Analysis of IP delay variation in edge OBS nodes

(Invited)

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This paper evaluates the packet delay from its arrival at the burstifier until the burst is finally released. Such evaluation comprises the delay due to burstification together with the delay which is due to waiting in the transmission queue. More specifically, we focus on the delay jitter, which has an impact on the performance of multimedia applications.

1. Introduction

Optical Burst Switching (OBS) has been proposed as a promising IP-over-WDM solution that can provide flexible bandwidth allocation at the burst level. A burst is composed by IP packets, which are assembled together by a functional unit called *burstifier*. Typically, the aggregation of packets into bursts is performed per Forwarding Equivalence Class (FEC), which are groups of packets classified by destination node and service class. Then, the bursts are statistically multiplexed for transmission into the optical core network, as depicted in Fig. 1. Notice that the electrical transmission buffer can be applied to solve the contention in transmissions of bursts from different FECs.

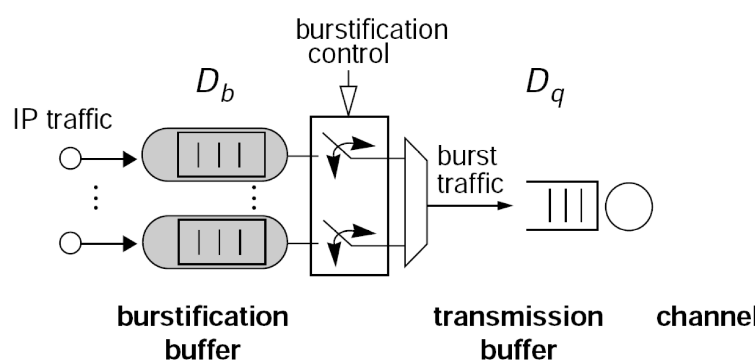

Figure 1: Burst transmission model at the edge OBS node.

Both the burstification and queuing processes at the edge node result in substantial variable components in the E2E delay of IP packets, which have significant influence on delay-sensitive services (e.g. real-time and interactive applications) and need to be carefully inspected. In this paper, the IP Packet Delay Variation (IPDV) [1] in the edge node will be analyzed for the first time.

Following the ITU-T recommendation, the IPDV can be defined by η_ε^T. Here, η_ε^T denotes the percentile of packet delay *T*, i.e., $P(T > \eta_\varepsilon^T) \le \varepsilon$. In the OBS edge node, an arbitrary IP packet mainly experiences a burstification delay D_b and a transmission queueing delay D_q (cf. Fig. 1). In a cascade system, the overall IPDV can be calculated as the sum of IPDV in each network element approximately. So the IPDV in the edge node can be approximated by the sum of the percentiles of D_b and D_q, i.e., $\eta_\varepsilon^{D_b} + \eta_\varepsilon^{D_q}$. The probability density function of D_b and D_q are to be derived for the determination of the IPDV.

Concerning the burstifier analysis, previous studies have analyzed in detail the burst-assembly process, mainly focusing on the characterization of outgoing burst traffic [2,3,4,5], its impact on different aspects of global network performance, such as link utilization and blocking probability at intermediate nodes [5,6], or a combination of some of these aspects. To the best of our knowledge, only a few studies have paid attention to the actual burstification delay in the OBS edge node [7]. However, these studies provide only limited delay statistics like maximum and average delay value [7] or the delay distribution of the first packet in the burst [4].

In this paper, the distribution function of the burstification delay D_b is firstly derived for an *arbitrary* IP packet. Alternatively, the first packet of a burst, which experiences the highest waiting time (tighter guarantee), is also studied. Finally, we also derive the burst-assembly delay distribution of a metric that represents the average packet delay per burst, which is used for a loose assurance of the delay variation. In the transmission buffer, the definition of the delay variation is self-explanatory since packets of one burst experience the same burst queuing delay D_q. The result in [8] is applied to determine D_q.

The remainder of the paper will be structured as follows: In Section 2, the traffic model and system parameters are introduced. The probability density function for the burstification delay is derived in Section 3 with respect to different definitions as mentioned above. In Section 4, the overall IPDV in the edge node is estimated and compared with simulation results. Finally, this paper is concluded in Section 5.

2. Traffic and system parameters

The incoming IP traffic at each burstification buffer is mostly aggregated from many users, so it can be modeled by the Poisson process [9]. Additionally, we assume that the packet size is constant, which is typical for voice services but it also serves as a good approximation in more general cases wherein the burst size is much larger than the packet size, which is common in OBS networks.

In burstification control, generally a timer is set upon the arrival of the first packet in an empty burstification buffer. A burst will be generated either when the total size of packets in the burstification buffer reaches a specified maximum burst size or the timeout occurs, depending on which condition is met first. In a properly configured edge node, however, the size-based burstification condition should dominate when the system operates at high loads so that the signaling and processing overhead for the burst switching in the core node is limited. When the system operates at low loads, the timer-based burstification plays a more important role to bound the delay. Since the high load situation is more interesting for QoS guarantees, we focus on the *size-based* burstification and neglect the effect of the timeout. As the packet size is constant, the maximum burst size is denoted by *N*, referring to the number of packets in a burst.

In our scenario depicted in Fig. 1, the transmission FIFO buffer is equipped with a single channel, which corresponds to a feasible system implementation that provides separate and dedicated transmission buffer for each wavelength channel.

3. Analysis of burstification delay

In this section, we inspect the burst-assembly delay distribution with respect to an arbitrary IP packet, the first packet in a burst and average packet delay in a burst.

We shall assume that packets from a given FEC arrive at the border OBS node following a Poisson process with rate λ packets/sec. The burst assembler employs a size-based burstification algorithm with parameter *N*, that is, each burst contains exactly *N* packets. Finally, we use $X_i,\ i = 1,\dots,N-1$ to refer to the inter-arrival time elapsed between the *i*-th and the *i+1*-th packet arrivals, since the counting starts from the first packet arrival at an empty burstification buffer. Note that, with Poissonian traffic, the X_i values are independent and identically distributed, each following a negative exponential distribution with mean value $1/\lambda$.

3.1 Arbitrary IP packet delay

Let *Y* denote the number of packets already in the burstification buffer when an arbitrary IP packet arrives. In other words, the arriving packet itself is the *Y+1*-th packet and obviously $0 \le Y \le N-1$. The burstification delay D_b of this packet is then equal to the sum of the packet inter-arrival times of the subsequent packets until the *N*-th packet arrives, and the burst is thus generated. Therefore:

$$D_b = \begin{cases} \sum_{j=Y+1}^{N-1} X_j, & 0 \le Y < N-1 \\ 0, & Y = N-1 \end{cases}$$

From the above, it can be realized that D_b has a compound distribution characterized by random variable X_i and *Y*.

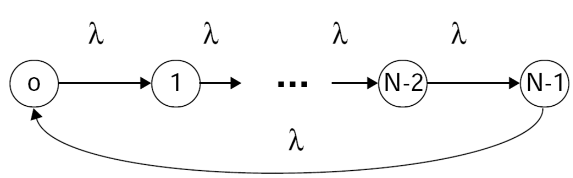

Figure 2: State-transition diagram for the burstification process.

To determine the distribution function of *Y*, the size-based burst-assembly process can be analyzed with the state-transition diagram of Fig. 2 with respect to the random variable *Y*. From the local balance condition, a discrete uniform distribution is obtained: $P(Y=i)=1/N$, $0 \le Y \le N-1$.

Based on the distribution function of X_i and *Y*, the Laplace-Stieltjes Transform (LST) of D_b is derived from:

$$\psi(s) = G(z)\big|_{z=\phi(s)} = G(\phi(s)) = \frac{(s+\lambda)^N - \lambda^N}{Ns(s+\lambda)^{N-1}}$$

Here, *G(z)* is the probability generating function for *Y* and $\phi(s)$ is the LST for X_i. From this, and by applying the property of the LST and carrying out inverse LST, the complementary distribution function of D_b is given by:

$$P(D_b > t) = \frac{1}{N}\sum_{j=1}^{N-1} \frac{(N-j)(\lambda t)^{j-1}}{(j-1)!} e^{-\lambda t}$$

3.2 Maximum packet delay in a burst

Now, let us concentrate on the first packet in a burst, which is the one that experiences maximum burst-assembly delay since it must wait for the other *N-1* packets to arrive. This is a useful case scenario to investigate since it gives the worst possible case for burst-assembly delay. In this light, the maximum burst assembly delay is:

$$D_b = \sum_{j=1}^{N-1} X_j = \frac{\lambda^{N-1} t^{N-2}}{(N-2)!} e^{-\lambda t} = \Gamma_t(\lambda, N-1), \quad t > 0$$

since the sum of *N* exponential random variables follows a gamma distribution with parameter λ and *N* degrees of freedom. This has the following survival function:

$$P(D_b > t) = \frac{\gamma(\lambda t, N-1)}{(N-1)!}$$

3.3 Average packet delay in a burst

Clearly, the burst-assembly delay observed by the packets in a burst highly depends on its position within the burst, that is, on whether it happens to arrive when the burst assembly queue is full or empty. This section aims to derive an "average" packet delay metric, which gives a measure of the delay observed by an IP packet which founds a random number of packets in the burst-assembly queue. This metric might be considered as the burst-assembly delay that a random arrival would experience, since it weights the burstification delay of all packets in a burst of size *N*. Thus, let D_b be defined as:

$$D_b = \frac{1}{N}\left[(X_1 + \ldots + X_{N-1}) + (X_2 + \ldots + X_{N-1}) + \ldots + (X_{N-2} + X_{N-1}) + X_{N-1}\right] = \sum_{j=1}^{N-1} jX_j$$

Note that the random variable jX_j/N is negative exponentially distributed with parameter $\lambda N/j$. Thus, it is required to compute the sum of *N-1* exponential distributions, with decreasing parameter $\lambda N/j$, with $j=1,\ldots,N$. In this case, we cannot make use of the properties of the sums of exponential random variables. Instead, the easiest way to proceed makes use of the moment generating function.

Recall that the moment generating function of an exponential distribution with parameter θ is $M_x(\theta)=(1-s/\theta)^{-1}$. Hence, the moment generating function of D_b is the product of the moment generating function of each component in the sum above, due to the independence of the X_j, i.e.:

$$M_D(s)=\prod_{j=1}^{N-1}\frac{1}{1-j\dfrac{s}{N\lambda}}$$

which can be decomposed into partial fractions:

$$M_D(s)=\sum_{j=1}^{N-1}\frac{A_j}{1-j\dfrac{s}{N\lambda}}$$

whereby the A_j coefficients must be thus computed. By inspection, it can be shown that the A_j coefficients take the following values:

$$A_j=\left(\prod_{k=1,k\neq j}^{N-1}\left(1-\frac{k}{j}\right)\right)^{-1}$$

for $j=1,\ldots,N$. Accordingly, the above can be transformed back to:

$$f_D(t)=\sum_{j=1}^{N-1}A_j\frac{\lambda N}{j}e^{-\frac{\lambda N}{j}t}$$

for $t>0$. With this result, the probability to exceed a given value is straightforward:

$$P(D_b>t)=\sum_{j=1}^{N-1}A_je^{-\frac{\lambda N}{j}t}$$

and the quantile $\eta_\varepsilon^{D_b}$ for a given tail probability ε is obtained by solving:

$$P(D_b>\eta_\varepsilon^{D_b})\leq\varepsilon$$

4. Comparison and simulation

In this section, the delay variation is studied with respect to specific system scenarios and the analytical results obtained according to Section 3 are compared with simulations.

We look at an edge node with 20 FECs, unlimited FIFO buffer and a wavelength data channel of 10 Gbps. The incoming IP packets are generated according to Poisson process with constant packet size of 1 KBytes and are equally distributed to each FEC. The burst size is set to be 16 KBytes, i.e., N=16. For the evaluation of the delay variation, $\varepsilon = 0.001$.

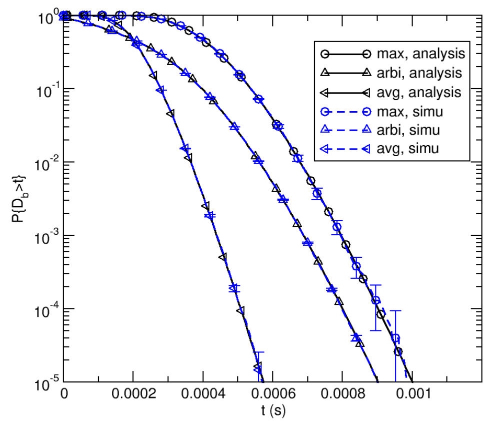

Figure 3: CCDF of burstification delay

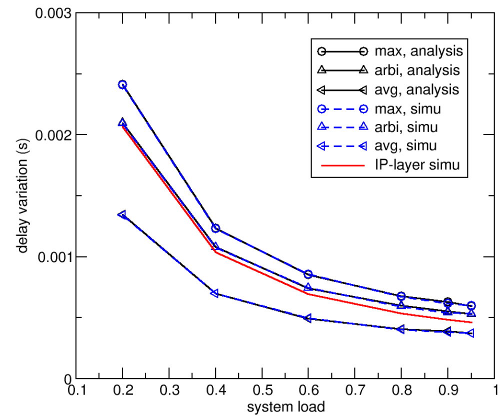

Figure 4: IPDV at the edge OBS node.

In Fig. 3, the CCDF functions of the burstification delay D_b are plotted for all three definitions (maximum packet delay in a burst, arbitrary IP packet delay and average packet delay in a burst) at a system load of 0.6. Both analytical results and simulation results are depicted and they show perfect fitting between each other. This verifies the accuracy of the analysis in Section 3.

In Fig. 4, the total IPDV in the edge node is calculated by summing up $\eta_\varepsilon^{D_b}$ and $\eta_\varepsilon^{D_q}$. For analytical results, $\eta_\varepsilon^{D_b}$ is calculated according to the CCDFs obtained in Section 3 respectively. The burst queuing delay D_q in the FIFO buffer can be approximated by a ND/D/1 model with small queuing length (see [8] for further details), based on which $\eta_\varepsilon^{D_q}$ is derived. Sum of $\eta_\varepsilon^{D_b}$ and $\eta_\varepsilon^{D_q}$ can also be obtained by simulation and plotted in Fig. 4. It shows that the analytical results serve as very good estimation of the delay variation with respect to all three definitions under the different load situations.

The transit delay distribution in the edge node is measured on the IP-layer in the simulation between the input and output of the edge node. The values of delay variation, derived from percentile of the IP transit delay under different system loads, are plotted in Fig. 4 as the solid line referred by “IP-layer simu”. We see that the analytical results for the arbitrary IP packet delay give a good estimation of the transit IPDV with a bit of overestimation. A small over-estimation is, however, desired in the provisioning of guaranteed services.

5. Conclusions

In this paper, the IP packet delay variation in the OBS edge node is analyzed by looking at the burstification delay and queuing delay separately. For the burstification delay, the complementary distribution function is derived for arbitrary packet delay, maximal packet delay per burst and average packet delay per burst, respectively. The queuing delay is approximated by the ND/D/1 model. By comparison with simulation results, it shows that the analytical results can serve as very good estimations of the delay variation in the OBS edge node.

The analysis of the delay variation is essential for the admission control and resource allocation for QoS-guaranteed delay-sensitive services. In our future work, the influence of the delay variation on the admission control process will be inspected.

Acknowledgements

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