

Shared-Wavelength WDM-PON Access Network

--- Bursty Traffic Accommodation and User-defined SLA Support

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Abstract - We investigate the shared-wavelength WDM-PON architecture which accommodates bursty downstream traffic. Based on the architecture, the proposed flow-scheduling algorithm can support user-specified Service Level Agreements (SLAs), especially under high traffic load. Illustrative results demonstrate that the new architecture can provide a user with a number of streaming flows with bandwidth and maximum delay guarantees, as well as average bandwidth guarantee for data flows, as specified by the user-defined SLA.

1. Introduction

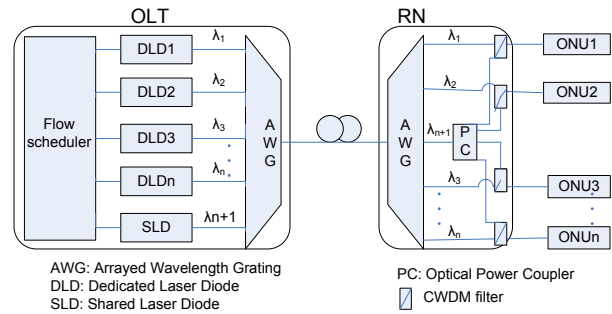
WDM-PON is a promising technology for “first mile” access, which provides multiple high-speed services to end users [1,2,3]. Legacy WDM-PON architectures allow only one dedicated downstream wavelength per Optical Network Unit (ONU), with a fixed line rate (typically 1 Gbps). This fixed allocation scheme has difficulty in accommodating the bandwidth-intensive and bursty [4] traffic such as real-time video streaming.

We address this problem using new shared-wavelength WDM-PON architecture, first proposed in [5]. In this architecture, each ONU has an extra downstream wavelength shared with other ONUs besides the dedicated wavelength, so that extra bandwidth is provided to support bursty traffic, and downstream bandwidth is exploited more effectively by multiplexing the usage of the shared wavelength.

Traffic flows carrying WDM-PON services mainly include streaming flow and Best Effort (BE) flow [2]. The streaming flow has strict delay and bandwidth requirements. The Service Level Agreement (SLA) of a user specifies a number of streaming flows with guaranteed average bandwidth and maximal packet delay, and BE flows with total average bandwidth. We discuss how to provide Quality-of-Service (QoS) according to the user SLA. By using flow scheduling, we can identify a user’s flow request, and redirect the out-of-SLA (illegal) flow or low-priority flow to the shared wavelength in case of bursty overload, thus leaving enough capacity on the dedicated wavelength for the legal (within SLA) traffic flows. Therefore, our architecture guarantees the user SLA and prevents a user’s illegal flow requests from deteriorating network performance, especially at heavy traffic load.

2. Shared-Wavelength WDM-PON

Figure 1 shows the shared-wavelength WDM-PON architecture. Each ONU has an extra shared downstream wavelength and is connected to one or more end



users. C-band (1530nm~1560nm) and L-band (1560nm~1600nm) spectra are used for the dedicated ($\lambda_1 \sim \lambda_n$) and the shared (λ_{n+1}) wavelengths, respectively, which facilitates the usage of low-cost CWDM filter at the ONU. The ONU has two receivers, one for dedicated wavelength and the other for shared wavelength. The number of ONUs that shares the shared wavelength can be different according to the ONU’s bandwidth request, and may be constrained by power budget ($n \leq 16$). The “flow scheduler” at the OLT identifies and dispatches service flows from the backbone network to dedicated or shared queue that is connected to dedicated or shared wavelength respectively. Although signal power on the shared wavelength is split, power budget calculation [5] shows our architecture still keeps the “passive” property.

3. Flow Scheduling

3.1 Flow Classification and User-Defined SLA

WDM-PON service bundle has three types of service flows: voice, streaming and data. Voice flow uses pulse-code modulation at constant bit rate. As we focus on the bursty flow, and voice takes very small bandwidth, we will not discuss it in this paper. The streaming flow is a collection of various kinds of video streaming with coding schemes such as MPEG2 or H.264. Important properties of these flows are burstiness and stringent QoS requirements. The third type is data flows. Although these are bursty, delay and jitter are not the important issues. These are Best Effort (BE) flows and are given lower priority than the streaming flow.

Based on the above service flow classification, we can not provide user SLA only by average bandwidth, and therefore a more detailed scheme is required. We define user SLA as a number of streaming flows with guaranteed average bandwidth and maximal packet delay, and BE flows with total average bandwidth. For example, a user SLA may includes 5 streaming flows with average 20 Mbps each and maximal packet delay less than 5 msec, as well as 20 Mbps BE flow bandwidth.

A user can specify its own SLA profile. The flow scheduling must guarantee different user SLAs

3.2 Flow Scheduling Algorithm

The flow scheduler at the OLT maintains two tables: a SLA table recording all the users' SLA and a flow table recording all the existing flows' flow ID, instant rate, type (streaming or BE), status (legal or not according to user SLA), user of the flow, and flow routing (transmitted by dedicated or shared queue).

Flow scheduling includes three parts: admission control, polling time scheduling, and termination control, which are triggered by the generation of a flow, polling time interval (which is a fixed time interval after which the flow scheduler periodically checks the status of the various queues), and termination of a flow respectively.

To help understand the algorithm, we define the symbols:

$sf_{i,j}$: j th streaming flow of user i ;

$ef_{i,j}$: j th BE flow of user i ;

Inst_rate (sf), Inst_rate (ef): instantaneous rate of flow;

Legal (sf), Legal (ef): flow is legal/illegal by user SLA;

SLA (i): SLA of user i ;

Length (k): buffer length of dedicated queue k ;

up_threshold (k), down_threshold (k): parameters;

When a new flow, e.g., $sf_{i,j}$ or $ef_{i,j}$, arrives at the OLT,

the admission control is triggered. It identifies the flow (including flow ID, type, etc.). Suppose the flow will be transmitted through dedicated queue k or shared queue, the algorithm is as follows.

if (Length(k) > up_threshold (k))

 Congestion (k) = true;

else Congestion (k) = false;

if ($sf_{i,j}$)

 if ($j >$ number of streaming flows of SLA(i))

 Legal ($sf_{i,j}$) = false;

 else Legal ($sf_{i,j}$) = true;

if ($ef_{i,j}$)

 if ($\sum_j Inst_rate(ef_{i,j}) >$ BE bandwidth of SLA(i))

 Legal($ef_{i,j}$) = false;

 else Legal($ef_{i,j}$) = true;

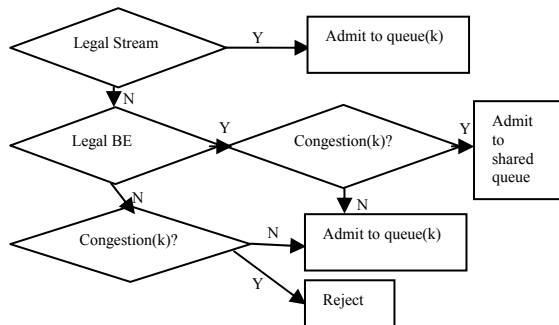


Fig. 2. Admission control.

Next, admission control treats the incoming flow as shown in Fig. 2. Generally admission control accepts a legal flow and registers it to flow table in all cases, while it rejects an illegal flow if queue k is congested.

The polling time scheduling is triggered at the end of each polling interval. For each dedicated queue, it calculates its flows' instant rate and Legal (ef) by the procedure in the admission control; then, it updates the flow table and computes up_threshold (k) and down_threshold (k). Next, if congestion (k) is true, the flow scheduler randomly picks the illegal flows in dedicated queue k (if no illegal flows, it picks the BE flows) and redirects them to the shared queue until the aggregated incoming flows' rate to queue k is lower than the downstream rate. If the length of dedicated queue k is lower than down_threshold (k), we expect the traffic on dedicated downstream k is not at bursty overload. Flow scheduler will take some flows back to the dedicated queue k from the shared queue, until the aggregated rate of incoming flows of queue k starts to be larger than the downstream rate or it has taken back all its flows from shared queue. Finally, flow scheduler updates the flow table due to the flows' route changes above.

When an existing flow is over, the termination control is triggered. It updates the flow table by deleting the flow's entry and recalculating other flows' states (legal or not).

An important challenge is how to calculate the threshold value. The threshold is important to control the queue size, which in turn decides the packet delay. As flow scheduling shows that the legal streaming flows are always routed to the dedicated queue, if we can control the maximal size of dedicated queue by threshold, we can control the max packet delay of streaming flows.

The analysis considers the worst situation. If each flow in dedicated queue k reaches its peak rate right after the polling time scheduling, the accumulated traffic during the next polling interval must be less than the maximal dedicated queue size. Assuming $f_{k,jMax}$ is the peak rate of flow j in dedicated queue k , C is the output rate of dedicated queue k (1 Gbps), p is the polling interval, and D_{max} is the maximal packet delay, then the up_threshold value must satisfy the following inequality:

$$\left(\sum_j f_{k,jMax} - C\right) \times p + up_threshold \leq D_{max} \times C \quad (1)$$

$$down_threshold = \alpha \times up_threshold$$

where α is (0, 1), which affects the frequency of flow redirection between the dedicated and shared queues.

When planning the shared-wavelength WDM-PON, we must guarantee enough bandwidth for streaming flows on dedicated wavelength and provide redundant capacity for user upgrading. We illustrate by the number of users M one dedicated wavelength can support. Assuming $sf_{i,jmax}$ is the j th streaming flow's peak rate of user i ,

$sf_{i,j,average}$ is the j th streaming flow's average rate of user i , and $ef_{i,k,average}$ is the k th BE flow's average rate of user i , the number of user M must satisfy:

$$\sum_{i=1}^M \sum_j sf_{i,j,max} < C \quad (2)$$

$$\sum_{i=1}^M \sum_j sf_{i,j,average} + \sum_{i=1}^M \sum_k ef_{i,k,average} < (1 + \beta)C$$

where $\beta = 1/n$, e.g., if four ONUs share one shared wavelength, β is $1/4$. The first inequality guarantees a dedicated wavelength can support streaming flows even if they are at bursty overload; and second inequality says total average traffic must be lower than average capacity provided by the shared scheme.

4. Illustrative Examples

We use the architecture shown in Figure 1. There are 4 dedicated wavelengths, 1 shared wavelength (all at 1 Gbps), and 4 ONUs. Each ONU has two receivers to receive signals from its dedicated wavelength and shared wavelength. OLT has 4 dedicated queues for 4 dedicated wavelengths and 1 shared queue for the shared wavelength. Flow packets take the form of Ethernet frames (64 to 1518 bytes) and arrive at OLT from the backbone network, at link rate of 2.5 Gbps for each dedicated downstream wavelength (10 Gbps totally). Note that there will be no buffering problem if the OLT's input and output line rates are the same.

We generate bursty flows by aggregating multiple sub-streams, each consisting of alternating Pareto-distributed on/off periods, with a Hurst Parameter of 0.8. Flow arrival interval is exponential-distributed and flow length is uniform-distributed. Define arrival rates of streaming flows and BE flows for one ONU as λ_s and λ_e , with average flow size $size_s$ and $size_e$ respectively. Then average normalized traffic load is (assuming each ONU gets the same traffic in average),

$$(\lambda_s \times size_s + \lambda_e \times size_e) / C \quad (3)$$

Each ONU is connected to 7 users. For each user, the user SLA includes 2 streaming flows with 20 Mbps average bandwidth and 5 ms max packet delay, plus 100 Mbps BE flows. For purpose of illustration, we set the peak rate of streaming flow as 40 Mbps. If each user requests all the bandwidth in his SLA, the traffic load is $(100 + 2 \times 20) \times 7 / 1000 = 0.98$. Correspondingly, we set parameters as $\lambda_s = 10$, $size_s = 49$ Mbits, $\lambda_e = 50$, $size_e = 9.8$ Mbits to generate traffic load 0.98 according to formula (3). Under this heavy load, we investigate the performance of different flows (legal and illegal, both streaming and BE). Note that, as each streaming flow lasts $49/20 = 2.45s$ in average, the system stabilizes after 2.45s from initiation. Finally we set α as 0.5.

To test the performance of illegal streaming flows, we randomly pick a user and manually insert one more streaming flow (average 20 Mbps, ever lasting) besides the user's SLA at starting time. Figure 3 shows instant packet delay of legal stream, illegal stream, and BE flow of the user; and figure 4 shows instant bandwidth of the legal stream, BE flow of the user, and aggregated traffic of the 7 users belonging to the same ONU. The aggregated traffic in Figure 4 shows two bursty periods: 3.1~3.47 second and 3.9~4.3 second, in which the BE flow and illegal stream suffer longer delay and decreased bandwidth. But the average bandwidth of BE flow during a long time is 98 Mbps, which is very close to 100 Mbps. Even during bursty periods, the legal streaming flows still get guaranteed delay (< 5 msec) and can even keep peak rate (40 Mbps) at the first bursty period with a long-run average bandwidth 20 Mbps.

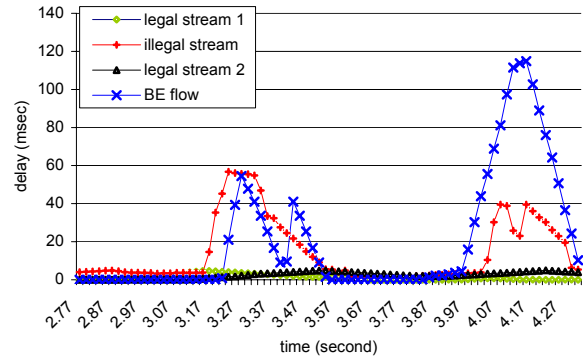


Fig. 3. Flow instant delay.

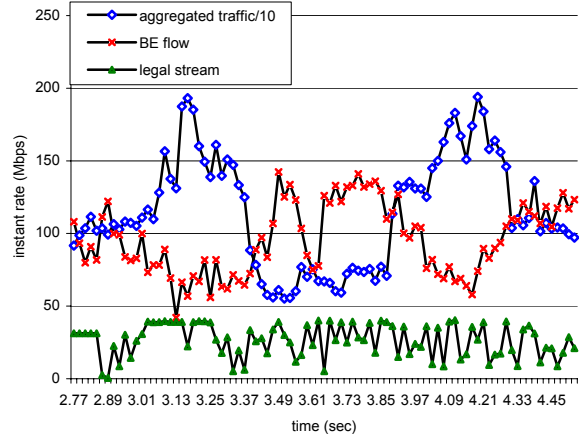


Fig. 4. Flow instant bandwidth.

5. References

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