Modeling of a controlled retransmission scheme for loss recovery in optical burst switching networks

Phuoc Dat Duong¹ | Hong Quoc Nguyen² | Thanh Chuong Dang³ | Viet Minh Nhat Vo⁴

¹School of Hospitality and Tourism, Hue University, Hue City, Vietnam
²University of Education, Hue University, Hue City, Vietnam
³University of Sciences, Hue University, Hue City, Vietnam
⁴Department of Academic and Students' Affairs, Hue University, Hue City, Vietnam

Abstract
Retransmission in optical burst switching networks is a solution to recover data loss by retransmitting the dropped burst. The ingress node temporarily stores a copy of the complete burst and sends it each time it receives a retransmission request from the core node. Some retransmission schemes have been suggested, but uncontrolled retransmission often increases the network load, consumes more bandwidth, and consequently, increases the probability of contention. Controlled retransmission is therefore essential. This paper proposes a new controlled retransmission scheme for loss recovery, where the available bandwidth of wavelength channels and the burst lifetime are referred to as network conditions to determine whether to transmit a dropped burst. A retrial queue-based analysis model is also constructed to validate the proposed retransmission scheme. The simulation and analysis results show that the controlled retransmission scheme is more efficient than the previously suggested schemes regarding byte loss probability, successful retransmission rate, and network throughput.

KEYWORDS
byte loss probability, controlled retransmission, mathematical analysis, network throughput, optical burst switching (OBS) network, successful retransmission rate

1 | INTRODUCTION

The rapid increase in data exchanged over the Internet has significantly pressurized the existing transmission infrastructure that is mainly based on copper cable. Various transmission technologies have been proposed, such as optical transmission and 5G wireless transmission [1] in which the optical transmission technology is the most suitable alternative because of its high transmission speed, low signal attenuation, high security, and great bandwidth potential [2].

To date, three optical switching models have been proposed, namely, optical channel switching (OCS), optical packet switching (OPS), and optical burst switching (OBS), in which the latest is the most feasible packet switching technique for future optical internet because of its ability to exploit bandwidth more efficiently than OCS, while inheriting the characteristics of flexible...
packet switching of OPS that does not require immature devices, such as optical buffers or switches at nanosecond speeds [3,4]. In the OBS network, data (internetworking protocol packets or ethernet frames) from access networks are aggregated into larger data carriers, called bursts. A burst control packet (BCP) is created and sent ahead into the core network to reserve resources at the intermediate nodes. After an offset time, a completed burst follows the BCP and cuts through at these intermediate nodes. The offset time must be calculated so that resources are reserved before burst arrival. When the burst reaches its egress node, a reverse process is executed, where the original data are restored and forwarded to access networks.

Burst contention is a well-known challenging problem in OBS networks. Contention occurs when two arrival bursts simultaneously contend for the same wavelength at the same output port. Burst contention can be solved using one of the following approaches: wavelength conversion, in which the contending burst is diverted to another available wavelength; fiber delay link-based buffering, which delays the arrival time of the contending burst to the output port; and deflection routing, which routes the contending burst to another available output port [5]. Retransmission is not a contention resolution, but a data loss recovery resolution after contention. It retransmits the dropped bursts at core nodes from the ingress nodes. This paper mainly focuses on burst retransmission.

Several published burst retransmission models can be divided into two categories: active and passive. With active retransmission, the ingress node retransmits the burst copy periodically after each preset interval, whereas the passive retransmission is only triggered whenever the ingress node receives a request from a core node. Retransmission efficiency depends on factors, such as the network load, the available bandwidth of wavelength channels, and the path length.

Active retransmission [6,7] is suitable at low network loads because they always send the required number of bursts to the core network at least twice, whereas passive retransmission [8,9] can be operated at higher network loads, but network conditions such as the contention probability [8], transmission control protocol (TCP) throughput [9], burst loss ratio, and link use [10] must be considered further. Therefore, if retransmission is uncontrolled, multiple burst contentions occur and become worse when the network load increases. This paper proposes a new controlled retransmission scheme where the network load and burst lifetime, regarding hop counts, are the conditions for controlling retransmission.

The main contributions of this paper include the following. First, a new controlled retransmission scheme for loss recovery is proposed where retransmission is only triggered when the network load is less than a threshold and the lifetime of the retransmitted burst is less than a threshold for a new end-to-end transmission. Second, a retrial queue-based analytical model is constructed where the retransmission at core nodes is considered to pass a dropped burst into an orbit where the burst then attempts to reschedule. The third contribution is the comparisons and analysis of retransmission schemes based on simulation.

The remaining part of the paper is organized as follows. Section 2 presents related works, in which previous retransmission models were analyzed and evaluated. Section 3 proposes a new controlled retransmission scheme, including the operation principle and algorithms. The proposed retransmission model is analyzed mathematically in Section 4. Simulation results and analysis are shown in Section 5, and the conclusion is presented in Section 6.

2 | RELATED WORKS

Retransmission in OBS networks resends a burst copy from an ingress node when the original burst is dropped at any related core node because of contention. Figure 1 shows that a BCP is sent at time \( t_0 \) and, after an offset time, the corresponding burst is sent at time \( t_1 \). Because the burst cannot be scheduled at a core node (Node 3), at time \( t_2 \), the burst is dropped, and an automatic retransmission request (ARQ) message is sent to the ingress node. Based on receiving the ARQ message at

![FIGURE 1](https://example.com/figure1.png) The passive retransmission mechanism in optical burst switching (OBS) networks
time $t_2$, the ingress node resends a new BCP at time $t_3$ (the processing time is assumed negligible) and, after an offset time, the burst copy is followed at time $t_4$. Thus, the ingress node must have a buffer to temporarily store the burst copy. Assuming that the second transmission is successful, the burst reaches the egress node at time $t_5$. A message (ACK) that requires deleting the burst copy is sent back to the ingress node.

Two approaches exist for burst retransmission models, active and passive. For the active approach, Huang and others [6] proposed the burst clone schema (BCS), in which the main idea is to duplicate the burst and send the duplicated burst simultaneously with the original burst. If a contention drops the original burst, the duplicated burst could still reach the destination. At the egress node, the first burst will be chosen to restore the data carried inside. BCS reduces the burst loss probability but is only suitable in low network loads. When the network load increases, doubling the same burst also increases the contention probability quickly. Another published dual-burst sending model is the duplicate burst transmission mechanism [7], in which the original and duplicated bursts are assigned the same ID. Their BCPs are sent simultaneously, but the offset time of the original burst is increased to be larger than that of the duplicated burst. The core nodes remember the ID of the bursts that passed through them to determine whether the duplicated burst is dropped. If the duplicated burst is dropped, the core node duplicates the original burst and transmits it after an increased offset time.

For the passive approach, a core node sends an ARQ message to the related ingress node when a burst is dropped. On receiving this message, the ingress node resends the burst copy. A prime example of the passive approach is the framework for retransmission proposed in Venkatesh and others [8], in which two parameters $\alpha_1$ and $\alpha_2$ are introduced, indicating the probability with which a lost burst is retransmitted (the retransmission probability). $\alpha_1$ controls the retransmission probability for the first retransmissions and $\alpha_2$ for all subsequent retransmissions. Both parameters are adjusted according to the network load’s requirement. By adjusting the parameters $\alpha_1$ and $\alpha_2$, the load caused by the retransmitted bursts can be controlled while increasing the end-to-end recovery.

Subsequent studies mainly combine retransmission with other contention resolution techniques. Specifically, Zhang and others [9] examined the retransmission problem in the relationship between the OBS and TCP layers. Because of the bufferless nature of OBS networks, random burst losses can occur even at low network loads, and the TCP layer will mistakenly interpret burst loss as contention at the OBS layer repeatedly. These authors proposed a controlled retransmission model at the OBS layer to reduce false contention detection. An analytical model was also developed for evaluating the burst loss probability in the OBS network. The model uses the retransmission scheme and analyzes TCP throughput when the OBS layer implements the retransmission scheme.

Hosny and others [10] proposed a model called the adaptive hybrid deflection and retransmission approach that combines deflection and retransmission techniques dynamically based on network conditions of the burst loss ratio and link use. Simulation results show that the approach outperforms static approaches for burst loss ratio and goodput.

Thachayani and Nakkeeran [11] proposed a similar combination model, the combined probabilistic deflection and retransmission (CPDR) model to achieve loss minimization, overcoming the adverse effects of pure deflection and retransmission. Simulation results show that CPDR can provide a 25% to 60% reduction in burst loss for other similar protocols at higher load conditions. An analytical model was also developed to estimate the burst loss probability and the predicted results correlate well with simulation-based results.

Riaidi and Maach [12] proposed a hybrid model, implemented on a star OBS network to control the extra load because of the burst retransmission and cloning. In the hybrid model, the advantages of the retransmission mechanism at a low load and the benefits of the cloning mechanism at a high load are combined. Based on the current state of arriving bursts and the retransmission buffer, the ingress node must decide whether a recovery mechanism processes a burst or not; if yes, the ingress node must also decide which mechanism is used.

Hou and others [13] proposed a controlled retransmission scheme for prioritized burst segmentation to support the quality of service in OBS networks. In this scheme, a different value of retransmission probability is set for each contention based on the link load. A retransmission analytical model for a burst segmentation contention resolution scheme was also proposed. Simulation-based evaluations of network performance for the path blocking and byte loss probabilities for high- and low-priority bursts have shown that the retransmission scheme can be used to provide reasonable retransmissions in prioritized burst segmentation to gain better performance for each blocking.

With a queue theory-based approach, Vanitha and Sabrigiriraj [14] modeled retransmission as a single-server retransmission-queuing system, including impatient bursts, link failure, and maintenance activity. Specifically, they propose a hybrid scheme that combines buffering and retransmission. Retransmissions with controllable and uncontrollable arrival were analyzed. Numerical results show the effect of impatience and link failure on the number of processed bursts in the network. An extension of this model was also considered and
evaluated to examine the effect of maintenance activity and buffer search of the server on the bursts being processed in the network [15].

In short, controlled retransmission is needed to avoid unnecessary retransmissions, especially in cases of a high network load and low successful retransmission probability. Uncontrolled retransmission often increases the network load, increasing the contention probability, requiring retransmission conditions. This paper proposes a new controlled retransmission scheme based on network load and burst lifetime.

3 | CONTROLLED RETRANSMISSION SCHEME

Considering an OBS network that supports retransmission, the ingress node is responsible for the retransmission of the burst copy whenever it receives a request, whereas the core node sends feedback if a burst is dropped. Specifically, the ingress node keeps a copy of the completed burst in a dedicated buffer until the delivery is successful at the egress node or its lifetime has expired. At the core node, a scheduling algorithm is called whenever a burst arrives. If the scheduling is successful, the burst is sent to the next node and the process is repeated until the burst reaches its egress node. However, if the scheduling fails, the retransmission operation is triggered. The core node checks for network conditions and might request a retransmission from the ingress node. Retransmission from the input node can be performed multiple times, depending on the burst’s lifetime. Figure 2 shows the operations of the controlled retransmission scheme.

An unscheduled burst (ub) is characterized by a quadruple of ub (idub, sub, eub, and Tub). Table 1 defines their meanings. The conditions for retransmitting a burst are that the network load is not too high and the burst lifetime, in terms of hop counts, is sufficient for at least an end-to-end transmission. For the first condition, the normalized network load (NLcur) should be less than or equal to 0.7, as recommended in [16],
For the burst lifetime condition, the value $T_{ub}$ is determined based on the time-to-live ($TTL_{pkt}$) of packets carried in bursts; therefore,

$$T_{ub} + T_a + T_d \leq TTL_{pkt}. \tag{2}$$

The burst lifetime must be greater than the total processing time at the core nodes and end-to-end propagation time to make a meaningful burst transmission (Figure 3). If the lifetime is less than this sum, the packets carried will expire before the burst reaches its egress node.

In OBS networks supporting retransmission, the burst lifetime also depends on the probable number of transmissions. Given that $k$ is the allowed number of transmissions, $T_{ub}$ is calculated as

$$T_{ub} = k \times (n - 1) \times (T_s + T_p), \tag{3}$$

where $n$ is the total number of hops to go through.

Assuming that the burst is dropped at the core node $m$ ($m \leq n$) and the time to propagate the feedback message to the ingress node is negligible, the remaining burst lifetime is

$$T_{ub} = T_{ub} - m \times (T_s - T_p). \tag{4}$$

This lifetime must be sufficient for an end-to-end transmission

$$T_{ub} \geq (n - 1) \times (T_s - T_p). \tag{5}$$

The core node decides if a feedback message should be sent for retransmission based on the remaining burst lifetime. Therefore, the lifetime must be carried in the BCP and this value is deducted as the BCP goes through each hop. Based on the suggestions in previous works [17,18], the structure of the BCP carrying this information is modified where the LIFETIME is 4 bytes (Figure 4).

From the controlled retransmission model described above, the implemented algorithms at nodes include

- the retransmission controlling (RTC) algorithm, which evaluates the network conditions at core nodes, and
- the passive retransmission (PRT) algorithm, which resends a burst copy when receiving a request at ingress nodes.

In the RTC algorithm, the function BFVF $(ub, W)$ is the scheduling algorithm with void-filling that finds the best-fit void on $W$ channels to schedule the burst $ub$. Schedule $(ub, sc)$ schedules the burst $ub$ on channel $sc$. SendARQ $(id_{ub}, T_{ub})$ sends the message ARQ back to the corresponding ingress node to request a retransmission. Drop $(ub)$ drops the burst $ub$ if network conditions are not met.
The RTC algorithm’s complexity depends mainly on the BFVF function’s complexity. As demonstrated in Nandi and others [19], the BFVF function’s complexity for \( w \) output channels is \( O(w \times \log(\|SB_w\|)) \). Hence, the RTC algorithm also has the same complexity.

At the ingress node, every time an ARQ message is received, the PRT algorithm is called, which simply resends the BCP and the burst copy after an offset time.

\[ P_{rt} = \begin{cases} 1 & \text{if } (T_{ub} > (n-1) \times (T_s + T_p)) \land \left( \frac{\lambda}{\mu \times w} \leq 0.7 \right) \\ 0 & \text{otherwise} \end{cases} \]

(6)

Figure 5 illustrates the retrial queue-based analytical model for the controlled retransmission in OBS networks.

### 4 | MATHEMATICAL ANALYSIS

With the proposed retransmission model, a burst is retransmitted after a period if the scheduling is unsuccessful at a core node. The length of this period depends on how many hops the burst has passed through and the length of the burst’s offset time. If a pair of core-edge nodes is considered as service provider system, where an unscheduled burst arrives at an output port of the core node and requests to be scheduled, the system can provide service if there is an idle wavelength or can decline if all resources are busy. In the second case, the burst is dropped, and its copy will return to this core node after a period to try requesting service again. Because bursts arriving at the core node can come from different origins (ingress nodes) and have different offset times, the return period to request the service of a burst can be considered a random distribution. With this approach, the retransmission model can be viewed as similar to the retrial queue model [20], in which a dropped burst is placed into orbit and will try to reschedule after a random period. With the controlled retransmission model, a probability value \( P_{rt} \) is added to control retransmission corresponding to different network conditions.

### 4.1 | Assumptions

In the mathematical analysis model, we make some assumptions.

- Original and retransmitted bursts arrive at an output port with an average rate \( \lambda \) and \( \lambda' \), respectively. The average service rate for these bursts is \( \mu \), where \( 1/\mu \) is their average length.
- A retransmitted burst must meet two conditions in 1 and 5; thus, the actual average arrival rate of retransmitted bursts is \( \lambda' \times P_{rt} \).
- A maximum of \( M \) retransmitted bursts arrive simultaneously at the core node. Thus, when no retransmission request arrives at the ingress node, \( M = 0 \), but when there is contention at the core node and a retransmission request is sent back to the ingress node, \( M > 0 \).
- The retransmitted burst’s route is identical to that of the original burst.
- Original and retransmitted bursts arriving at the output port have a Poisson distribution and their lengths have an exponential distribution.

---

**Figure 5** The retrial queue model for controlled retransmission

**Figure 6** Two-dimensional state transition diagram of wavelength resources at an output port
Contestion at the output port is considered to occur randomly at any time $t$.

### 4.2 State transition diagram

Let $N(t)$, $0 \leq N(t) \leq M$, and $S(t)$, $0 \leq S(t) \leq w$ be the number of retransmitted bursts and the number of busy wavelengths at an output port at time $t$, $t \geq 0$, respectively. The state of an output port can, therefore, be represented as a 2-dimensional Markov model (Figure 6), where the state at time $t$, $(N(t) = i, S(t) = j)$, and the transition between the states represents the following:

- An original burst comes in and is served. The system transfers from state $(i, j)$ to $(i, j + 1)$ with rate $\lambda$, where $0 \leq i \leq M$ and $0 \leq j < w$.
- A retransmitted burst comes in and is served. The system transfers from state $(i, j)$ to $(i - 1, j + 1)$ with rate $\lambda' \times P_{rt}$, where $0 \leq i \leq M$ and $0 \leq j \leq w$.
- An original or retransmitted burst is served completely. The system transfers from state $(i, j)$ to $(i, j - 1)$ with rate $\mu$, where $0 \leq i \leq M$ and $0 \leq j \leq w$.
- An original or retransmitted burst comes in and is not served because of running out of resources, and the system falls into a contention. A retransmission process is activated. The system transfers from state $(i, M)$ to $(i + 1, M)$ at rate $\lambda$, where $0 \leq i \leq M$ and $j = w$, but a contention is still logged.
- The state $(M, w)$ indicates a case of $M$ retransmitted bursts that arrive at the output port and $w$ wavelength busy. The system falls into complete blocking.

### 4.3 Pseudo-birth–death process analysis

Let $\pi_{ij}$ be the equilibrium probability of the system at state $(i, j)$. Possible equilibrium equations are as follows:

- With $0 \leq i < M$ and $0 < j < w$,
  \[
  (\lambda + j\mu + i\lambda'P_{rt})\pi_{ij} = \lambda\pi_{i-1,j} + (i + 1)\lambda'P_{rt}\pi_{i+1,j-1} + (j + 1)\mu\pi_{ij+1};
  \]
  with $i = M$ and $0 < j < w$,
  \[
  (\lambda + j\mu + i\lambda'P_{rt})\pi_{ij} = \lambda\pi_{i-1,j} + (j + 1)\mu\pi_{ij+1};
  \]
- With $0 \leq i < M$ and $j = 0$,
  \[
  (\lambda + i\lambda'P_{rt})\pi_{ij} = \mu\pi_{ij+1};
  \]

with $0 < i < M$ and $j = w$ (contention state),

\[
(\lambda + j\mu)\pi_{ij} = \lambda\pi_{i-1,j} + (i + 1)\lambda'P_{rt}\pi_{i+1,j-1} + \lambda\pi_{ij-1};
\]

with $i = 0$ and $j = w$ (contention state),

\[
(\lambda + j\mu)\pi_{ij} = \lambda\pi_{i,j-1} + \lambda'P_{rt}\pi_{i,j-1};
\]

and with $i = M$ and $j = w$ (contention state),

\[
j\mu\pi_{ij} = \lambda\pi_{i-1,j} + \lambda\pi_{ij-1}.
\]

As suggested in Triay et al. [17], we can use the pseudo-birth–death process to illustrate the state transition through matrices $A_m$, $B_m$, and $C_m$ ($m = 1, 2, ..., M$) of a matrix $Q$.

- Let $A_m (n, k)$ denote the transition rate from state $(m, n)$ to $(m, k)$ (where $0 \leq n, k \leq w$, $0 \leq m \leq M$), which is caused by either the departure of a burst after service or the arrival of a burst. The matrix $A_m$ of $(w + 1) \times (w + 1)$ elements $A_m (n, k)$ is represented as

\[
A_m = \begin{bmatrix}
0 & \lambda & 0 & \cdots & 0 \\
\mu & 0 & \lambda & \cdots & 0 \\
0 & 2\mu & 0 & \cdots & 0 \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
0 & 0 & 0 & \cdots & w\mu
\end{bmatrix}.
\]

Because $m$ is the independent level of $A_m$, we can write $A_m = A$. The nonzero elements of $A_m (n, k)$ are calculated as $A_m (n, n - 1) = n\mu$, $j = \Gamma, w + 1$ and $A_m (n, n + 1) = \lambda$, $n = 0, w$.

- Let $B_m (n, k)$ denote the transition rate from state $(n, k)$ to $(m + 1, n)$ (where $0 \leq n, k \leq w$, $0 \leq m \leq M - 1$), which is caused by joining a burst into orbit. The matrix $B_m$ of $(w + 1) \times (w + 1)$ elements $B_m (n, k)$ is represented as

\[
B_m = \begin{bmatrix}
0 & 0 & \cdots & 0 \\
0 & 0 & \cdots & 0 \\
\vdots & \vdots & \ddots & \vdots \\
0 & 0 & \cdots & \lambda
\end{bmatrix}.
\]

Because $m$ is the independent level of $B_m$, we can write $B_m = B$. The nonzero elements of $B_m$ are calculated as $B_m (w, w) = \lambda$.

- Let $C_m (n, k)$ denote the transition rate from state $(m, n)$ to $(m - 1, k)$ (where $0 \leq n, k \leq w$, $0 \leq m \leq M$),
which is caused by a retransmitted burst is served successfully by a successfully served retransmitted burst. The matrix \( C_m \) of \((w + 1) \times (w + 1)\) elements \( C_m (n,k) \) is represented as

\[
C_m = \begin{bmatrix}
0 & m'p_{rt} & 0 & 0 & \cdots & 0 \\
0 & 0 & m'p_{rt} & 0 & \cdots & 0 \\
0 & 0 & 0 & \ddots & \ddots & \ddots \\
\vdots & \vdots & \ddots & \ddots & \ddots & \ddots \\
0 & 0 & 0 & \cdots & m'p_{rt} & 0 \\
0 & 0 & 0 & \cdots & 0 & 0
\end{bmatrix}.
\] (15)

Because \( m \) is the independent level of \( C_m \), we can write \( C_m = C \). The nonzero elements of \( C_m \) are \( C_m (n,n+1) = m'p_{rt} (0 \leq n \leq w - 1) \).

The matrix \( Q \) is represented as

\[
Q = \begin{bmatrix}
Q_1^{(0)} & Q_0^{(0)} \\
Q_2^{(1)} & Q_1^{(1)} & Q_0^{(1)} \\
& Q_2^{(2)} & Q_1^{(2)} & \cdots \\
& & Q_2^{(M-1)} & Q_1^{(M-1)} & Q_0^{(M-1)} \\
& & & & Q_2^{(M)} & Q_1^{(M)}
\end{bmatrix}.
\] (16)

where

\[
\begin{align*}
Q_1^{(m)} &= B_m (0 \leq m \leq M - 1), \\
Q_2^{(m)} &= C_m (1 \leq m \leq M), \\
Q_1^{(0)} &= -D^A - B, \\
Q_1^{(m)} &= -D^A - B - C_m (1 \leq m \leq M - 1), \\
Q_1^{(M)} &= -D^A - C_M.
\end{align*}
\] (17)

Accordingly, the average number of busy wavelengths and the number of retransmitted bursts in the system is calculated using

\[
E[S] = \sum_{j=0}^{w} j \pi_j^{(S)} = \sum_{j=0}^{w} j \sum_{i=0}^{M} \pi_{ij} \quad \text{and} \quad E[N] = \sum_{i=0}^{M} \pi_i^{(N)}.
\] (19)

The contention probability \( (P_{cont}) \) of the system is

\[
P_{cont} = \pi_{M,w} + \sum_{j=0}^{w-1} (1 - P_{rt}) P_{rt} [S = j]
\] (20)

where an arrival burst is considered contended if there are \( j \) busy wavelengths, and the retransmission is not allowed with the probability \( 1 - P_{rt} \).

5 \quad RESULTS AND DISCUSSION

The simulation was conducted on a 2.4-GHz Intel Core 2 CPU, 2GB RAM PC. The simulator is NS2 with obs0.9a package [21] and the simulation network is an NSFNET14, in which the length of links is converted to the corresponding propagation delay (ms). All links have a bandwidth of 1 Gb/s. Each link composes eight data channels and two control channels. The traffic of 512-byte packets arriving at ingress nodes has a Poisson distribution. The packets are aggregated into bursts by a hybrid assembly technique with a length threshold of 150 KB and a timer of 100 \( \mu \)s. Simulation is done in 20 s.

Simulation objectives include the following:

a. Compare the byte loss probability (BLP) between the models of non-retransmission (non-retrans), active retransmission (act_retrans) [7], passive retransmission (pas_retrans) [9], and controlled retransmission (ctrl_retrans). BLP is defined as the sum of dropped burst sizes divided by the sum of burst sizes.

\[
\text{BLP} = \frac{\sum_{i=1}^{\text{num of dropped bursts}} \text{size of dropped burst}_i}{\sum_{j=1}^{\text{total of bursts}} \text{size of burst}_j}.
\] (21)

b. Compare the successful retransmission rate (SRR) between the above retransmission models. SRR is defined as the number of successfully retransmitted bursts divided by the total of retransmitted bursts.

\[
\text{SRR} = \frac{\text{number of successful retransmitted bursts}}{\text{total of retransmitted bursts}}.
\] (22)

4.4 \quad Performance metrics

Let \( N \) and \( S \) be generic random variables for \( N(i) \) and \( S (i) \), respectively, in equilibrium. Let \( \pi_j^{(S)} = (0,1,..,w) \) be the probability that there are \( j \) busy wavelengths; therefore, \( P_{rt}[S = j] \), and let \( \pi_i^{(N)} = (0,1,..,M) \) be the probability that \( i \) burst retransmit; therefore, \( P_{rt}[N = i] \), we obtain

\[
\pi_j^{(S)} = \sum_{i=0}^{M} \pi_{ij} \quad \text{and} \quad \pi_i^{(N)} = \sum_{j=0}^{M} \pi_{ij},
\] (18)

where \( \pi_{ij} = P_{rt}[N = i, S = j] \).
c. Compare the normalized delay (ND) between the above retransmission models. ND is defined as the sum of the products of the burst sizes and their propagation delay divided by the sum of burst sizes [20].

\[
ND = \frac{\sum_{i=1}^{\text{num of received bursts}} (\text{size of burst}_i \times \text{delay of burst}_i)}{\sum_{j=1}^{\text{num of received bursts}} \text{size of burst}_j}.
\]

\[\text{(23)}\]

d. Compare the throughput from the TCP layer to the OBS layer of the above retransmission models.

Two types of arrival packet flows exist at the ingress nodes, TCP and user datagram protocol (UDP). In Scenario 1, four UDP flows and one TCP flow are provided at the ingress nodes. The TCP flow is added to take advantage of the TCP window control mechanism to create variation in arrival packet density. The first three objectives (from a to c) are considered in this scenario. With Scenario 2, only the TCP flows arrive at the ingress nodes. The fourth objective is considered in this scenario to evaluate the effect of retransmission on the load entering the OBS layer from the TCP layer.

5.1 Comparing BLP

Figure 7 shows a comparison of the models of non-, active, passive, and controlled retransmissions, in which the BLP of the controlled retransmission is always the lowest with all loads. The controlled retransmission has a lower BLP than non-retransmission. It also achieves a lower BLP level than that of the models of active and passive retransmissions by avoiding unnecessary 2 and nonperforming retransmissions if the network load is high. Based on the simulation results, the BLP of the controlled retransmission achieved approximately 14.47% and 0.24% lower than that of the active and passive retransmission models, respectively.

When loads are greater than 0.7, data loss caused by controlled retransmission occurs because of the natural characteristic of scheduling on wavelength channels in OBS networks where there are always voids between scheduled bursts. Therefore, although the total load that entered the OBS network is greater than 0.7, the instantaneous load at the arrival time of a burst is still less than 0.7. A retransmission request is still triggered, and retransmitted burst loss still occurs.

Figure 8 shows a comparison of the BLP between mathematical analysis and simulation results, where simulation and analysis are approximate, and the simulation curve is slightly higher than the analytical curve. This is reasonable because analysis results are considered under ideal conditions, whereas simulation results are subject to certain implementation errors. The approximation of the simulation and analysis curves validates the correctness of the implemented simulation.

**FIGURE 8** The byte loss probability (BLP) in simulation and analysis

**FIGURE 9** A comparison of successful retransmission rate (SRR) of the active, passive, and controlled retransmission models
5.2 | Comparing the successful retransmission rate

The controlled retransmission reduces the BLP because of its SRR, compared with that of other models. Figure 9 shows that the SRR of the controlled retransmission gradually increases from 1.79% at normalized load 0.5% to 31.63% at normalized load 0.9, higher than that of the passive retransmission. Compared with the active retransmission, the controlled retransmission achieves a much higher SRR. When the load is greater than 0.7, there is a slight decrease in SRR for all retransmission models because when the load is high, the retransmission causes additional contention, and SRR decreases.

5.3 | Comparing the ND

Retransmission increases the end-to-end delay of bursts. Figure 10 shows that the ND of the retransmission models is large and increases with load. Specifically, the ND of the controlled retransmission reached a low value and decreased from 0.44% at normalized load 0.3% to 40.47% at normalized load 0.9 compared with that of the passive retransmission. However, when compared with the active retransmission, the controlled retransmission has a high ND value because, in the active retransmission, the burst copy is retransmitted every fixed interval; in our simulation, it is one third of the offset time of each burst. In the passive and controlled retransmissions, the time to retransmit a dropped burst is not constant and is greater than one third of the offset time. SRR of the active retransmission is also not high (Figure 9), so the low ND of the active retransmission is also understandable.

5.4 | Comparing the throughput from the TCP layer to the OBS layer

Retransmission significantly influences the variation of throughput from the upper layer (TCP layer) to the OBS layer. Specifically, if the retransmission of a burst at the OBS layer significantly increases the delay of the packets carried within the burst (exceeding the round-trip time, RTT), the TCP layer assumes that contention has occurred, and the TCP window will be adjusted downward. Therefore, it reduces the throughput to the OBS layer and the efficiency of bandwidth exploitation at this layer. In other words, another criterion for evaluating the efficiency of retransmission models is to maximize the throughput from the TCP layer.

Figure 11 shows that the controlled retransmission has the largest throughput; therefore, the model performed timely retransmissions of dropped bursts, avoiding false contention detection at the TCP layer. However, significant fluctuations exist in the throughput to the ingress nodes because of unavoidable contentions and the TCP window reduces the provision of traffic. When the load is greater than 0.7, there is a gradual decrease in the throughput. However, when compared with the non- and passive retransmissions, the controlled retransmission consistently achieves the highest throughput level, affirming the advantage of the controlled retransmission.

6 | CONCLUSIONS

Retransmission is an effective solution for reducing data loss in OBS networks, where contention is unavoidable at any given load. However, uncontrolled retransmission will exacerbate contention in the core network. This study proposes a controlled retransmission model where a dropped burst is retransmitted when its lifetime is greater than the required end-to-end transmission time and the network load of each output link is smaller than 0.7. However, because the void between scheduled bursts exists in the output links, the load measured at the time of an arriving burst could be less than 0.7, although the total load across the link is greater than 0.7, explaining...
why retransmission can still occur when the network load of each link is greater than 0.7. An analytical model is also constructed to validate the correctness of the proposed controlled retransmission model. The simulation results and analysis have shown that controlled retransmission is effective for reducing BLP and ND and increasing the successful burst retransmission rate and throughput delivered to the core network. However, the factors influencing the retransmission decision are not only the burst lifetime and load but also the contention location, path length, and contention rate at other nodes in the network. The development direction of this research is to further examine the above conditions in the controlled retransmission model and combine it with other recovery models, such as cloning, double transmission, and deflection.

ACKNOWLEDGEMENT
This work was supported by Hue University under the Core Research Program, Grant No. NCM.DHH. 2019.05.

AUTHOR CONTRIBUTION
Phuoc Dat Duong and Hong Quoc Nguyen conceived of the presented idea. Phuoc Dat Duong, Viet Minh Nhat Vo, and Hong Quoc Nguyen developed the theory and performed the simulation. Viet Minh Nhat Vo and Thanh Chuong Dang verified the analytical methods. All authors discussed the results and contributed to the final manuscript. Phuoc Dat Duong and Hong Quoc Nguyen wrote the manuscript with support from Viet Minh Nhat Vo. All authors contributed to the final version of the manuscript.

ORCID
Phuoc Dat Duong https://orcid.org/0000-0003-3117-9747
Hong Quoc Nguyen https://orcid.org/0000-0001-7635-126X
Thanh Chuong Dang https://orcid.org/0000-0002-2102-965X
Viet Minh Nhat Vo https://orcid.org/0000-0002-0686-5529

REFERENCES


AUTHOR BIOGRAPHIES

**Phuoc Dat Duong** received his MSc degree in computer science in 2013 from Hue University, Vietnam. He currently works as an officer at Hue University, Vietnam. His research interests include optical packet/burst-based switching networks, optical burst grooming, quality of service, and traffic engineering.

**Hong Quoc Nguyen** received his PhD degree in computer science in 2018 from the Faculty of Sciences, Hue University, Vietnam. He currently works as a lecturer at the University of Education, Hue University, Vietnam. His research interests are all-optical networks with an emphasis on packet/burst-based switching, scheduling, and quality of service.

**Thanh Chuong Dang** received his PhD degree in mathematical foundation for computers and computing systems in 2014 from the Institute of Information Technology, Vietnam Academy of Science and Technology, Vietnam. He currently works as a lecturer with University of Sciences, Hue University, Vietnam. His research interests are all-optical networks with an emphasis on packet/burst-based switching, contention resolution, quality of service, queuing theory, and retrial queue.

**Viet Minh Nhat Vo** received his PhD degree in cognitive informatics in 2007 from the University of Quebec in Montreal, Canada. He is currently an associate professor with Hue University, Vietnam. His research interests include optical packet/burst-based switching networks, mobile RFID/sensor systems, quality of service, optimization, and traffic engineering.