ENERGY-EFFICIENT DESIGN FOR IP OVER WDM NETWORKS WITH CLOCK FREQUENCY ADAPTIVE ROUTER CARDS

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ABSTRACT

Because a router card consumes less energy at a lower clock frequency, we can minimize the energy consumption of an IP over WDM network by adaptively adjusting the clock frequencies of a router card according to its actual carried traffic demand. We develop a mixed integer linear programming (MILP) model and an efficient heuristic algorithm to adjust the clock frequency of a router card in different time slots. Results show that the clock frequency adaptation strategy can significantly reduce the energy consumption of an IP over WDM network compared to the non-adaptive case, and the heuristic algorithm is efficient to perform as close as the MILP model.

Keywords: Clock frequency adaption, energy-efficient, IP over WDM, MILP model, router card

1. INTRODUCTION

The increasing coverage of Information and Communication Technology (ICT) makes it consume more energy [1]. Reducing energy consumption of networks becomes an important research topic. Recently many energy-saving approaches have been proposed, such as mixed line rates (MLR) [2], traffic grooming [3], energy-efficient wavelength assignments [4], network device sleeping [1], and so on. When a router is active, we may adapt or scale the clock frequency of each router card to reduce energy consumption because the power consumption of a router card is found to be proportional to its adopted clock frequency [5]. In this study, we focus on reducing the energy consumption of a point-to-point (P2P) (i.e., non-optical bypass) IP over WDM network by applying the adaptive clock frequency strategy for a router card according to its actual traffic demand. The key idea is to choose the lowest clock frequency for the router card that is just fast enough to support the traffic on all the router ports.

For a network node, we develop an MILP model and an efficient heuristic that assign traffic demand to different ports of a router card to maximally take advantage of the adaptive clock frequency strategy and minimize total energy consumption. The proposed approaches are found to be efficient to significantly reduce energy consumption compared to the non-adaptive case. The current study is practical to consider reducing energy consumption on the basis of a router card as it is relatively easier to implement an adaptive clock for a router card than for a router port.

The rest of the paper is organized as follows. In Section 2, we briefly introduce the network model and the strategy of clock frequency adaption for router cards. Section 3 describes the MILP optimization model. Section 4 introduces the heuristic algorithm. In Section 5, we elaborate on the test conditions and networks. The simulation results are shown in Section 6. We conclude the paper in Section 7.

2. NETWORK MODEL AND CLOCK FREQUENCY ADAPTATION STRATEGY

We focus on a P2P IP over WDM optical network [6], in which traffic carried by lightpaths cannot optically bypass intermediate nodes, but is converted into an electronic format, processed by the intermediate routers, and then converted back to an optical format. Also, the traffic demand between each pair of nodes that are physically neighboring is assumed to vary following a certain fixed pattern every day. Router cards at each node are planned and pre-deployed based on the peak traffic demand. We assume that there is a constant power consumption overhead when a router card is active and the power consumption of the router card is proportional to the clock frequency. Assuming a router card consumes one unit of power at its highest frequency, the power consumption of the router card at different clock frequencies can be modelled as

$$P(f_i) = \alpha + (1 - \alpha) \frac{f_i}{f_{max}}$$

where $\alpha$ is the overhead of power consumption, $f_i$ is the used clock frequency, and $f_{max}$ is the highest clock frequency. In this study, we assume that $\alpha$ is equal to 0.2 and there are five clock frequencies, under which each port can support maximal transmission speeds at 0, 10, 20, 30, and 40 Gb/s, respectively.

The time-dependent traffic demand creates an opportunity to reduce energy consumption of IP routers
by applying the clock frequency adaption strategy. The traffic demand on each router port decides the clock frequency adopted by a router card, which further decides its power consumption. Fig. 1 shows an example of how different port traffic distributions on a router card can affect its power consumption. Assume the total traffic on a card is 40 Gb/s. Fig. 1(a) shows a traffic distribution of aggregating all the traffic on a port while keeping all the other ports free of traffic. Such a distribution needs the highest clock frequency and consumes the highest power, i.e., one unit. In contrast, if the traffic demand is evenly distributed on the four ports as in Fig. 1(b), the router card only needs to use the second clock frequency that supports a 10-Gb/s port speed, and therefore consumes only 0.4 unit of power.

Fig. 1. Example of power consumption versus port traffic distribution.

3. PROBLEM STATEMENT AND MILP MODEL

Because the traffic distribution on router ports decides the clock frequency used and further the power consumption of a router card, it is important to optimally distribute traffic demand on different ports to minimize the power consumption of a router card. In this section, we focus on designing an energy-minimized P2P IP over WDM network based on the router card clock frequency adaption strategy.

Given the network physical topology and traffic demand matrices, in which each element indicates the traffic demand between two neighboring nodes in the physical topology in a certain time slot, we need to decide the number of router cards based on the peak traffic demand between a pair of neighboring nodes and optimally allocate traffic demand on each of the router ports in different time slots such that the clock frequency adaption strategy can maximally reduce the energy consumption of router cards.

We develop an MILP model for the above optimization problem aiming to minimize the energy consumption of all the router cards in one day subject to the condition that all the traffic demand can be accommodated in all the time slots. The sets and parameters of the model are defined as follows.

Sets and parameters:

- \( N \) the set of network nodes.
- \( N_i \) the set of neighboring nodes (in the physical topology) of node \( i \).
- \( T \) the set of time slot indexes in a day. We evenly divide a day into 24 time slots, i.e., one hour per time slot.
- \( C_i \) the index set of router cards at node \( i \), which are planned based on the peak traffic demand. More specifically, we deploy router cards that are just enough to support the peak traffic demand to all the neighboring nodes.
- \( K \) the set of port indexes on each router card. We assume that there are four ports on each router card.
- \( P \) the set of clock frequencies that can be adopted by router cards. All the router cards adopt the same set of five clock frequencies, which are linearly scaled within the range from zero to full port capacity.
- \( B_p \) the maximum transmission capacity of a router port supported by the \( p^{th} \) clock frequency.
- \( T_{ij}^t \) the traffic demand between node \( i \) and its neighboring node \( j \) in time slot \( t \).
- \( P_{L_p} \) the power consumption of a router card at the \( p^{th} \) clock frequency and \( B_p \)-Gb/s port capacity.
- \( \Delta \) a very large value.

Variables:

- \( x_{ij}^{mn} \) a binary variable indicating whether the \( n^{th} \) port of the \( m^{th} \) card is configured to carry traffic between node \( i \) and its neighboring node \( j \) in all the time slots.
- \( a_{ij}^{mn,t} \) the amount of traffic demand between node \( i \) and its neighboring node \( j \) carried by the \( n^{th} \) port of the \( m^{th} \) card in time slot \( t \) (real).
- \( c_i^{m,p,t} \) a binary variable indicating whether the \( m^{th} \) card at node \( i \) uses the \( p^{th} \) clock frequency in time slot \( t \).

Objective: to minimize the total energy consumption of all the router cards in the whole day:

\[
\sum_{i \in N} \sum_{m \in C_i} \sum_{p \in P} \sum_{t \in T} C_i^{m,p,t} \cdot P_{L_p}
\]

Subject to:

1. \( \sum_{j \in N_i} x_{ij}^{mn} \leq 1 \quad \forall i \in N, m \in C_i, n \in K \) (1)
2. \( \Delta \cdot x_{ij}^{mn} \geq a_{ij}^{mn,t} \quad \forall i \in N, j \in N_i, m \in C_i, n \in K, t \in T \) (2)
3. \( \sum_{m \in C_i} \sum_{k \in K} a_{ij}^{mn,t} \geq T_{ij}^t \quad \forall i \in N, j \in N_i, t \in T \) (3)
4. \( \sum_{j \in N_i} a_{ij}^{mn,t} \leq \sum_{p \in P} B_p \cdot c_i^{m,p,t} \quad \forall i \in N, m \in C_i, n \in K, t \in T \) (4)
5. \( \sum_{p \in P} c_i^{m,p,t} = 1 \quad \forall i \in N, m \in C_i, t \in T \) (5)

Constraint (1) ensures that in the P2P IP over WDM network, each router port can be connected to only one neighboring node. Constraint (2) ensures that a router port at node \( i \) must be connected to its neighboring node \( j \) as long as there is any traffic to node \( j \) that needs to use this port in any time slot \( t \). Constraint (3) ensures that all the traffic demand between two neighboring nodes can be supported by the sum capacity provided by all the router ports connected from node \( i \) to node \( j \) in any time slot. Constraint (4) ensures that the traffic on each router port can never exceed the upper limit of the port capacity at the \( p^{th} \) clock frequency. Constraint (5) means that each router card can only choose one clock frequency in any time slot \( t \).

The model is practical to ensure fixed port connections between two neighboring nodes,
independent of time-variable traffic demand. Such a constraint is necessary because once a pair of ports connecting two neighboring nodes is configured, it is almost impossible to manually change these port connections from time to time. Rather, it is more practical to change the traffic demand on these ports and adapt a clock frequency for each router card based on its actual port traffic demand. In addition, as the clock frequency adopted by a router card is based on the highest port speed on the card, the optimization model tends to distribute traffic evenly onto the ports such that a lowest clock frequency can be allocated.

4. HEURISTIC APPROACH

For computational complexity, the MILP model has a total of \(O(|T||K| |C||N|d)\) variables and \(O(|T||K| |C||N|d)\) constraints, where \(|T|\) is the number of time slots in a day, \(|K|\) is the number of ports on a card, \(|C|\) is the number of cards deployed at a network node based on the peak traffic demand, \(|N|\) is the total number of nodes in a network, and \(d\) is the average nodal degree of the network. The MILP model would suffer from the difficulty of high computational complexity with the increase of network size. Thus, we also develop an efficient heuristic algorithm to solve the problem. In the heuristic algorithm, we minimize the energy consumption at each network node in any time slot subject to the condition that all the traffic demand in the time slot is satisfied; we repeat the same process for all the nodes in the network to find the total energy consumption of the whole network.

The energy-saving capability of the adaptive clock frequency strategy is related to the allocation of the ports connected to different neighboring nodes onto different router cards. We consider three port allocation modes, including interleaving mode, sequential mode, and mixed mode [7]. Assume node A has two neighboring nodes, B and C, and each neighboring node needs four ports to carry traffic from A during the peak traffic hour. The interleaving mode evenly allocates all the ports connected to nodes B and C onto the two router cards in an interleaving way as shown in Fig. 2(a). In contrast, the sequential mode aggregates the ports to a certain neighboring node onto one router card as shown in Fig. 2(b). Finally, the mixed mode is an intermediate case, in which a certain \(\beta\) percentage of router ports are allocated in the interleaving mode while the remaining percentage of router ports are allocated in the sequential mode.

Meanwhile, for a certain port allocation, different traffic distributions among router ports can also lead to different clock frequencies and power consumption of a router card because the used clock frequency of a card is decided by its highest port traffic. As shown in the example of Fig. 1, an even traffic distribution on router ports requires a lower clock frequency and consumes less energy by a router card. Given the set of ports allocated to each of the neighboring nodes based on a certain port allocation mode and the traffic demand to the neighboring nodes in a certain time slot, we next introduce an algorithm that can evenly distribute traffic demand onto different ports:

1. For each neighboring node, compute the traffic on each port \(D\) through evenly distributing the total unserved traffic demand onto all the ports connected to the node. (2) For the first free router card, choose a clock frequency \(F\) that can ensure a maximal capacity for all the ports on the card to support the allocated traffic \(D\). (3) The total unserved traffic to every neighboring node is subtracted by the highest capacity that the recently considered router card can support at clock frequency \(F\). (4) If all the traffic demand to the neighboring nodes have been distributed onto router ports, stop the process; otherwise, go to (1) to consider the next router card and repeat the same process.

We use an example to explain the above algorithm. Assume that the peak traffic is 330 Gb/s between nodes A and B and 120 Gb/s between nodes A and C, which corresponds to 9 and 3 ports to carry traffic to nodes B and C, respectively, if the maximal port speed is 40 Gb/s. We also assume that the five adaptable clock frequencies correspond to five port speeds, i.e., 0, 10, 20, 30, and 40 Gb/s. In a certain time slot, if the current traffic demands from node A to nodes B and C are both one third of the peak-hour traffic, i.e., 110 Gb/s and 40 Gb/s, respectively. Based on the principle of even traffic distribution onto each router port, the traffic demand on each port at node A under the different port allocation modes is shown in Fig. 3.

![Fig. 2. Two modes of port allocations](image)

For the port allocation by the interleaving mode (i.e., Fig. 3(a)), in the first iteration, each port to node B needs to be allocated with 110/9=12.23 Gb/s demand and to node C allocated with 40/3=13.34 Gb/s demand. Thus, on the first router card, we will adopt the third frequency clock that can maximally support a 20-Gb/s port speed. After distributing the traffic on the first card, there are 70 Gb/s and 0 Gb/s traffic demands remained to nodes B and C, respectively. For the remaining 70-Gb/s traffic demand to node B, we find that each of the remaining 7 ports on the second and third router cards is
required to carry 10 Gb/s traffic demand, which is just equal to the second clock frequency. Fig. 3(a) shows the consequential traffic demand distribution on each of the ports and we can calculate the corresponding power consumption of the router cards as 0.6+0.4+0.4=1.4 units. For the port allocation of the sequential mode, we can implement a similar process to have a port traffic demand distribution as shown in Fig. 3(b), from which we can find the total power consumption as 0.6+0.4+0.6=1.6 units. Comparing the two examples, we can see that the interleaving mode can achieve lower power consumption than the sequential mode even when the traffic demand is evenly distributed onto all the router ports.

In addition to the interleaving and sequential modes, we can consider the mixed mode to make β% router ports allocated in the interleaving mode, while the remaining ports allocated in the sequential mode. Based on this port allocation mode, we evenly distribute traffic demand onto different router ports in the way as described in this section. To find an optimal interleaving percentage that can have the lowest power consumption, we scan the whole range of β starting from 100% and decreased by 5% each time to decide an optimal interleaving ratio that can achieve the lowest power consumption.

5. TEST NETWORKS AND CONDITIONS

To evaluate the benefit of applying adaptive clock frequencies to router cards, we consider three test networks, including (1) a six-node, eight-link (n6s8) network, (2) the 14-node, 21-link NSFNET network, and (3) the 24-node, 43-link USA backbone network (USNET) [6]. In addition, we have the following assumptions: (1) The peak-hour traffic demand between each node pair is random with a uniform distribution within a certain range, which is centered at an identical average. That is, given an average traffic intensity \(X \in \{20,\ldots,80\}\) Gb/s, the peak-hour traffic between a pair of nodes is evenly distributed among a range of \([10, 2X-10]\) Gb/s. (2) Five clock frequencies can be chosen for each router card, under which the corresponding port speeds are 0, 10, 20, 30, and 40 Gb/s, respectively. (3) The traffic demand between each pair of nodes follows the same pattern every day as shown in Fig. 4 [8]. This pattern can be approximated as a sinusoidal function

\[\lambda_{sd} = \lambda_{sd}^{max} \left[ \frac{1 - \rho}{2} \left(1 + \sin\left(\omega_0 (t - 8)\right)\right) + \rho \right]\]

where \(\omega_0 = \frac{\pi}{12}\) and \(\rho = 0.2\), which means that the lowest traffic demand occurred between 02:00 and 03:00 (in very early morning) is equal to 20% of the peak traffic occurred between 14:00 and 15:00 (in the middle afternoon).

6. RESULTS AND PERFORMANCE COMPARISON

We first evaluate the total energy saving by the different approaches with adaptive clock frequencies compared to the non-adaptive case, in which each port always support 40-Gb/s capacity regardless of its carried traffic. The results of the three test networks under different traffic intensities are shown in Figs. 5(a), (b), and (c), respectively, in which “MILP_scaling” corresponds to the result of the MILP model and “interleaving mode” represents the case of the heuristic algorithm with \(\beta =100\%\) interleaving ratio. Because the size of the NSFNET network is large, we cannot find its solutions using the MILP model when the traffic demand between each node pair is higher than 50 Gb/s, but we can use a dotted line to approximately represent its trend. Also, because the size of USNET is large, we cannot find an optimal solution for any traffic demand scenario, so we only provide the results of the heuristic algorithm.
We can see that both the MILP model and the heuristic algorithm (under the interleaving mode) with clock frequency adaptation can reduce more than 30% energy consumption compared to the non-adaptive case, and the heuristic algorithm is very efficient to perform close to the MILP model. This is reasonable since the non-adaptive case always uses the highest clock frequency regardless of the actual traffic demand, while the adaptive case is intelligent to use the most energy-efficient clock frequency to support the traffic demand.

We also evaluate the impact of the interleaving ratio $\beta$ on the energy-saving performance. Given the average traffic intensity $X=60$ Gb/s between each pair of nodes, the results for the three test networks are shown in Fig. 6. We can find that the most energy-efficient interleaving ratio is about 45% and the percentage of energy saving is about 30% under this interleaving ratio. This percentage is related to the average traffic intensity $X$. Under the current intensity, the results show that with 55% ports allocated in the sequential mode and the remaining 45% ports allocated in the interleaving mode, we can achieve maximal energy saving by applying the clock frequency adaptation strategy compared to the non-adaptive case.

7. CONCLUSION

Based on the adaptive clock frequency strategy for router cards, we developed an MILP model and an efficient heuristic to reduce the energy consumption of a P2P IP over WDM network. Simulation results show that the proposed heuristic can perform close to the MILP model and save more than 30% energy consumption compared to the non-adaptive case. It is also found that we can maximally save energy consumption by properly configuring an optimal interleaving ratio.

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