Impairment-aware QoS provisioning in dual-header OBS networks

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Received December 7, 2010; accepted January 18, 2011; posted online May 18, 2011

Signal degradation due to physical impairments may result in unacceptable bit-error rates of received signals at the destination. Based on earlier work, we study the impairment-aware quality of service (QoS) provisioning problem in dual-header optical burst switching (OBS) networks that employ two control packets for each data burst. At an OBS node, the proposed algorithm schedule bursts for transmission by searching for available resources using admission control and preemption. The algorithm also verifies signal quality. Simulation results show that this algorithm is effective in providing QoS support in OBS networks while considering physical impairment effects.

OCIS codes: 060.1155, 060.4251, 060.4510.
doi: 10.3788/COL201109.070602.

In optical burst switching (OBS) networks, a burst control packet (CP) is sent on a control channel ahead of the data burst to reserve resources and configure switches. This type of network is called single-header OBS networks. Burst scheduling algorithms must strike a balance between blocking probability performance and scheduling complexity.

A signaling architecture called dual-header OBS (DOBS) has been proposed to reduce the complexity of scheduling algorithms[1]. Two CPs, CP_1 and CP_2, are used for each burst in DOBS networks. The packets decouple the resource request from the resource reservation. However, CP_1 may be forwarded to the downstream node without waiting for the burst scheduling result. Therefore, a burst may be successfully scheduled at a downstream node while it is blocked at an upstream node. This incurs the so-called phantom burst resource waste.

Many previous studies on all-optical networks have assumed an ideal physical optical network. However, signal quality is subject to various physical impairments introduced by network components during transmission[2−5]. Signal quality degradation accumulated through the network may result in unacceptable bit-error rate (BER) at the destination.

At the physical layer, physical impairment effects on OBS networks have been investigated[6]. Examples of such impairments are noise and crosstalk. An analytical model has been established to analyze the burst blocking probability in OBS networks with no wavelength conversion[7]; the model focuses on polarization mode dispersion (PMD) and amplifier related noise. Routing optical signals of various types in an OBS network while maintaining optical signal quality is a common problem, and this has been addressed in the context of just-in-time (JIT) signaling protocol[8]. The use of impairment-aware algorithms that provide manycasting service in OBS has also been proposed[9,10].

We have done research on the effects of physical impairment on scheduling algorithms under the just-enough-time (JET) signaling protocol and DOBS networks in our previous work[11,12]. In this letter, we tackle the problem of quality of service (QoS) provisioning in DOBS networks, while still taking physical impairment effects into consideration.

Similar to previous work[7,13,14], we consider PMD and amplified spontaneous emission (ASE). The PMD constraint can be expressed as[13,14]

$$B \times \sqrt{\sum_{k=1}^{H} D_{\mathrm{PMD}}^2(k) \times L(k)} \leqslant \delta, \tag{1}$$

where B is the data rate, $D_{\mathrm{PMD}}(k)$ is the fiber PMD parameter in the kth hop of the signal path, H is the total number of hops, $L(k)$ is the fiber length of the kth hop, and δ is the user requirement parameter, which indicates the tolerable limit of the fractional pulse broadening.

The noise figure (NF) of an amplifier can be defined as

$$\mathrm{NF} = \frac{1}{G}[1 + 2n_{\mathrm{sp}}(G-1)], \tag{2}$$

or

$$\mathrm{NF} \approx 2n_{\mathrm{sp}}, \tag{3}$$

for $G \gg 1$, where n_{sp} is the spontaneous emission factor, and G is the total amplifier gain.

The NF of a signal path consisting of M consecutive amplifiers can be calculated as

$$\mathrm{NF_p} = \mathrm{NF}_1 + \frac{\mathrm{NF}_2 - 1}{G_1} + \frac{\mathrm{NF}_3 - 1}{G_1 \cdot G_2} + \cdots + \frac{\mathrm{NF}_M - 1}{G_1 G_2 \cdots G_{M-1}}, \tag{4}$$

where $\mathrm{NF}_i (1 \leqslant i \leqslant M)$ and $G_i (1 \leqslant i \leqslant M, G_i \gg 1)$ are the NF and amplifier gain of the ith amplifier, respectively[6,15].

BER can be directly correlated to optical signal-to-noise ratio (OSNR) using

$$\mathrm{BER(OSNR)} = \frac{1}{\sqrt{2\pi}} \int_{\mathrm{OSNR}}^{\infty} \exp\Big(-\frac{t^2}{2}\Big) \mathrm{d}t. \tag{5}$$

Lower OSNR means higher BER and, hence, worse signal quality. We can calculate the NF of a signal path using Eq. (4), after which a decision can be made as to whether or not the noise level is qualified by comparing it with a pre-specified noise threshold.

We assumed that DOBS networks provided a two-class service differentiation. High priority bursts should experience a lower blocking probability than low priority bursts. A preemptive approach was adapted to service the differentiation problem in the DOBS networks. The proposed impairment-aware QoS provisioning algorithm consists of three parts: (1) offline primary route computation, (2) offline deflection route computation, and (3) online physical impairment-aware QoS provisioning.

A burst may be associated with a PMD path-constrained parameter δ as shown in Eq. (1). An ingress node can also determine the minimum OSNR requirement of a signal ($\mathrm{OSNR}_{\min}$) based on the client BER requirement. OSNR of the burst-carrying signal should not fall below this value during transmission of the client bursts; this can be expressed as

$$\mathrm{OSNR} \geqslant \mathrm{OSNR}_{\min}. \qquad (6)$$

The network topology is generally modeled as a directed graph $G = (V, E)$, where V is the set of nodes, and E is the set of links. The cost of a link was assigned a value of $D^2_{\mathrm{PMD}}(e)L(e)$, where $D^{(e)}_{\mathrm{PMD}}$ and $L(e)$ represented the link PMD parameter and length, respectively.

Definition 1: path-degree of a link $e \in E$, deg(e), is the number of primary paths that traverse link e.

The path-degree of a link was taken into account when we computed the deflection route for a burst destined to node d. In this letter, we created an auxiliary graph G^* given an incoming link e to node v, as illustrated in Table 1.

Node v performs admission control upon the arrival of the first data burst CP. If the burst is admitted, node v forwards the packet to the downstream node. At the functional offset time before the arrival of the data burst, node v selects the outgoing wavelength for the incoming burst and transmits the second CP to the downstream node.

1) Admission control: assuming that the number of wavelengths on each link is W, time is divided into time slots, each of which has the same span $\mathit{\Delta}$. A time slot i corresponds to the time interval between $(i-1)\mathit{\Delta}$ and $i\mathit{\Delta}$. We maintain three lists for time slot i: (1) start which lists the start time of bursts; (2) finish with bursts end time; (3) full list where bursts use the full time slot. The numbers of bursts in these three lists are assumed to be N_i^{s}, N_i^{e}, and N_i^{f}, respectively. Given that N_i represents the total number of bursts placed in a time slot i, we also maintain an attribute associated with this time slot, $N_i^* \leqslant N_i$. All time slots should satisfy

$$N_k^* \leqslant W, \quad \forall k \in i \cdots j \qquad (7)$$

after admitting a burs.

Table 1. Algorithm 1 CreateAuxGraph (G^*, e)

```
Require: Network Topology $G = (V,E)$, and Link $e$
Ensure: Auxiliary Graph Created $G^* = (V^*,E^*)$
$G^* = G$;
Remove Link $e$ from $G^*$;
for All $e^* \in E^*$ do
    Update the Cost of $e^*$ as $D^2_{\mathrm{PMD}}(e^*) \cdot L(e^*) \cdot \deg(e^*)$ in $G^*$;
End for
Return $G^*$;
```

We set the time slot span $\mathit{\Delta}$ as the transmission time of a burst with minimum burst length $L_{\min}$. A burst with length L may occupy $L/L_{\min}$ time slots. After admitting a new burst DB, the node checks whether free resources are still available to accommodate all the bursts (Table 2). In the worst case scenario, there are W bursts in both the start and finish lists. Therefore, the worst case time complexity for Table 2 is $O(2W) = O(W)$. Note that it takes $O(\log W)$ time to insert a burst into the start or finish list. Accordingly, the admission control process has time complexity of $O(W)$.

2) Quality of transmission verification: once a burst is admitted in the previous free resource search step, quality-of-transmission (QoT) verification then checks whether or not the PMD and OSNR constraints are satisfied. The signal quality is unacceptable if either of the two constraints cannot be satisfied. The PMD constraint is estimated using Eq. (1), and the OSNR constraint is tested using Eq. (6).

Table 2. Algorithm 2 Checkslot (i)

```
Require: Burst $DB$ Whose Start or End Time Falls within
         Time Slot $i$; $n_i^* \leqslant W$
Ensure: Return TRUE If Slot $i$ Can Provide Enough
        Resources to Accommodate All the
        Bursts in Slot $i$; Otherwise,
        Return FALSE; $n_i^* \leqslant W$
New $n_i^* = n_i^e + n_i^f + n_i^s$;
Mark All Bursts in Start and Finish Lists as Unmatched;
$N^e = 1$;
$N^e = 1$;
While $n^s \leqslant N_i^s$ and $n^e \leqslant N_i^e$ DO
    If Finish Time of Burst $BF_{n^e}$<Start Time of Burst $BS_{n^s}$ Then
        Decrement New $N_i^*$;
        Mark $BF_{n^e}$ and $BS_{n^e}$ As Matched;
        Increment $n^e$;
    End If
    Increment $n^s$;
End While
If New $N_i^* > W$ Then
    Return FALSE;
Else
    $N_i^*$ = New $N_i^*$;
    Return TRUE;
End If
```

3) Deflection routing: if the primary route cannot accommodate the incoming burst due to either resource or QoT blocking, the deflection route is retrieved and tried. In contrast, if available resources on the deflection route satisfy the physical impairment constraints, the burst is then scheduled on this alternate link.

4) Preemption for high priority bursts: burst preemption has two steps. A network core node first searches for a low priority burst arriving later than the contending high priority burst. If the first step fails, the network core node tries to preempt one of the low priority bursts arriving earlier than the contending high priority burst. If the previous two steps fail, the high priority burst is dropped due to resource blocking. Therefore, the preemption complexity on a given route is $O(2W) = O(W)$.

5) Outgoing wavelength selection: each node stores a list of free channels (wavelengths) available for burst scheduling in a free-channel queue (FCQ). A burst with service interval $[t_s^{DB}, t_e^{DB})$ is scheduled onto the channel at the head of the FCQ, after which the channel is placed back into the FCQ at time t_e^{DB}. The time complexity of outgoing wavelength selection is $O(1)$. Given the most K deflection routes to be checked, the time complexity of the QoS provisioning alogorithm is $O(KW)$.

The performance of our proposed algorithm was evaluated by implementing algorithms using ns-obs version 0.9a. The network topologies used in the simulation were the National Science Foundation of USA (NSF) (Fig. 1) and the 16-node Torus (Fig. 2) with link length in kilometers. The numbers of data and control wavelengths on each link were 8 and 2, respectively. The line transmission rate of each wavelength was 10 Gb/s, and an amplifier was applied every 100 km. Optical fibers can transmit light at a speed of about 2×10^5 km/s. The incoming self-similar traffic from the OBS traffic generator was uniformly distributed between all pairs of edge nodes.

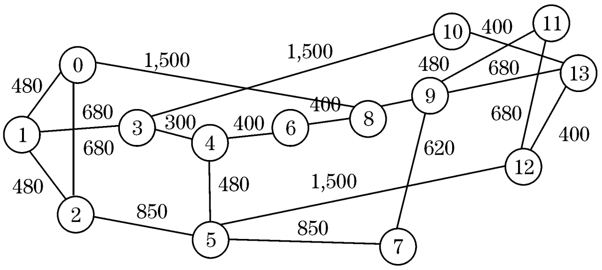

Fig. 1. 14-node NSF network.

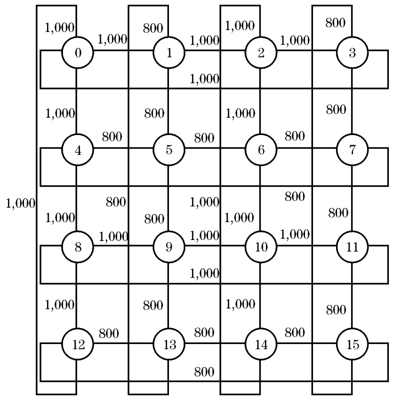

Fig. 2. 16-node torus network.

The parameters used in the simulations are amplifier gain of 15 dB; ASE factor n_{sp} of 1.5; $D_{\mathrm{PMD}}(k)$ of 0.2 ps·km$^{-\frac{1}{2}}$; fractional pulse broadening parameter δ of 0.1; OSNR$_{\min}$ of 7.4 dB (BER $=10^{-9}$).

In the Torus network, link PMD parameter $D_{\mathrm{PMD}}(k)$ of links with length of 1000 km was 0.1 ps· km$^{-\frac{1}{2}}$.

The simulation was run with different offered loads defined by

$$\rho = \frac{N_{\mathrm{IE}} \cdot h \cdot r}{C \cdot (2L)}. \tag{8}$$

In the simulation, we compared the performance of our QoS provisioning algorithm in the DOBS networks and the corresponding algorithm in the single-header OBS networks[16].

The burst blocking probability performances for increasing offered load are shown in Figs. 3 and 4. High priority bursts experience lower blocking probability than low priority bursts due to the preemption that occurs when no resource is available. The difference of the blocking performances between high and low priority bursts becomes more evident as network load increases. This is because more bursts compete for network resource, and high priority bursts have better chances to reserve the required resources through preemption. At high offered loads, more low priority bursts are preempted to make resources available for high priority bursts.

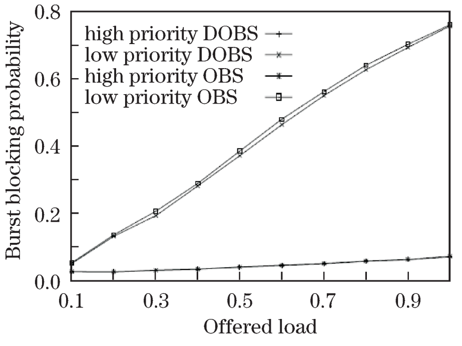

Fig. 3. Burst blocking probability under QoS provisioning scheduling algorithms for the NSF network in DOBS and single-header systems.

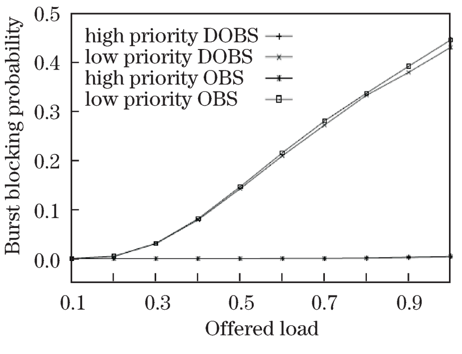

Fig. 4. Burst blocking probability under QoS provisioning scheduling algorithms for the Torus network in DOBS and single-header systems.

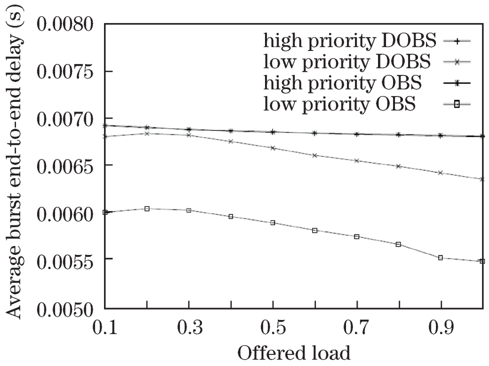

Fig. 5. Average burst end-to-end delay under QoS provisioning scheduling algorithms for the NSF network in DOBS and single-header systems.

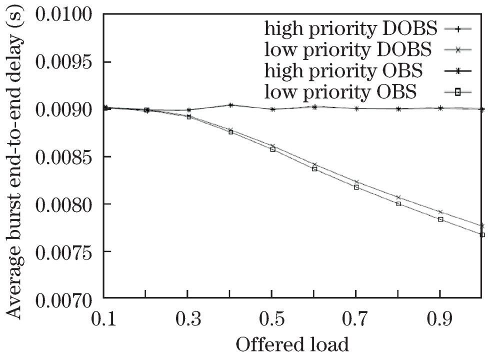

Fig. 6. Average burst end-to-end delay under QoS provisioning scheduling algorithms for the torus network in DOBS and single-header systems.

In all these networks, the QoS provisioning algorithm in DOBS systems achieves similar blocking performance for high priority bursts. This performance is better than what the algorithm achieves in single-header OBS networks, where bursts are scheduled once they arrive at a node. Scheduling is delayed until functional offset time before burst arrival. This delay allows bursts to be scheduled in order of arrival. This first-come-first-served (FCFS) scheduling alleviates the void problem on transmission channels, thereby increasing resource utilization and potentially improving blocking performance. In addition, this FCFS scheduling can better utilize the voids caused by preemption.

Simulation results for average burst end-to-end delay are depicted in Figs. 5 and 6. In general, the delay for high priority bursts is quite stable. The average burst end-to-end delay for low priority bursts decreases as network offered load increases. High priority bursts may preempt low priority bursts to find QoT-qualified free resource. Low priority bursts that must traverse more hops in the network have a higher probability of being dropped. Consequently, bursts that traverse more hops constitute a smaller portion in the total number of bursts successfully received by the destinations at higher offered load.

The QoS provisioning algorithm in DOBS system results in similar average burst end-to-end delay performance for high priority bursts. This algorithm also provides larger burst end-to-end delay for low priority bursts than those in single-header OBS networks. End-to-end delay is also potentially increased. More low priority bursts can be scheduled with this algorithm in DOBS networks due to its better blocking performance.

In conclusion, signal degradation due to various physical impairments may result in unacceptable BER at the destination. Based on earlier work, we study the impairment-aware QoS provisioning problem in OBS networks that employ two CPs for each data burst. A physical impairment-aware QoS provisioning algorithm is proposed, which accommodates incoming bursts by admission control, preemption upon contention, outgoing channel selection, and signal quality verification. Simulation results demonstrate that the proposed algorithm is effective in terms of providing service differentiation in OBS networks while considering physical impairment effects.

This work was supported in part by the National "973" Program of China under Grant No. 2009CB326203.

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