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Packet Scheduling in WDM Ring Networks with Non-uniform Traffic Demands and Arbitrary Transceiver Tuning Latencies

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Abstract: This paper considers the scheduling problem of packet transmissions in a TDM/WDM unidirectional optical ring network. Our objective is to design a scheduling scheme for packet transmission with minimum scheduling length satisfying a set of traffic requirements. We focus on a fairly general case in that non-uniform traffic demands and arbitrary transmitter tuning latencies are allowed. Since the scheduling problem in TDM/WDM ring networks is known to be NP-Complete, we formulate the problem as an Integer Linear Program (ILP) and propose some heuristic algorithms to find feasible solutions.

Key–Words: Packet Scheduling, TDM, WDM, Integer Linear Program, NP-Complete

1 Introduction

Wavelength Division Multiplexing (WDM) technologies have been considered as a promising approach to build the next generation networks. Using WDM technique, the vast bandwidth of optical fiber can be divided into a lot of high-speed channels. Each channel uses a wavelength to transmit packets, in other words, many packets can be transmitted simultaneously on a single optical fiber with different wavelengths. All-to-All Personalized Communication (AAPC) supports the most densest communications between every source-destination pair [1, 2]. Specially, in an n-node network, AAPC consists of a total of $n(n-1)$ connections. These connections are personalized because loads of different connections can be different. Considering a Wavelength Division Multiplexing (WDM) network, if there are sufficient wavelengths per link and each node is equipped with enough transmitter-receiver pairs, connections can be built simultaneously to support AAPC. Due to the limited number of wavelengths per link and the limited number of transceivers of each node, not all connections can be established at the same time. However, Time Division Multiplexing (TDM) technique can be applied to each wavelength [3]. The scheduling problem of minimizing the transmission period in TDM/WDM hybrid networks is NP-Complete even for the simplest regular topology, e.g. star and ring networks [4, 5, 6]. In order to fully utilize bandwidth, several heuristic strategies have been proposed for TDM/WDM hybrid ring networks [4, 7, 8].

Several studies on the pipelined transmission have been conducted in [2, 3]. They assume that each node is equipped with at least one fully tunable transceiver and the tuning time is negligible. However, the fully tunable transceiver is expensive and the tuning time of the components is always much longer than the packet transmission time [9]. In this paper, we focus on a more practical situation in which each node is equipped with only one tunable transmitter and one fixed receiver (TT-FR). Besides, the tuning time of transceiver and the propagation delay of optical fiber cannot be neglected. We formulate the scheduling problem of packet transmission as an Integer Linear Program (ILP) and propose several heuristic approaches to increase the bandwidth utilization and shorten the scheduling length.

2 Problem Formulation

Consider a unidirectional ring that consists of a set of nodes, $N = \{0, 1, \cdots, n-1\}$, and a set of links, $L = \{0, 1, 2, \cdots, n-1\}$, where link i connects node i and $(i+1)\ mod\ n$ in the clockwise direction. Let $Path(i, j)$ denote a set of links which form a clockwise path between node i and j, and then the distance d_{ij} between node i and node j can be determined by that $d_{ij} = (j - i + n)\ mod\ n$. Each node is equipped with one tunable transmitter and one fixed receiver so that a node can only receive one packet on a fixed wavelength at the same time. We assume that the transmission time of a packet is equal to one time slot and both the tuning time of transceivers denoted as TT and the propagation delay of optical fiber denoted as PD cannot be neglected. There are $W = \{0, 1, ..., w-1\}$ multiplexed wavelengths per link and node j can only receive packets on a given wavelength w_j. A traffic demand matrix R is given, each entry r_{ij} in R represents the number of packets that will be transmitted from node i to node j. Let $res^{ij}(l,t)$ be a binary decision variable for recording the status of wavelength usage, i.e., $res^{ij}(l,t) = 1$ if node i transmits a packet to node j via link l with wavelength w_j at time slot t, otherwise $res^{ij}(l,t) = 0$. For example, if there is a packet transmitting from node 0 to node 2 and the packet now is transmitted on link 1 at time slot 3, we then record $res^{02}(1,3) = 1$. It means the packet uses wavelength w_2 at time slot 3 via link 1. Note that the transmitting wavelength of packets is implicit because it is assigned to the receiving wavelength of destination node. In the above example, the destination node is node 2, and we know that the receiving wavelength of node 2 is w_2. On the contrary, if $res^{02}(1,3) = 0$, it means that the wavelength w_2 at time slot 3 via link 1 is not used by the connection from node 0 to node 2, but may be used by another connection. Furthermore, the binary variable $usg(t)$ is defined for recording the utilization of the time slot t, i.e., $usg(t) = 1$ if the t-th time slot of a wavelength is in use among all wavelengths, otherwise $usg(t) = 0$.

We formulate the scheduling problem as an Integer Programming Problem (ILP) as following:

1. Transmitter Constraint:

   $$\sum_j (res^{ij}(i,t)) \leq 1 \qquad \forall i, t$$

   This equation ensures that node i can transmit at most one packet via its clockwise link i at any time slot t because each node on the unidirectional ring has only one transmitter. The equation also implies that there is only one wavelength can be used by the node to transmit a packet.

2. Receiver Constraint:

   $$\sum_i (res^{ij}(j-1,t)) \leq 1 \qquad \forall j, t$$

   The equation ensures that node j can receive at most one packet via link $j-1$ on wavelength w_j in any time slot t, because every node has only one receiver.

3. Flow Constraint:

   $$\sum_l \sum_t (res^{ij}(l,t)) = r_{ij} \times d_{ij} \qquad \forall i, j$$

   The equation means that the total number of used time slots of each connection should be equal to $r_{ij} \times d_{ij}$ during the transmission period.

4. Link Constraint:

   $$\sum_i \sum_{w_j = w} (res^{ij}(l,t)) \leq 1 \qquad \forall l, t, w$$

   The equation means that link l carries no more than one packet at the same time on the same wavelength $w \in W$.

5. Tuning Time Constraint:

   $$res^{ij}(i,t) + \sum_{w_k \neq w_j} (res^{ik}(i,t+c)) \leq 1 \quad \forall i, j, t$$

   and $c \in (0 \sim TT)$

   The equation ensures that node i cannot send a packet on different wavelength in the tuning period. In other words, if node i sends a packet to node j at time slot t on wavelength w_j, then node i cannot transmit any packet on wavelength w_k which is different from w_j during the tuning time TT.

6. Propagation Delay Constraint:

   $res^{ij}(l,t) = res^{ij}(l+1, t+PD) \;\; \forall i, j, l, t$ and $l, l+1 \in Path(i,j)$

   The equation ensures that packets will propagate to next link and use the same wavelength after the amount of time slot for the propagation delay. If the link l transmits a packet from node i to node j at time slot t using wavelength w_j, the packet should appear in the link $l+1$ at time slot $t+PD$ using the same wavelength w_j. This constraint will hold for each link l and its next link $l+1$ of the path from node i to node j.

7. Time Utilization Constraints

   $$res^{ij}(l,t) \leq usg(t) \qquad \forall i, j, l, t$$

   The equation ensures that if any connection uses any link at t-th time slot, $usg(t)$ will be set to 1. For example, if $res^{13}(1,0)$ and $res^{21}(2,0)$ are used for connection (1,3) and (2,1), respectively, the value of $usg(0)$ is 1 which indicates that 0-th time slot is in use in some wavelength on some link. If no connection uses 0-th time slot to send packet, $usg(0)$ is 0.

8. Objective Function

   $$min \sum_{0 \leq t \leq T} (usg(t) * 2^t)$$

   The objective function is to minimize the overall transmission period as short as possible, i.e., to minimize the schedule length. Entries in usg are either 0 or 1, so each 2^t, $t \in T$, is 0 or 1 weighed. For any positive integer x, equation $2^0 + 2^1 + \cdots + 2^{x-1} < 2^x$ will hold, and we know that the value of 2^x will dominate the summation of series of 2^0 to 2^{x-1}. In order to minimize the total cost, let previous time slots have less weigh. In this way, the scheduling will use the previous time slots as many as possible and accomplish the purpose of finding the minimal scheduling length.

3 Solving The ILP Directly

The above ILP can now be solved by a variety of techniques. We implement this ILP by using the ILOG's optimization package, which includes AMPL and CPLEX modules [10, 11]. We use AMPL as the ILP modeling language and employ CPLEX as the ILP solver. CPLEX is a computational kernel of linear programming and developed by ILOG Corporation [10]. AMPL is an algebraic modeling language for linear and nonlinear optimization problems and developed at Bell Lab [11].

However, we find that the above objective function is hard to find the optimal scheduling when the problem size is large ($n \geq 10, w \geq 2$). The main reason could be the computing complexity of exponential number 2^t in the objective function that greatly increases the difficulty of solving ILP. In consideration of this problem, we relax the time utilization constraint by setting $usg(t) = \sum_i \sum_j \sum_l res^{ij}(l,t)$ and use $min \sum_t usg(t) * t$ as our new objective function instead.

The new objective function is to minimize the total used time slots as less as possible. However, $usg(t)$ is no longer a binary variable but the summation of t-th used time slots on all wavelengths. For example, if $res^{13}(1,0)$ and $res^{21}(2,0)$ are used for connection (1,3) and (2.1), respectively, then the value of $usg(0)$ is 2. Each entry of usg is added by a weight of $t, t \in T$ to substitute for 2^t. In this way, we can find an optimal solution up to the case of $n = 20$. We find that the obtained results of the two objective functions are almost the same in all of our experiments. However, when ring size increases ($n \geq 20, w \geq 2$), the problem exceeds the computational ability of our 800Mhz PC and CPLEX is unable to find the optimal solution after one hour's running time even though we use the second objective function.

4 Heuristic Algorithms

The pipelined transmission scheduling can be formulated as an ILP problem. However, finding the optimal scheduling solution by solving the ILP directly is impractical in the real environment. Hence, we propose three polynomial-time heuristic algorithms in this section to find feasible solutions more efficiently.

In a practical situation, the tuning time of transceivers and the propagation delay of optical fiber cannot be neglected. Our objective is to design a packet scheduling scheme with minimum scheduling length satisfying a set of traffic requirements. Generally, the number of wavelength per link is less than the number of nodes (i.e. $w < n$) in a WDM network. Even in a WDM ring with a fewer nodes such that w may be equal to n, it is not necessary that let the receiver of each node use distinct wavelength when tuning time is long. If each node receives packet on distinct wavelengths and there are sufficient wavelengths such that $w = n$, transmitter of each node must tune $n - 2$ times to perform $n - 1$ packet transmissions to support AAPC. But for a system with larger tuning time, it is easy to see that there will be many time slots wasted by tuning. In such condition, it seems better if we let more than one receiver share the same wavelength. Furthermore, this observation introduces the concept that a node should transmit packets to a group of nodes using the same wavelength, tune the transmitter/receiver, and transmit packets in another group of nodes using another wavelength. In this scheme, times of wavelength tuning can be reduced and this observation inspires us to develop the ”Same Group First” algorithm. On the other hand, if the propagation delay of optical fiber is long, the time of longer-distance transmissions can overlap all or part of tuning and propagation time of shorter-distance packets. This also inspires us to develop the ”Longest-Distance-First” algorithm. These heuristic algorithms are described in the following subsection.

4.1 Longest Distance First

The basic idea of ”Longest-Distance-First” algorithm is that each node should send a packet to the longest-distance destination node first, and then send to the second longest-distance node during the propagation period of the first packet, and so on. If a node transmits packet to other different nodes on different wavelength, the tuning time should be added to scheduling period. Due to the propagation delay, it will take more time to complete transmission when it has longer-distance from source node to destination node. So the transmission time of longer-distance packet can overlap all or part of tuning and propagation time of shorter-distance packets.

Algorithm $Longest\_Distance\_First:$

1. For every source-destination pair, sort the trans-

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mission sequence in descending order by their distances.

2. Assign the transmission scheduling in order and use a greedy method, called ”Earliest-Finish-Assignment”, to find the first available sequence of successive unused time slots.

If a node wants to transmit a packet, it must get a sequence of successive unused time slots. In order to shorten the scheduling length, we use a greedy method to find the first available sequence of successive unused time slots, which is called ”Earliest-Finish-Assignment”. This method acts as the role of a dispatcher, which receives the scheduling request and finds the earliest finished assignment according to the information about the source-destination pair and the current state of TDM/WDM channels. Since the receiver's wavelength is fixed, it checks the receiving wavelength if there are some successive unused time slots and according to the direction from source node to destination node, the dispatcher knows that it should assign which wavelength after a node has completed its previous packet transmission and/or wavelength tuning and is ready to transmit the next packet. By the dispatcher, another available starting time is replied to the source node and the path is marked to avoid the other nodes' usage.

The main drawback of the ”Longest-Distance-First” algorithm is the wavelength tuning becomes frequent. It decides the transmission queue by distance, hence each transmitter must tune to next different wavelength after transmitting one packet and wavelength tuning happens frequently. If we do not consider the tuning time or the tuning time is small enough, the Longest-Distance-First algorithm can work efficiently. However, the tuning time is generally large and the times of wavelength tuning will increase when the number of receivers increases.

4.2 Same Group First

The second heuristic algorithm is named ”Same-Group-First”. In previous discussion, we know that decreasing the times of wavelength tuning may obtain better performance when the tuning time needs more time slots. We assume that all nodes in the same group receive packets on the same wavelength. If node i sends a packet to node j, then the next destination node of node i should belong to the same group with node j. In other words, the destination nodes in the same group are transmitted by node i first. So the total tuning time of node i is at most $(w-1)TT$.

Algorithm $Same\_Group\_First$:

1. For each source node, sort the transmission sequence of destination nodes by their group numbers.

2. Since each node in the same group receives packets on same wavelength. We assign the transmission scheduling for each source node by using the ”Earliest-Finish-Assignment” method to find the first available sequence of successive unused time slots.

In this algorithm, the reduction of the total tuning time is limited when each group consists of a few nodes. Besides, the transmission time of longer-distance packet cannot overlap the propagation time of shorter-distance packets because the destination node in same group is not sorted in descending order by distance to source node.

4.3 Double Sort

The third heuristic algorithm is called ”Double-Sort” which can avoid the drawbacks in the previous two methods. This algorithm is based on two opinions: (1) Reduce the number of wavelength tuning as many as possible. (2) Transmit a packet to the farthest destination node first.

Algorithm $Double\_Sort$:

1. For each source node, arrange its destination nodes according to their group number.

2. All nodes in the same group are sorted in descending order by the distances from their source node.

3. All groups are sorted in descending order by the distance between the first element of the group and source node.

4. Assign the transmission scheduling in order and use the ”Earliest Finish Assignment” method to find the first available scheduling for each source-destination pair.

Step 1 means that this algorithm preserves the merit of Same-Group-First. Step 2 ensures that source node will transmit to the farthest node first. The transmission time for longer-distance packet can overlap the shorter-distance packet. Step 3 means that this algorithm preserves the merit of Longest-Distance-First for the farthest group member.

5 Simulation Result

In this section, we evaluate the performance of heuristic algorithms and compare it to the optimal solution.

Consider a unidirectional ring network where nodes are labelled around the ring from 0 to $n-1$ in the clockwise direction. Assume that node j receives packets on wavelength $j\ mod\ W$ and the minimum propagation delay of optical fiber links is equal to a transmission time slot, i.e. $T = PD = 1$. We assume that the receivers' wavelengths are determined previously and focus on the case of general AAPC transmission such that node i needs to transmit r_{ij} packets to node j and the traffic demands $r_{ij}, \forall i, j$ are randomly generated with restriction $\sum r_{ij} = n(n-1)$. Therefore, a total of $n(n-1)$ packets need to be scheduled in the simulation environment. Our objective is to minimize the scheduling length, i.e. the duration of AAPC packet transmission period.

We begin by considering the tuning time TT in different cases of $TT = 2$ and $TT = 5$. Fig. 1 and Fig. 2 show the schedule length when $w = 2$ and the network size is increasing. The results indicate that the Double-Sort algorithm finds near-optimal solutions even if the network size and tuning time are increasing. The optimal solutions in both case of $TT = 2$ and $TT = 5$ are the same when the network size is large enough. The reason is that the tuning time can be overlapped with the time waiting for a available wavelength channel when the number of wavelengths is much less than the number of nodes. Due to the computing complexity, the optimal solution cannot be found by ILP when the problem size becomes large. Such as $w \leq 2, n \leq 20$ and $w \leq 4, n \leq 10$, the ILP solver could not find the optimal solution after one hour's running time. If the tuning time is negligible, the Longest-Distance-First algorithm can find very satisfied solutions as shown in Fig. 3. Because the packet transmission time to longest node could overlap that to the shorter ones. Except for the extreme case of $TT = 0$, the Double-Sort algorithm can also find the best solution among those three heuristic algorithms. Note that there is an interesting phenomenon of Double-Sorting. In the case that n is divisible by w, the scheduling length found by the Double-Sort algorithm is closer to the optimal solution than in the case that n is not divisible by w. Especially, in the case that $w \leq 4$ and n is not divisible by w, the Double-Sort scheduling needs more time slots than in the case that n is larger and divisible by w. For example, Fig. 4 shows that the scheduling length of the Double-Sort algorithm is 66 and 54 when $n = 15$ and $n = 16$. respectively. This anomaly of Double-Sorting is due to the nature of wavelength grouping. When $(n\ mod\ w) = 0$, each wavelength group in transmission queues has the same number of packets. For example when $n = 4$ and $w = 2$, the transmission queue of node 0 is a sequence of (3,1)(2), nodes in parentheses mean that they use the same wavelength to receive packets. Similarly, the transmission queue of node 1 is (0,2)(3). There are two elements in the first wavelength group and one in second group. When node 0 finishes its transmissions in the first group, node 1 does too. They will tune the wavelength at the same time and then transmit packets to the nodes in next wavelength group.

6 Conclusion

In this paper, we have studied the scheduling problem for AAPC transmissions in WDM/TDM ring networks. We applied the pipelined transmission technique to reduce the overall scheduling length and formulated the scheduling problem as a 0/1 Integer Linear Programming (ILP) problem. However the time for solving the ILP is too long in a practical situation. Hence we propose three heuristic algorithms to find effective solutions in polynomial time. The main idea of our algorithm includes two optimality criteria. One is to reduce the times of wavelength tuning as less as possible because the tuning time is much longer than the transmission time. The other is to have the packet transmitted to the farthest destination node first so that the transmission of the latter packet can be overlapped with the propagation delay of the previous packet. According to the simulation results, we find that the "Longest-Distance-First" algorithm has better performance when the tuning time is very small and the "Double-Sort" algorithm is usually good enough when compared to the optimal solution.

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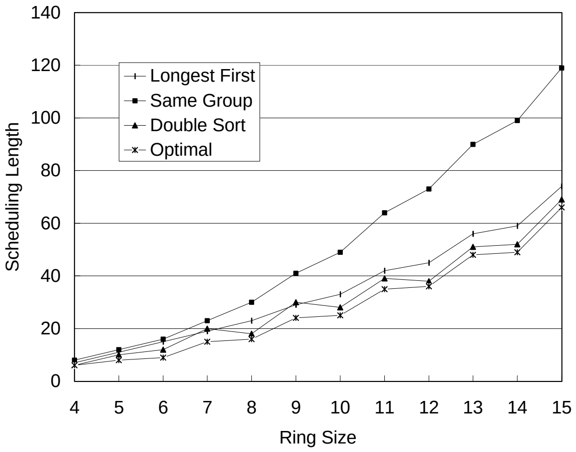

Figure 1: $w = 2, TT = 2$

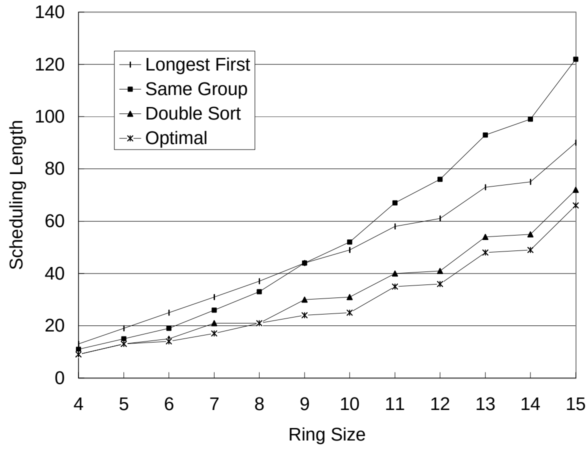

Figure 2: $w = 2, TT = 5$

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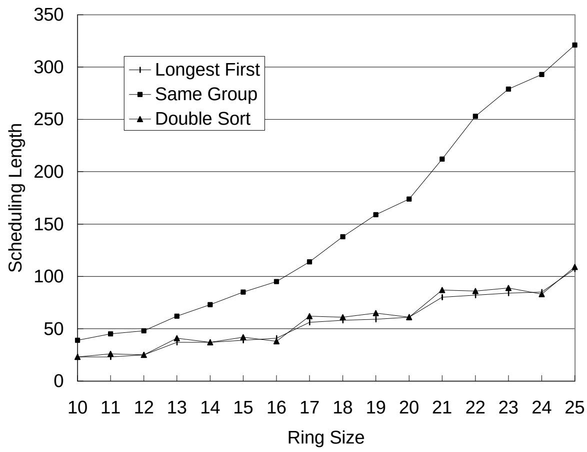

Figure 3: $w = 4, TT = 0$

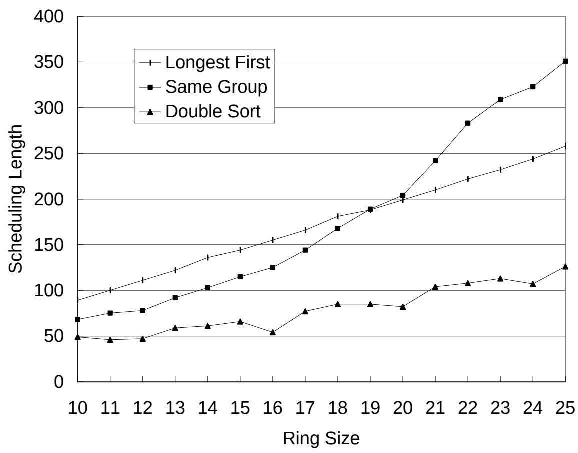

Figure 4: $w = 4, TT = 10$