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Bandwidth allocation with a particle swarm meta-heuristic for ethernet passive optical networks

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ABSTRACT

This paper considers the bandwidth allocation problem for an Ethernet Passive Optical Network (EPON). An EPON is one of the best options for high-speed access networks. This paper formulates the optimal bandwidth allocation problem with an analytical model to maximize throughput and weighted fairness simultaneously. First, the optimal solution under certain conditions is characterized. Then, two heuristic algorithms are devised which optimize the allocation problem under general conditions. One heuristic is a straightforward constructive one while the one use the Particle Swarm Optimization (PSO) meta-heuristic, the first known application of PSO to the EPON bandwidth allocation problem. The heuristics are tested and compared with previously published results. The computational experience shows that our algorithms are both effective and efficient in allocating bandwidth on an EPON.

1. Introduction

This paper considers the bandwidth allocation problem on an Ethernet Passive Optical Network (EPON), where there is one common fiber connecting several access points which share the bandwidth of the fiber. To provide service, two types of passive components are used. One is the Optical Line Terminal (OLT) and the other is the Optical Network Unit (ONU). The OLT provides connection between the backbone and access networks at a central office, and the OLT allocates the common bandwidth according to requested demands from the connected access points. The requests for bandwidth occur from ONUs located on the access side of the network. The ONU has buffer memory for incoming traffic from customers and for outgoing traffic to the OLT, and considers the transmission priority of the packets waiting in the buffers. To transmit the traffic from OLT to ONU, OLT broadcasts the traffic and then each ONU receives the packets. However, channels must be classified for transmission of the packets from ONUs to an OLT since there are many ONUs and there are conflicts when ONUs try to transmit packets simultaneously. EPON uses the Time Division Multiple Access (TDMA) method to resolve conflicts. The bandwidth allocation problem is to find a mechanism for sharing the common bandwidth without conflict.

Many studies have been published on how to allocate the common bandwidth to the ONUs. For example, Kramer et al. [1] and Bai et al. [2] developed bandwidth allocation algorithms of interleaved polling with adaptive cycle time (IPACT), and Kramer et al. [3] developed a two-stage buffer mechanism to reduce the light-penalty problem of IPACT. Assi et al. [4] suggested an Enhanced Dynamic Bandwidth Allocation (EDBA) algorithm. An et al. [5] developed a Hybrid Slot-Size/Rate (HSSR) algorithm, and Yang et al. [6] presented a burst polling algorithm for bandwidth allocation. A good survey on these methods is given by Zheng and Mouftah [7]. These papers all address finding good heuristic solutions with respect to some specific measure such as throughput, fairness or delay time. For example, Bai et al. [2] developed a weighted-based bandwidth algorithm (W-DBA) to improve fairness, delay time and link utilization. W-DBA assigns the excess bandwidth to each ONU proportionally to each relative weight. The authors showed that W-DBA is superior to another published algorithm (M-DBA) for randomly generated asymmetric traffic.

Our paper formulates the allocation problem as a nonlinear mathematical one and develops bandwidth allocation algorithms which maximize throughput and weighted fairness simultaneously. Characterizing the optimal allocation under certain conditions is one goal of this paper. The other goal is to develop an effective optimizer to the problem under general conditions. This paper is structured as follows: Section 2 describes and formulates the bandwidth allocation problem. The bandwidth allocation problem is characterized, and two heuristic algorithms are developed in

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Section 3. These algorithms guarantee an optimal solution under a specific condition derived in Section 3. Section 4 carries out a number of numerical tests to evaluate the proposed algorithms by considering throughput, fairness, and computation time. Finally, Section 5 contains concluding remarks.

2. Problem description

This section defines the bandwidth allocation problem in detail. Let us define some notation for the formulation.

N: number of customers (ONUs).
r_i: demand of ONU i measured in bits per second, $i = 1, 2, \ldots, N$.
w_i: weight of ONU i for the fairness metric.
C: capacity of fiber (bits per second).
X_i: proportion of allocated bandwidth to demand of customer i, $0 \leqslant X_i \leqslant 1$ for all i.

According to the Multi-Point Control Protocol (MPCP) of EPON [8], the OLT allocates bandwidth and determines time of transmission to N ONUs according to their requests $\{r_i\}$. The allocation is performed periodically during each cycle time, and each ONU transmits the packets waiting in its buffer forward to the OLT as a predetermined amount and time of transmission along the common link. To transmit packets, setup is required between each transmission for laser on/off and guarding information, but this is independent of the ONU type and size of transmission and can be ignored. The time duration to transmit a unit packet also depends on the distance between the OLT and the ONU. However, we can set the unit time to 1 for all ONUs for simplicity without loss of generality.

Due to the capacity restriction C on the common link, only some waiting packets in each buffer will be serviced at the current cycle. The remaining will be serviced during succeeding cycles. Each ONU has one chance to transmit its packets at each cycle. Therefore, we can model the problem by considering just one cycle. There are several classes of service (CoS) packets in an ONU. Each ONU i has a weight w_i to represent its CoS according to the Service Level Agreement (SLA). EPON is required to utilize its capacity as much as possible and to provide fair service. Our paper considers the bandwidth allocation problem to maximize utilization (throughput) and weighted fairness simultaneously.

The bandwidth allocation problem is formulated as following:

$$\max \left(\sum_{i=1}^{N} r_i X_i\right)\left(\sum_{i=1}^{N} X_i \Big/ w_i\right)^2 \Big/ \left[N \cdot \sum_{i=1}^{N} (X_i/w_i)^2\right] \tag{1}$$

$$\text{s.t.} \quad \sum_{i=1}^{N} r_i X_i \leqslant C \tag{2}$$

$$0 \leqslant X_i \leqslant 1, \quad i = 1, 2, \ldots, N \tag{3}$$

Our aim is to find the optimal $\{X_i\}$ which maximizes the objective function value of Eq. (1) subject to Eqs. (2) and (3). The first term of Eq. (1) represents throughput, and the remaining terms represent fairness, where the fairness is a weighted variant of Jain's equal-weight version [9]. To maximize throughput, $\sum_{i=1}^{N} r_i X_i$, we need to increase the value of X_i as much as possible. If we set the value of X_i/w_i as evenly as possible, then the fairness term $\left(\sum_{i=1}^{N} X_i \Big/ w_i\right)^2 \Big/ \left[N \cdot \sum_{i=1}^{N} (X_i/w_i)^2\right]$ becomes close to its maximum value of 1. Eq. (2) implies that the total amount of assigned bandwidth cannot be larger than the capacity C. The decision variable X_i represents the proportion of demand allocated by OLT. We can obtain the allocated bandwidth $r_i X_i$ for ONU i by solving the bandwidth allocation problem.

3. Bandwidth allocation algorithms

This section formulates the optimal allocation to maximize throughput and fairness. We first consider the problem characterization under certain situations.

3.1. Problem characterization

First, as a special case, if all weights of ONUs are identical, the optimal allocation is determined as defined in Proposition 1.

Proposition 1. *If $w_i = w_0$ for all i, then optimal allocation is $X_i = \min\left\{C \Big/ \sum_{i=1}^{N} r_i, 1\right\}$ for all i and its optimal objective value is $\min\left\{\sum_{i=1}^{N} r_i, C\right\}$.*

Proof. If $w_i = w_0$ for all i, throughput is maximized when $X_i = 1$ for all i and fairness is maximized when $X_i = X_0$ for all i, where X_0 denotes a constant. We can easily show the optimal value of X_0 is $\min\left\{C \Big/ \sum_{i=1}^{N} r_i, 1\right\}$ and its objective value is $\min\left\{\sum_{i=1}^{N} r_i, C\right\}$. This completes the proof. □

If the weights of all ONUs are identical, we can easily obtain the optimal solution such that the objective value is C when $X_i = C \Big/ \sum_{i=1}^{N} r_i$ for all i if $\sum_{i=1}^{N} r_i \geqslant C$, and is $\sum_{i=1}^{N} r_i$ when $X_i = 1$ for all i otherwise.

However, if the weights are not identical, it is not straightforward to find the optimal solution. For the remainder of the paper, we will consider only the general weight problem. For the general problem, let $Y_o = \min\left\{C \Big/ \sum_{i=1}^{N} w_i r_i, \sum_{i=1}^{N} r_i \Big/ \sum_{i=1}^{N} w_i r_i\right\}$ be the total amount of required bandwidth divided by the total weighted amount of required bandwidth, where Y_o is determined by the requested bandwidth $\{r_i\}$. The relationship among Y_o, $\sum_{i=1}^{N} r_i$ and C is derived as follows.

Lemma 1. *If $Y_o \leqslant \min_{1 \leqslant i \leqslant N}\{1/w_i\}$, then $\sum_{i=1}^{N} r_i \geqslant C$.*

Proof. It is noticed that $Y_o \geqslant [\min_{1 \leqslant i \leqslant N}\{1/w_i\}]\left[\min\left\{C \Big/ \sum_{i=1}^{N} r_i, 1\right\}\right]$. Therefore, if $Y_o \leqslant \min_{1 \leqslant i \leqslant N}\{1/w_i\}$, then $C \Big/ \sum_{i=1}^{N} r_i \leqslant 1$. This completes the proof. □

According to Lemma 1, it is true that if $\sum_{i=1}^{N} r_i < C$ then $Y_o > \min_{1 \leqslant i \leqslant N}\{1/w_i\}$. However, the inverse of Lemma 1 is not true. For example, consider an EPON system with link capacity of C. Suppose that there are two ONUs with demand of $(r_1, r_2) = (100, 60)$. Assume that their weights are $(w_1, w_2) = (1, 2)$. Then, $Y_o = C/220 > \min_{1 \leqslant i \leqslant N}\{1/w_i\} = 0.5$ and $\sum_{i=1}^{N} r_i = 160 \geqslant C$ if the capacity C has a value of $110 \leqslant C \leqslant 160$. Therefore, we use the relationship $Y_o \leqslant \min_{1 \leqslant i \leqslant N}\{1/w_i\}$ instead of $\sum_{i=1}^{N} r_i \geqslant C$ for formulations of the optimal solution.

Proposition 2. *If $Y_o \leqslant \min_{1 \leqslant i \leqslant N}\{1/w_i\}$, the optimal allocation is obtained as $X_i = w_i Y_o$ and has the optimal objective value of C.*

Proof. By Lemma 1, if $Y_o \leqslant \min_{1 \leqslant i \leqslant N}\{1/w_i\}$ then $\sum_{i=1}^{N} r_i \geqslant C$. Therefore, the throughput term of Eq. (1) has maximal value C at $\left\{X_i \middle| \sum_{i=1}^{N} r_i X_i = C\right\}$ and the remaining terms of Eq. (1) have the maximal value of 1 when $X_i/w_i = Y_1$ for all i, where Y_1 is a constant. For the solution of $\sum_{i=1}^{N} r_i X_i = C$, let us substitute $w_i Y_1$ for X_i and simplify the equation; then we obtain the result of $Y_1 = C \Big/ \sum_{i=1}^{N} w_i r_i$ which equals Y_0 by Lemma 1. The solution $\{X_i\}$ also satisfies Eq. (3) since $Y_o \leqslant \min_{1 \leqslant i \leqslant N}\{1/w_i\}$. For the solution of $X_i = w_i Y_o$, the objective value becomes C since $\sum_{i=1}^{N} r_i \geqslant C$ by Lemma 1. This completes the proof. □