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Throughput-based fair bandwidth allocation in OBS networks

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Fair bandwidth allocation (FBA) has been studied in optical burst switching (OBS) networks, with the main idea being to map the max-min fairness in traditional IP networks to the fair-loss probability in OBS networks. This approach has proven to be fair in terms of the bandwidth allocation for differential connections, but the use of the ErlangB formula to calculate the theoretical loss probability has made this approach applicable only to Poisson flows. Furthermore, it is necessary to have a reasonable fairness measure to evaluate FBA models. This article proposes an approach involving throughput-based-FBA, called TFBA, and recommends a new fairness measure that is based on the ratio of the actual throughput to the allocated bandwidth. An analytical model for the performance of the output link with TFBA is also proposed.

KEYWORDS

burst blocking probability, fair bandwidth allocation, ingress OBS node, QoS differentiation, throughput fairness index

1 | INTRODUCTION

Optical burst switching (OBS) [1] is considered as a promising technology for the next-generation optical Internet, and is a response to the rapid growth of Internet traffic and the increasing deployment of new services (such as VoIP, video on demand, cloud computing, and data centers). The implementation of OBS aims to utilize the bandwidth of fibers more efficiently, to create a flexible network infrastructure that can be configured at burst level, and to handle various types of bursty traffic that are generated by the above services.

The typical architecture of OBS networks consists of core nodes connected to edge nodes in a mesh (Figure 1). Edge nodes are responsible for assembling the packets coming from access networks (such as IP packets) into larger carriers, called bursts, which are the main transport units in OBS networks. Each edge node maintains queues corresponding to destinations as well as QoS classes, if necessary. When a timer or size threshold is reached, the packets in a queue will be aggregated into a burst. A burst control packet (BCP) is sent on a dedicated control channel to reserve required bandwidths and configure the switching nodes along its path from the source to destination. The corresponding burst follows an offset time on an available data channel, and it is switched all-optical at all these nodes.

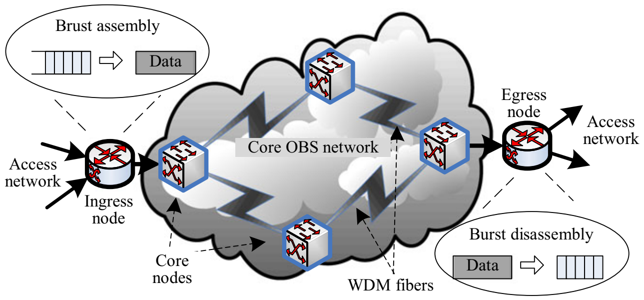

FIGURE 1 Typical architecture of OBS networks with their operations

In OBS networks, each established connection carries a flow[1)] of data belonging to a particular service (with a given QoS level). The connections that have the same destination can share one common link (or fiber) or one (a

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[1)] In this paper, the terms “flow” and “connection” are used interchangeably.

group) common wavelength in a link. Therefore, if there is no isolation mechanism and no service protection, over-rate connections[2)] can send too much traffic into the core network, which results in under-rate connections[3)] subjected to the common high-data-loss probability. In order to solve this problem, the authors in [2,3] proposed the methods of fair bandwidth allocation (FBA) for OBS networks, where the main idea is based on the max-min fairness in IP networks [4], but converts it to a theoretical fair-loss probability for each connection; the FBA process attempts to shift the real loss probability closer to the theoretical loss probability. However, because it is based on the ErlangB formula to calculate the theoretical loss probability, these models only apply to Poisson flows.

In fact, several types of Internet traffic have non-Poisson distribution (ie, that are self-similar) [5], so it is necessary to have another approach that can be applied to incoming Poisson and non-Poisson flows. Furthermore, the authors in [2,3] do not provide any reasonable fairness measure to evaluate their FBA methods. This paper proposes a new FBA approach with a new fairness measure that can be applied to many kinds of incoming flows.

Our contributions in this paper are as follows:

- introducing the architecture of the ingress OBS node, which supports the bandwidth allocation for QoS differentiation;
- formulating a new fairness measure that is based on the ratio of the actual throughput to the allocated bandwidth;
- proposing the throughput-based FBA (TFBA) model and then simulating it to evaluate its performance compared with that of previous proposals; and
- analyzing the performance of the output link when applying TFBA using the Markovian queuing model.

The remainder of this paper is organized as follows: Section 2 analyses the previous FBA models and shows their drawbacks. Section 3 describes our proposed throughput-based FBA model and analyzes the simulation results. The performance of the output link with TFBA is analyzed in Section 4. The conclusion is given in Section 5.

2 | RELATED WORKS

There are two main approaches for the fairness in OBS networks, namely the rate fairness and the distance fairness.

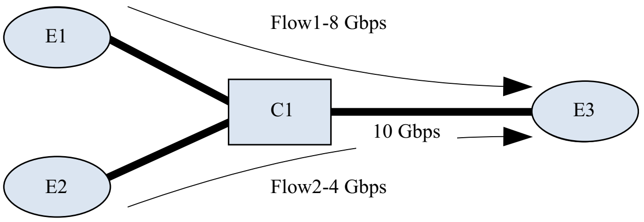

FIGURE 2 Example showing the requirements of bandwidth allocation of two flows which share one common link

The rate fairness, which is also called the FBA, involves protecting the under-rate connections from the over-rate connections by providing loss-probability isolation between connections [2,3], while the distance fairness addresses the fair-loss probability based on the distance (hop counts) [6,7]. This paper focuses on the FBA.

As shown in Figure 2, assume that there are two data flows that share one common link, including Flow1 from E1 to E3 and Flow2 from E2 to E3. Flow1 requires a bandwidth of 8 Gbps, and Flow 2 requires a bandwidth of 4 Gbps. With the conventional method, both Flow1 and Flow2 receive the same allocated bandwidth of 5 Gbps. However, this allocation is unfair because Flow2 never uses up its allocated bandwidth, while Flow1 always lacks bandwidth.

So far, the proposed FBA models for OBS networks are based on the max-min fairness in IP networks. In fact, the max-min fair-allocation technique in IP networks is only effective when the total individual throughput is greater than the link bandwidth capacity, and then individuals compete for shared bandwidth. The max-min fairness policy can be summarized as follows: (a) bandwidth is allocated in order to increase the demand; (b) the allocated bandwidth is never greater than the demand; and (c) all unsatisfied demands will be equally allocated. Under this policy, the bandwidth is initially allocated to the smallest demand, and the remaining unsatisfied demand would share the surplus bandwidth; the process continues until the surplus bandwidth is allocated for the demands.

One important difference is that OBS networks do not have buffers, such as IP networks. In particular, FBA in IP networks can be achieved using fair-arrangement algorithms, where if the whole required bandwidth exceeds the link capacity, packets are buffered and served again when the system is idle. Therefore, fair-queue algorithms can use all of the link capacity. However, the bandwidth of a link cannot be entirely used in OBS networks because there are always inevitable gaps (voids) between scheduled bursts. Owing to these large differences, the fair-queue algorithms developed for IP networks cannot be applied directly to OBS networks in order to achieve the same max-min fairness.

Therefore, the max-min fairness pre-emption (MMFP) in [2] converted the max-min fair rate (F_i) to a

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[2)] An over-rate connection is a connection whose traffic exceeds the allocated bandwidth.

[3)] An under-rate connection is a connection whose traffic is below the allocated bandwidth.

corresponding fair-loss probability (P_i) for each connection. An effective load (E_i) per connection is defined as

$$E_i = \sum_{j=1}^{N} \min\{F_i, F_j\}, \tag{1}$$

where N is the number of connections sharing one link. E_i is a factor in a reference system that is used to determine its corresponding fair-loss level for each connection in the actual system. In the case where the sending rates of the connections are smaller than their fair rates (the under-rate connections), their loss probability is determined by

$$P_i = Er(E_i) = \frac{(E_i)^W / W!}{\sum_{k=1}^{W} (E_i)^k / k!}, \tag{2}$$

where W is the number of wavelengths per output link; however, if the connections are with larger sending rates than their fair rates (the over-rate connections), the loss probability is given by

$$P_i = \frac{A_i - F_i \times (1 - Er(E_i))}{A_i}, \tag{3}$$

where A_i is the measured sending rate of connection i.

According to (1), for those connections with fair rates that are greater than F_i, connection i assumes that those connections are sending bursts in the same rate F_i as connection i in the reference system. If the fair rates of those connections increase, E_i will not be affected, and it will maintain a small loss probability according to (2) in order to provide an isolation to connection i. In the case involving connections with fair rates that are smaller than F_i, connection i assumes that those connections are sending bursts at their fair rates, which is smaller than F_i. If the fair rates of those connections decrease, E_i will also decrease, but connection i is subject to a high loss probability according to (3). Again, MMFP provides an isolation for connection i.

However, maintaining the real loss probability close to the theoretical level of MMFP may limit the incoming traffic. Therefore, using surplus bandwidth is ineffective. The authors in [3] proposed the rate fairness pre-emption (RFP) model, which is also based on the max-min fairness in order to fairly allocate bandwidth to all connections, while simultaneously and fairly resolving contentions among bursts. Specifically, in the case where there is a contention, the RFP method allows the bursts belonging to under-rate connections to occupy the channels of over-rate connections. The bursts belonging to over-rate connections are only given the priority when all wavelengths are busy (ie, all active connections have an idle bandwidth) to exploit their surplus bandwidth. Furthermore, only edge nodes track the rate of arriving bursts, and core nodes allocate bandwidth based on the RFP method only when the rate of arriving bursts varies significantly. Therefore, the RFP method does not cause heavy load in the core network. However, two packets, namely forward BCP (FBCP) and back BCP (BBCP) are always maintained in the RFP method to exchange information from the source and destination, which significantly increases the complexity of the system and the bandwidth for information exchange.

In short, there are drawbacks for the two above-mentioned FBA models, where MMFP does not efficiently exploit surplus bandwidth, while RFP maintains two control packets of FBCP and BBCP, which consume additional bandwidth for information exchange. In addition, RFP requires a model that predicts the rate of incoming traffic, but it does not always obtain accurate results. Both of these models use an ErlangB formula to calculate the loss probability that only matches for Poisson flows. These models address the issue of rate fairness, but do not suggest a reasonable fairness measure. The FBA model proposed below will overcome these drawbacks.

3 | MODEL OF THROUGHPUT-BASED FBA

3.1 | Architecture of ingress OBS nodes for QoS differentiation

Consider an ingress OBS node with the architecture shown in Figure 3. The arriving packets are first classified according to their destination by a destination classifier. In each assembly, plane per destination, packets with the same destination are next to be classified, based on their QoS classes, using a service classifier. Thus, the packets that enter into a queue have the same destination and the same QoS class. When the queue's timer or size threshold is reached, the packets in this queue are finally aggregated into a burst. The completed bursts with the same QoS class thus form a separated data flow at its output link.

The bandwidth allocation for the completed bursts at the output link is made by the bandwidth allocator (Figure 3). The considered ingress OBS node architecture assumes that there are no buffers for scheduling control;

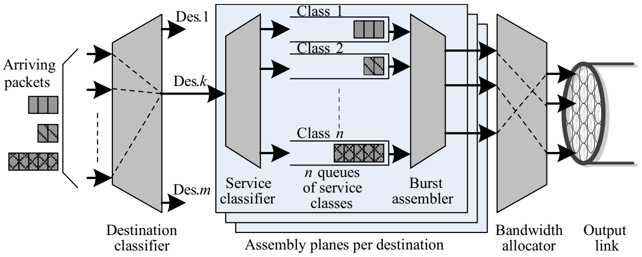

FIGURE 3 Architecture of ingress OBS node for QoS differentiation

this means that to reserve the bandwidth of the output link, a completed burst is transmitted immediately after sending its BCP an offset time, regardless of whether or not the control packet is successful. The purpose of this assumption is to evaluate the efficiency of the TFBA algorithm (Section 3.3) by actively dropping bursts during scheduling to achieve the best fairness between burst flows that share a common output link.

The throughput of the flows that share a common output link is limited by their allocated bandwidth. For the flows that do not use up their allocated bandwidth, this surplus bandwidth could be allocated to bandwidth-ravenous flows. Bandwidth allocation will be remade if there is a significant variation in the rate of incoming flows.

3.2 | Maximum usable bandwidth capacity of output link

In [2], the bandwidth capacity per link is given as $C = 1$; but this is not true in OBS networks because there are always gaps (voids) between scheduled bursts. Thus, the authors in [3] added a coefficient $\alpha = 0.7$, which represents the rate of the maximum usable bandwidth per link. This coefficient is appropriate because it is based on our simulation results shown in Table 1, with incoming normalized loads in the range of [0.5, 1.0]; the maximum achieved throughput per link is 0.72 on average. Therefore, the coefficient $\alpha = 0.7$ is used in our simulations.

TABLE 1 Maximum achieved throughput per link with various incoming normalized loads

Load (Erlang)	0.5	0.6	0.7	0.8	0.9
Maximum throughput	0.4862	0.5721	0.6715	0.7212	0.7213

3.3 | Throughput-based FBA algorithm

The idea of the proposed FBA approach is to push the actual throughput closer to the allocated bandwidth. Each time an arriving burst cannot be scheduled on an output link, the system assumes that the total throughput of the incoming flows has exceeded the bandwidth of the output link. A bandwidth reallocation request is therefore triggered. The TFBA process is carried out in four steps:

Step 1: Calculate the fair rate F_i for each connection (Lines 3–14)

If the arrival rate of flow i has a significant change (Line 3), the bandwidth is first divided equally for the connections (Line 7). The fair rate F_j of each connection is next defined as the minimum of its actual throughput and the allocated bandwidth (Line 9). Connections whose actual throughputs are less than the allocated bandwidth will not participate in sharing the surplus bandwidth in the next iteration. The allocation continues until the bandwidth has been allocated ($m = m_{\text{prev}}$) or all connections are satisfied ($m = 0$).

Step 2: Determine the allocated bandwidth AB_i for each connection (Line 15)

Given that Bw is the maximum bandwidth capacity of the output link, the allocated bandwidth for the connection i is

$$\text{AB}_i = F_i \times Bw \tag{4}$$

where F_i is the fair rate, which is given by Step 1.

Step 3: Measure the actual throughput AT_i of each connection (Line 16)

The actual throughput is determined by the formula:

$$\text{AT}_i = p_w(i)/T_w(i) \tag{5}$$

where $p_w(i)$ is the amount of data (in bytes) coming in the time window $T_w(i)$ of connection i.

Step 4: Resolve the burst contention

The burst contention is resolved by the comparison between AT_i and AB_i in order to determine whether the arriving burst belongs to under-rate or over-rate flows. Accordingly, if $\text{AT}_i > \text{AB}_i$, then the arriving burst belongs to an over-rate flow, and it will be dropped to reserve resources for under-rate flows. On the contrary, if $\text{AT}_i \leq \text{AB}_i$, then the arriving burst belongs to an under-rate flow; the ratio of AT_i/AB_i is then taken into account: if the value of AT_i/AB_i is less than that of AT_j/AB_j of the contending burst, the contending burst will be dropped to shift AB_i closer to AT_i; otherwise, if the value of AT_i/AB_i is greater than that of AT_j/AB_j, the arriving bursts are dropped.

The algorithm of TFBA is given in detail as follows:

```
TFBA Algorithm
Input:  - $b_i$;                               //arriving burst i, i = 1, 2, …, n.
        - $\Lambda = \{(\lambda'_i, \lambda_i)\}$;   //the previous and current rate of flows
Output: - $L = \{lost_i\}$                     //set of the lost bytes of connections
Begin
  $\alpha \leftarrow 0.7$;
  if ($b_i$ is failed to schedule) then
    if ($|\lambda_i - \lambda'_i| > th$) then   //the arriving rate has a big change
      $S \leftarrow \varnothing$; $m \leftarrow N$;          //N is the number of QoS classes
      $U \leftarrow \alpha \times C$;                  //the real capacity of output link
```

(Continues)

```
        repeat            //process of fair bandwidth allocation
          $FS \leftarrow U/m$;
          $m_{\text{prev}} \leftarrow m$;
          $F_{j \notin S} \leftarrow \min\{\lambda_{j \notin S}, \text{FS}\}$;   //fair rate of connection i
          $S \leftarrow \{j: \lambda_j \leq \text{FS}\}$;         //set of under-rate connections
          $U \leftarrow U - \Sigma_{j \in S}\lambda_j$;        //surplus bandwidth
          $m = m - |S|$;         //number of connections sharing the
                                 //surplus bandwidth in the next loop
        until ($m = m_{\text{prev}}$ or $m = 0$);
      end if
      $\text{AB}_i \leftarrow F_i \times Bw$;   //determine the rate of allocated bandwidth
      $\text{AT}_i \leftarrow p_{\text{w}}(i)/T_{\text{w}}(i)$;  //determine the actual throughput where
                          $p_w(i)$ is the
                          //number of packets arrived in the time
                          window $T_w(i)$
      if ($\text{AT}_i > \text{AB}_i$) then
        $lost_i \leftarrow lost_i + b_i$;
      else
        if ($\text{AT}_i/\text{AB}_i < \text{AT}_j/AB_j$) then     //in case of $y_i < y_j$
          $lost_j \leftarrow lost_j + b_j$;
        else
          $lost_i \leftarrow lost_i + b_i$;
        end if
      end if
    end if
  End
```

The complexity of TFBA depends mainly on the bandwidth reallocation (Lines 6–13), which is similar to that of MMFP and RFP; thus, the complexity of TFBA is equal to that of MMFP and RFP, which is $O(N^2)$.

3.4 | Throughput fairness index

In order to compare the fairness efficiency among FBA models, a fairness measure is proposed, which is based on the ratio of the actual throughput to the allocated bandwidth. Specifically, given that $y_i = \text{AT}_i/\text{AB}_i$ is the ratio of the actual throughput (AT_i) to the allocated bandwidth (AB_i) for flow i, the throughput fairness index (TFI) is proposed based on the Jain's formula [8] as follows:

$$\text{TFI} = \frac{\left(\sum_{i=1}^{n} \sigma_i y_i\right)^2}{N \sum_{i=1}^{n} \left(\sigma_i y_i\right)^2} \tag{6}$$

where σ_i is the weight factor of flow i, $0 < \sigma_i < 1$, and $\sum_{i=1}^{n} \sigma_i = 1$

Our purpose is to shift the actual throughput (AT_i) of each flow closer to its allocated bandwidth (AB_i), which results in closing the value of TFI to 1. The authors in [8] also proved that the maximum fairness index is reached when

$$\sigma_1 y_1 \approx \sigma_2 y_2 \approx \cdots \approx \sigma_N y_N. \tag{7}$$

3.5 | Throughput fairness efficiency of TFBA algorithm

The throughput fairness efficiency of the TFBA algorithm is based mainly on the bandwidth reallocation (Line 15 of the TFBA algorithm) and the selective burst-dropping process (Lines 17–25). Specifically, when there is a contention (Line 2), the fair rate of each connection (F_i) is recalculated (Lines 6–3), their bandwidth (AB_i) is reallocated (Line 15), and a selective burst-dropping process is then performed (Step 4 of the TFBA algorithm). One thing to note is that the selective burst-dropping process has the tendency to push the actual throughput closer to the allocated bandwidth. If the arriving burst belongs to an over-rate flow (Line 17), it is dropped, and the actual throughput of this flow therefore decreases to be closer to its allocated bandwidth ($y_i \rightarrow 1$). In the case of an arriving under-rate burst (Line 19), a comparison of the ratio of the actual throughput to the allocated bandwidth between flows (y_i and y_j) is taken into account: if $y_i < y_j$, burst j is dropped; otherwise, if $y_i \geq y_j$, burst i is dropped. Obviously, the dropping process pushes y_j closer to y_i or y_i closer to y_j. According to (6) and (7), this action of the TFBA algorithm pushes the TFI closer to 1, and it therefore increases the throughput fairness efficiency. A simulation-based demonstration to determine the TFBA efficiency is shown in Figure 4, where the values of y_1, y_2, and y_3 of three corresponding connections of 1, 2, and 3 converge in times of contention. The next section analyzes in detail the efficiency of the TFBA algorithm, which is based on simulation results.

3.6 | Simulation results and analyses

The simulation was run on a PC with a 2.4-GHz Intel Core 2 CPU, and with 2 GB of RAM. Compared with MMFP

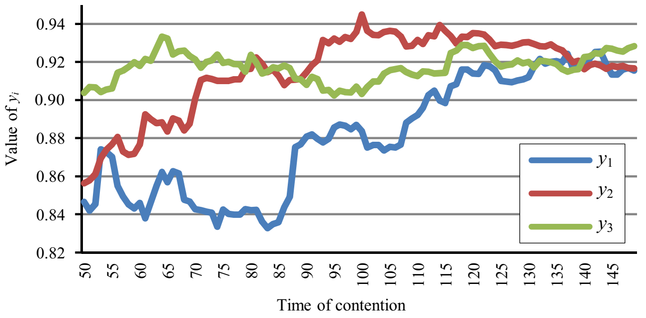

FIGURE 4 Convergence of the values y_1, y_2, and y_3 in terms of contention of the TFBA algorithm

and RFP, which only match Poisson flows, we assume that the packets that arrive at queues of an ingress OBS node have a Poisson distribution, and their sizes are within the range of [500, 1,000] in bytes. The burst assembly is based on a hybrid assembly algorithm. The simulation parameters are described in Table 2.

Assuming that there are three connections (Connections 1, 2, and 3) that share a common link from E1 to E2 of a Dumbbell network, as shown in Figure 5, the objectives of the simulation are to compare (1) the byte loss rate among these connections, (2) the average byte loss rate between our model (TFBA) and previous models (MMFP and RFP), and (3) the fairness efficiency (based on TFI) of these FBA models with varying incoming loads.

Therefore, two simulation phases are considered:

- Phase 1 is from 0.1 to 0.5 second, in which the incoming loads of three flows 1, 2, and 3 were 0.1, 0.2, and 0.3, respectively (the case where the total load is under the link capacity); and
- Phase 2 is from 0.6 to 1.0 second, where the load of flow 3 increases to 0.6, while those of other flows are constant (the case where the total load exceeds the link capacity).

The simulation tool is NS2-2.28 with the support of the package obs-0.9a.

Figure 6 shows a comparison of the byte loss rate among three connections in two simulation phases with the TFBA model. In Phase 1 (from 0.1 to 0.5 second), the byte loss rate of connections is kept at a fair rate, proportional to their actual throughputs; however, in Phase 2 (from 0.6 to 1.0 second), owing to the increased load of Connection 3, the total load of three connections exceeds the link capacity. The load of Connection 3 is greater than its allocated bandwidth; thus, it is considered to be an over-rate connection. More dropping the burst of Connection 3 has generated additional free bandwidth, which increases the number of opportunities to schedule the bursts of Connections 1 and 2; as a result, the byte loss rate of Connections 1 and 2 has decreased slightly.

TABLE 2 Simulation parameters.

Parameters	Value
No. of connections (N)	3
No. of wavelengths per output link (W)	8
Bandwidth per link (B)	1 Gbps
Rate of real link bandwidth (α)	0.7
Size threshold for burst assembly	20 KB
Timer threshold for burst assembly	10 μs
Range of normalized loads (λ_i)	[0.1, 0.6]

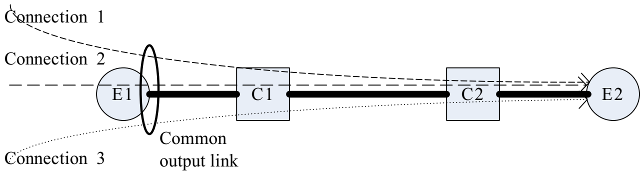

FIGURE 5 Simulation network

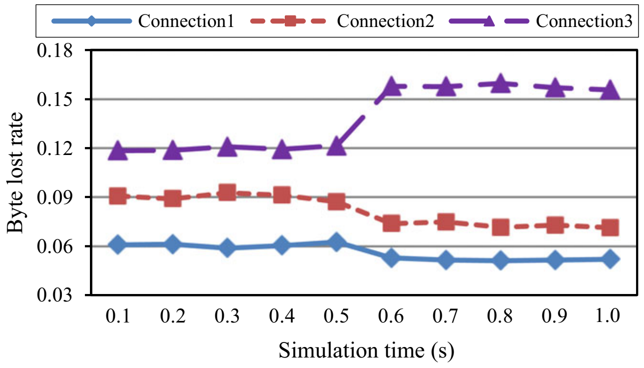

FIGURE 6 Byte loss rates of three connections in Phase 1 (from 0.1 to 0.5 second) and Phase 2 (from 0.6 to 1.0 second) with TFBA

When compared to MMFP and RFP, TFBA achieves the best performance in terms of the byte loss rate in both phases, as shown in Figure 7.

When compared to individual connections, the byte loss rate of Connection 1 with TFBA is higher than that in RFP (Figure 8); however, Connections 2 and 3 with TFBA have lower byte loss rates compared with those with RFP and MMFP (Figures 9 and 10). The reason is that RFP always gives greater priority to under-rate flows, which cause unfairness; meanwhile, the objective of TFBA not only minimizes data loss, but also regulates the FBA among connections (Figure 11).

In order to evaluate the performance of three FBA models, we proposed the TFI as in (6). Figure 11 shows a comparison of the TFI for TFBA, MMFP, and RFP. When the

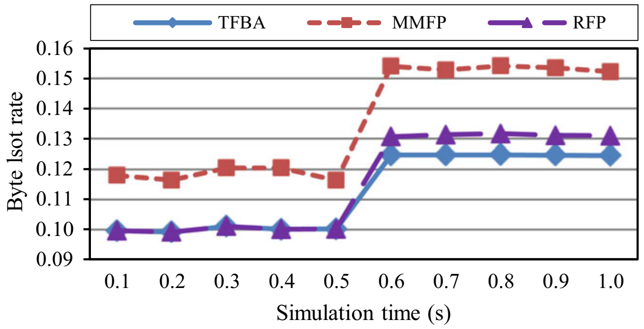

FIGURE 7 Average byte loss rates with TFBA, MMFP, and RFP

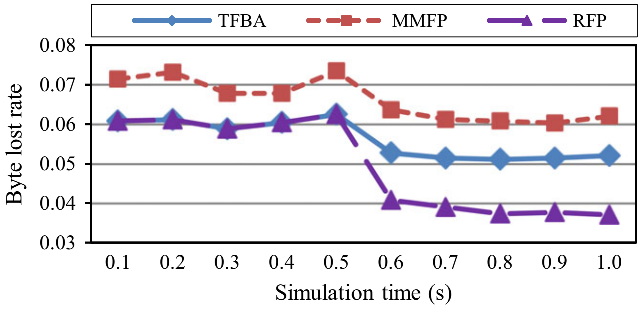

FIGURE 8 Byte loss rate of Connection 1 with TFBA, MMFP, and RFP

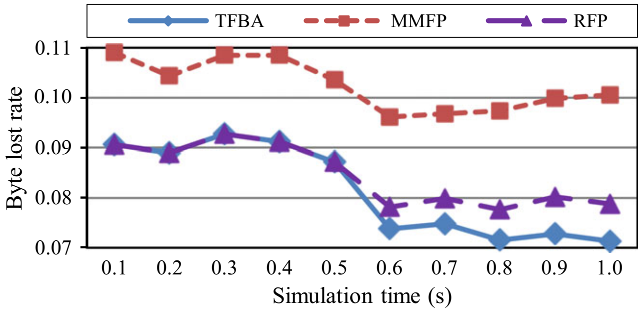

FIGURE 9 Byte loss rate of Connection 2 with TFBA, MMFP, and RFP

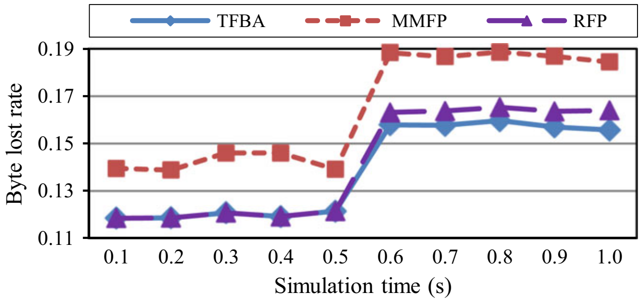

FIGURE 10 Byte loss rate of Connection 3 with TFBA, MMFP, and RFP

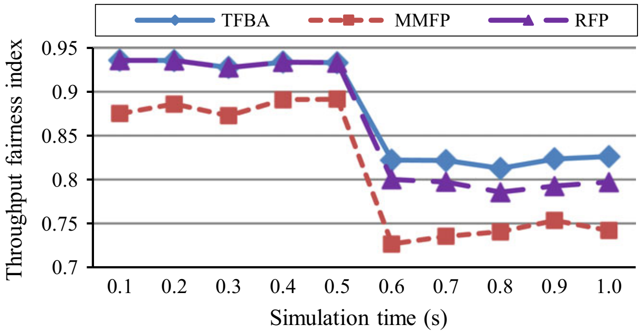

FIGURE 11 Throughput fairness index of TFBA, MMFP, and RFP

total loads do not exceed the link capacity, the fairness of the FBA models is greatest (near 1), but when the output link is overloaded, the FBA models reallocate the bandwidths for all three connections, and their fairness is reduced. This is due to the increasing of Connection 3, which makes its value of y_3 higher than those of Connection 1 and Connection 2. According to (7), the fairness is the best only when the values of y_i are approximate; so an increase in Connection 3 reduces the fairness of all three connections. However, TFBA always achieves the best TFI in both phases.

4 | PERFORMANCE OF OUTPUT LINK WITH TFBA

4.1 | Analytical model

In order to analyze the performance of the output link with TFBA, an analytical model is developed and the burst-blocking probability is estimated as a measure of the output link performance.

The parameters used in the analysis are described in Table 3.

Consider N burst flows arriving at an output link; they can be assigned to one of two groups: the group of under-rate flows or the group of over-rate flows. As an example of three connections in Section 3.6, Flow 1 and Flow 2 are assigned to the group of under-rate flows because their loads are under their allocated bandwidth; meanwhile, the load of Flow 3 exceeds its allocated bandwidth, the under-rate portion is included in the group of under-rate flows, and the over-rate portion is transferred to the group of over-rate flows (Figure 12).

With the arrival rate of λ_k and the allocated bandwidth AB_k, $k = 1, 2, \ldots, N$. The probability that flow k belongs to the group of under-rate flows (L_k^{U}) or the group of over-rate flows (L_k^{O}) is determined by the following equations.

TABLE 3 Parameters used in analysis.

Parameter	Description
k	Flow id
N	Total number of flows in the system
μ	Service rate
W	No. of wavelengths in output link
λ_i	Arrival rate of flow i
AB_k	Fairly allocated bandwidth for flow k
λ^{U}	Arrival rate of under-rate bursts
λ^{O}	Arrival rate of over-rate bursts
L_k^{U}	Burst-loss probability of under-rate bursts in flow k
L_k^{O}	Burst-loss probability of over-rate bursts in flow k

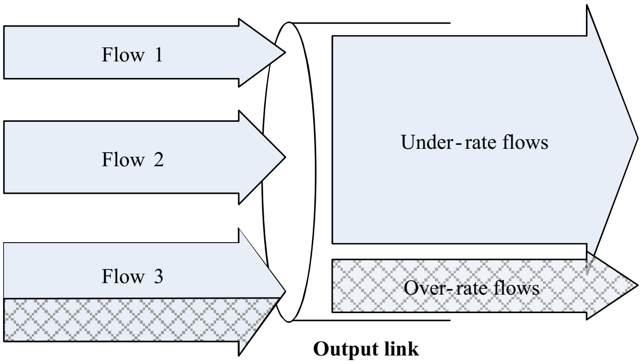

FIGURE 12 Example of three incoming flows that are assigned to the group of under-rate flows or the group of over-rate flows

$$L_k^{\mathrm{O}} = \begin{cases} 0 & \text{if } \lambda_k \le \mathrm{AB}_k \\ \frac{\lambda_k - \mathrm{TB}_k}{\mathrm{TB}_k} & \text{if } \lambda_k > \mathrm{AB}_k, \end{cases} \tag{8}$$

$$L_k^{\mathrm{U}} = 1 - L_k^{\mathrm{O}}. \tag{9}$$

Therefore, the arrival rates of the group of under-rate flows (λ^{U}) and the group of over-rate flows (λ^{O}) are

$$\lambda^{\mathrm{U}} = \sum_{k=1}^{n} (\lambda_k \times L_k^{\mathrm{U}}), \tag{10}$$

$$\lambda^{\mathrm{O}} = \sum_{k=1}^{n} (\lambda_k \times L_k^{\mathrm{O}}) \tag{11}$$

where $1/\mu$ is the average length of arrival bursts (for both cases of under-rate and over-rate flow).

In order to estimate the blocking probability, we used a Markov M/M/c/c queuing model [9,10]. At an output link with W wavelengths, it is assumed that the over-rate and under-rate burst arrivals are Poisson processes with mean rates λ^{O} and λ^{U}, respectively. The state-transition diagram of the multidimensional model is shown in Figure 13.

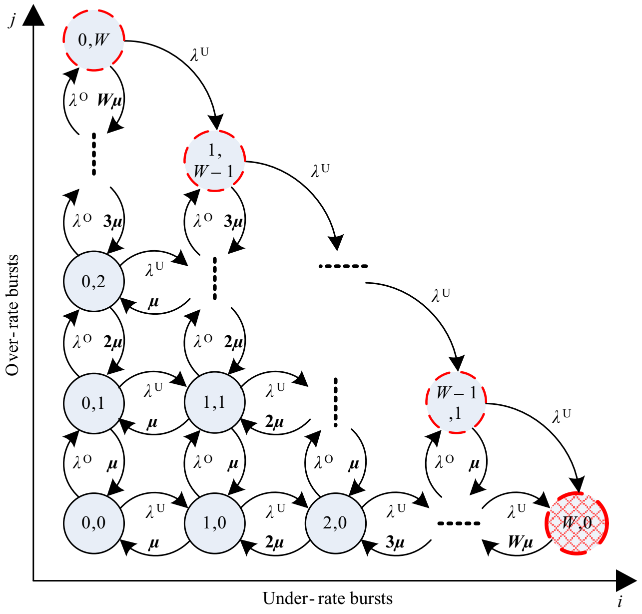

FIGURE 13 State-transition diagram of multidimensional model

Let $\pi_{i,j}$ denote the joint probability that i under-rate bursts and j over-rate bursts exist in the steady state. In Figure 13, each state is identified by notation (i, j), where $0 \le i \le W$, $0 \le j \le W$, $0 \le \ (i + j) \le W$. According to the state-transition diagram in Figure 13, we get a system of steady-state equations

$$(\lambda^{\mathrm{U}} + \lambda^{\mathrm{O}} + (i+j)\mu)\pi_{i,j} = \lambda^{\mathrm{U}}\pi_{i-1,j} + \lambda^{\mathrm{O}}\pi_{i,j-1} + (i+1)\mu\pi_{i+1,j} + (j+1)\mu\pi_{i,j+1} \tag{12}$$

for $0 \le i < W$, $0 \le j < W$, $0 \le i + j < W$,

$$(\lambda^{\mathrm{U}} + W\mu)\pi_{0,W} = \lambda^{\mathrm{O}}\pi_{0,W-1}, \tag{13}$$

$$(\lambda^{\mathrm{U}} + (j+i)\mu)\pi_{i,j} = \lambda^{\mathrm{U}}\pi_{i-1,j+1} + \lambda^{\mathrm{U}}\pi_{i-1,j} + \lambda^{\mathrm{O}}\pi_{i,j-1} \tag{14}$$

for $0 < i < W$, $0 < j \le W - i$, $i + j = W$ and

$$W\mu\pi_{W,0} = \lambda^{\mathrm{U}}\pi_{W-1,1} + \lambda^{\mathrm{U}}\pi_{W-1,0}. \tag{15}$$

The probability is $\pi_{\mathrm{i,j}} = 0$, for $i, j < 0$.

Denoting the individual under-rate and over-rate traffic load by $\gamma^{\mathrm{O}} = \lambda^{\mathrm{O}}/\mu$ and $\gamma^{\mathrm{U}} = \lambda^{\mathrm{U}}/\mu$, it can be shown that the product form solution $\pi_{i,j}$, from (12), (13), and (14) is:

$$\pi_{i,j} = \sum_{i=1}^{W} \frac{(\gamma^{\mathrm{U}})^i}{i!} \frac{(\gamma^{\mathrm{O}})^{W-i}}{(W-i)!} \pi_{0,0}. \tag{16}$$

From the normalization condition, $\pi_{0,0}$ is determined as:

$$\pi_{0,0} = \left[\sum_{i=1}^{W} \sum_{j=1}^{W-i} \frac{(\gamma^{\mathrm{U}})^i}{i!} \frac{(\gamma^{\mathrm{O}})^j}{j!} \right]^{-1}. \tag{17}$$

According to the transition rules defined in Figure 13, blocking occurs on one of the states of $(i, W - i)$, $0 \le i \le W$. The blocking cases are as follows:

- An under-rate burst arrives and no wavelength is free; a wavelength that was allocated to any over-rate burst is released to be allocated to the under-rate burst. The over-rate burst is dropped and system is transferred to the state of $(i + 1, W - i - 1)$;
- An over-rate burst arrives and no wavelength is free; it is dropped; and
- In the state of $(W, 0)$, an under-rate or over-rate burst arrives and no wavelength is free; it is dropped.

Finally, the average blocking probabilities of under-rate and over-rate bursts are

$$P^{\mathrm{O}} = \sum_{i=0}^{W} \pi_{i,W-i}, \tag{18}$$

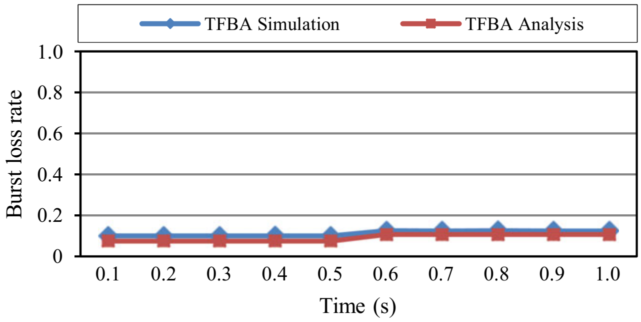

FIGURE 14 Comparison of the burst-loss probabilities for the analytical model and the simulation results

$$P^{\mathrm{U}} = \pi_{W,0}. \tag{19}$$

and the average blocking probability of the output link is

$$P = \frac{(P^{\mathrm{U}}\lambda^{\mathrm{U}} + P^{\mathrm{O}}\lambda^{\mathrm{O}})}{(\lambda^{\mathrm{U}} + \lambda^{\mathrm{O}})}. \tag{20}$$

4.2 | Numerical results

By using Mathematica, the average blocking probability of (20) is plotted with the parameters, as mentioned in Section 3.6. As analyzed in Section 3.2, the usable bandwidth of a link in OBS networks is only about 0.7; therefore, the link bandwidth in the analytical mode is reduced to 0.7. The curve of the burst lost probability of the analytical model in Figure 14 is similar to that of the simulation results. This confirms the correctness of the proposed TFBA model.

5 | CONCLUSION

By mapping the max-min fairness in IP networks to the ratio of the actual throughput to the allocated bandwidth, and shifting the actual throughput closer to the allocated bandwidth, our proposed TFBA model has been proven to have an efficient bandwidth utilization, namely lower byte loss rates compared with previous methods. The paper also proposes a fairness measure that is based on TFI to quantify the fairness of bandwidth allocations for flows. This approach can be applied to Poisson and non-Poisson flows. The simulation results have also shown that our proposal has the highest TFI. The analyses of the performance of the output link with TFBA showed the accuracy of the proposed model. The combination of various fairness criteria may be an extension that needs to be studied more in the future in order to improve the fairness control in OBS networks.

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