes are randomly selected. Then, the traffic matrix T is generated. First, the arrival rate of connection requests between two normal nodes is set as a basic traffic. Then, the arrival rate of requests between busy nodes is centuplicated from it, and the arrival rate of requests between normal nodes and busy nodes is decupled respectively. The termination rate r_o of any connection request is always fixed to 0.1.

For a given traffic matrix, an optimal optical-drop wavelength assignment is found by our ODWAP algorithm. Then, at each unit time, connection requests between node pairs are randomly generated by following probabilities in the traffic matrix, with duration times following the exponential distribution. Their lightpaths are established if they are feasible, in the *FIFO* fashion. The requests without lightpaths due to the established intersecting lightpaths are queued until their establishments. When the duration time is expired for an established connection, it is removed from the network.

In our simulation, each instance is executed from the initial null state until a total of $1,000,000$ requests have arrived at the network. The average waiting time for one request until its lightpath establishment is evaluated as the network performance. Note that first $100,000$ requests are excluded from average calculations as transient periods. In this paper, the *waiting time* for a request is defined by the number of slots between the arrival and its connection establishment. To avoid the bias in random numbers, for each case, 10 simulation runs are repeated using different random numbers, and their average results are used for evaluations.

The number of wavelengths W is set 4 and 16, and the number of nodes N is set 64 and 256. Here, we note that HORNET always satisfies $W = N$, to simplify the wavelength assignment and to avoid collisions between connections to destinations with the same wavelength as much as possible. However, the number of available wavelengths is usually limited due to the cost reason. The cost to accommodate a large number of wavelengths on a single fiber is too high to be practical for MANs. On the other hand, the number of nodes can increase for MANs depending on organizations to be covered.

4.2. Simulation Results and Discussion

Figures 3-6 illustrate changes of average waiting times of connection requests by the cyclic wavelength assignment and our ODWAP algorithm assignment in each case, when the average arrival rate r_i increases. Note that the cyclic wavelength assignment is the initial assignment of our algorithm. In any case, our algorithm assignment reduces waiting times for lightpath establishments to arriving connection requests from cyclic assignments. Thus, our ODWAP approach in this paper is very effective to improve the performance of the WDM ring network.

5. Conclusion

This paper has defined the optical-drop wavelength assignment problem (ODWAP) in a WDM double-ring network and presented its simple heuristic algorithm for the performance improvement of the network under heterogeneous traffic. The evaluation by dynamic traffic simulations shows that our ODWAP approach reduces waiting times for lightpath establishments to connection requests by decreasing the blocking probability of frequently arriving traffic. The evaluation of our scheme under different traffic patterns and the proof of the *NP*-completeness of ODWAP are in our future studies.

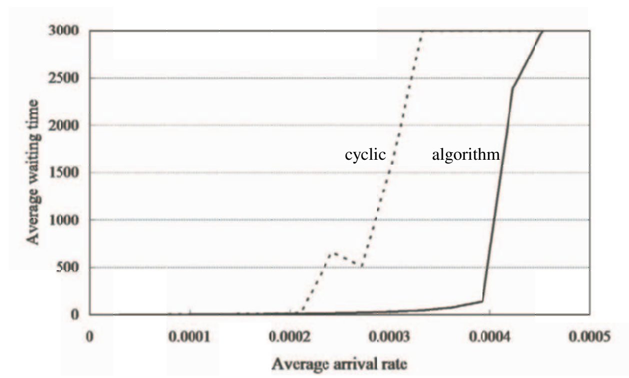

Figure 3. Average waiting times (5% busy nodes, $W = 4$, $N = 64$).

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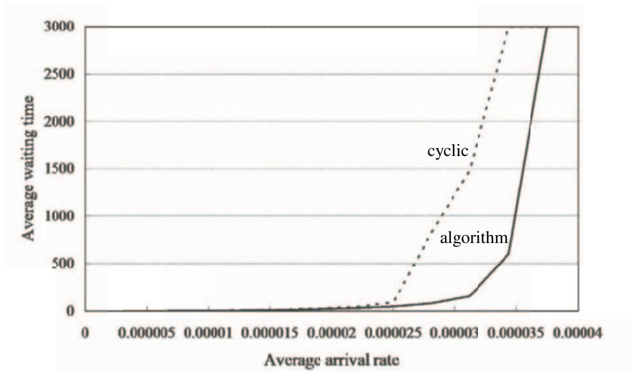

Figure 4. Average waiting times (5% busy nodes, $W = 4$, $N = 256$).

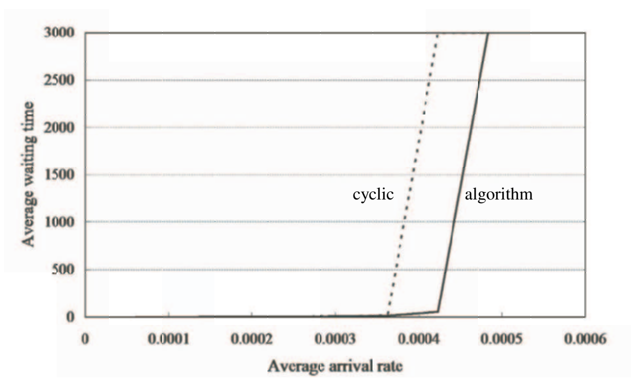

Figure 5. Average waiting times (5% busy nodes, $W = 16$, $N = 64$).

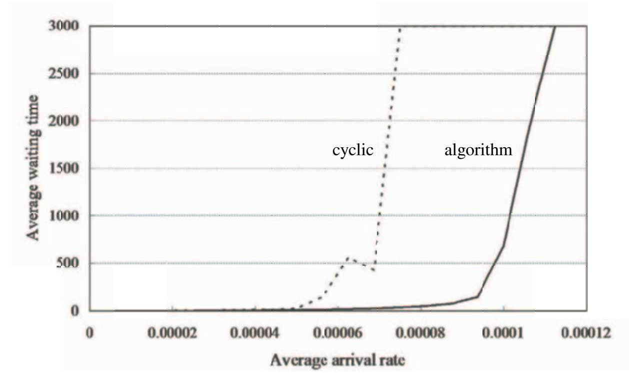

Figure 6. Average waiting times (5% busy nodes, $W = 16$, $N = 256$).

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