Course EE5134: Optical Communications and Networks

Assignment 1 Report

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Contents

List of Tables

List of Figures

Question 1

Consider a unidirectional WDM physical ring network with five nodes connected as $0 \rightarrow 1 \rightarrow 2 \rightarrow 3 \rightarrow 4 \rightarrow 0$. It is required to create six lightpaths for the node pairs P1: <0,2>, P2: <0,1>, P3:<3,0>, P4:<2,3>, P5: <1,4>, and P6: <4,0>.

(a)

Route the lightpaths using shortest-path-first heuristic with fixed-order wavelength assignment policy, and list the path and wavelength chosen for each lightpath in the table format as shown below. Determine the number of wavelengths required.

Lightpath P_i	Path	Wavelength

Solution:

Using shortest-path-first algorithm, the shortest lightpaths (P2, P4, P6) are processed first. They have no overlapping links (P2: 0→1; P4: 2→3; P6: 4→0), allowing all all three to share W0 without conflicts. Next, P1 (0→1→2) and P3 (3→4→0) use the next shortest paths and share no overlapping links with each other. Since parts of the paths assigned W0, they are assigned W1. Finally, P5 (1→2→3→4) requires the longest path, link 1→2 and 3→4 are already occupied by P1 (W1) and P3 (W1) and link 2→3 occupied by P4 (W0), to avoid conflicts, P5 must use the next available wavelength, W2.

Therefore, the number of wavelengths required is 3. The path and wavelengths chosen for each lightpath are shown in Table 1. The wavelength routed network is shown as Figure 1.

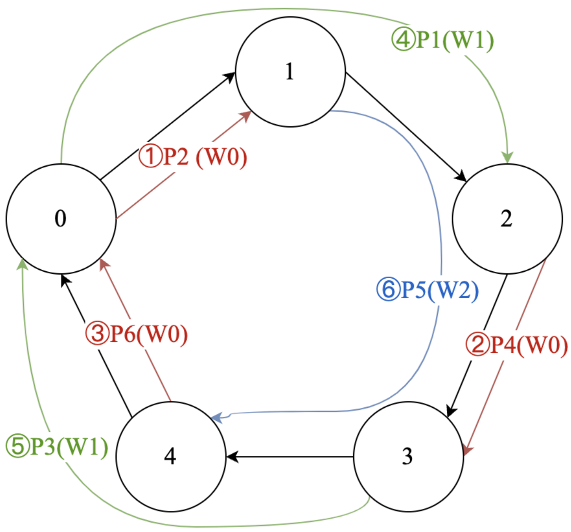


Figure 1: Shortest-Path-First

Lightpath P_i	Path	Wavelength
P_1	0→1→2	W_1
P_2	0→1	W_0
P_3	3→4→0	W_1
P_4	2→3	W_0
P_5	1→2→3→4	W_2
P_6	4→0	W_0

Table 1: Shortest-Path-First

(b)

Develop a better heuristic with fixed-order wavelength assignment policy, and list the path and wavelength chosen for each lightpath in the table format as shown below. Your heuristic should require fewer wavelengths than that used in part (i) above. Explain the intuitive reason why your heuristic is doing better.

Lightpath P_i	Path	Wavelength

Solution:

To reduce the number of wavelengths required, I consider longest-path-first method. The intuition is that we can prioritize longer lightpaths during assignment to reduce fragmentation. Longer path occupy more links, meaning suffering more from wavelength-continuity-constraint, so allocating wavelengths early minimizes conflicts.

Process lightpaths in descending order of hop count: P5 (3 hops)→P1/P3 (2 hops)→P2/P4/P6 (1 hop), and assign wavelengths using fixed order (W0, W1...). First, we assign W0 to the longest path P5. Next, since link 1→2 and 3→4 occupied by P5 (W0), we assign W1 to P1 and P3 without conflicts. Finally, three shortest paths should choose the first available wavelength respectively. Specifically, P2 (0→1 occupied by W1) chooses W0, P4 (2→3 occupied by W0) chooses W1, and P6 (4→0 occupied by W1) chooses W0.

We manage to reduce the number of wavelengths required to 2 by using longest-path-first method.

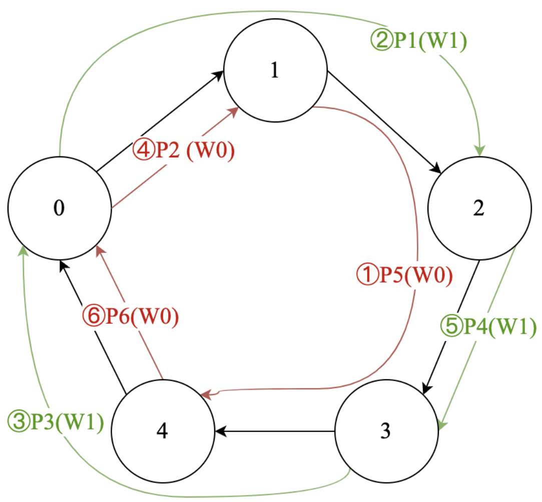


Figure 2: Longest-Path-First

Lightpath P_i	Path	Wavelength
P_1	0→1→2	W_1
P_2	0→1	W_0
P_3	3→4→0	W_1
P_4	2→3	W_1
P_5	1→2→3→4	W_0
P_6	4→0	W_0

Table 2: Longest-Path-First

(c)

It is required to route 0.3, 0.8, and 0.6 units of client traffic flows for the node pairs (0,3), (2,1) and (1,2), respectively, through shortest paths over the virtual topology. Determine the route traversed by each traffic flow and load carried by each lightpath. Tabulate the results in the format below. Calculate the congestion and average weighted number of (virtual) hops.

Traffic flow	route	hop

Lightpath P_i	Load

Solution:

Refer the virtual topology shown in Figure 3, traffic flow for node pair (0,3) is routed through the shortest virtual paths 0→2→3; traffic flow for node pair (2,1) is routed on path 2→3→0→1; traffic flow for node pair (1,2) is routed on path 1→4→0→2.

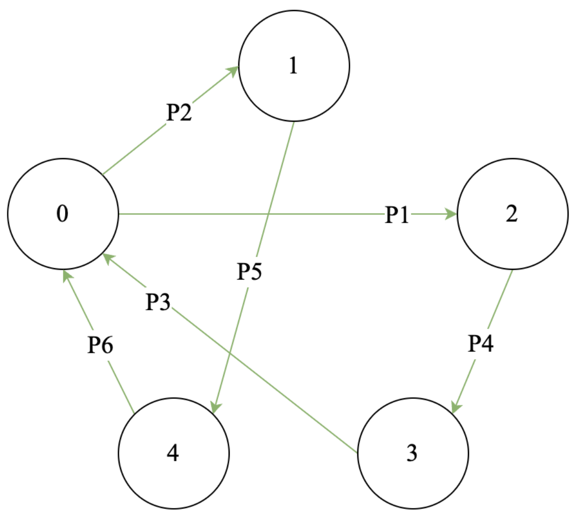


Figure 3: Virtual Topology

Lightpath P1 (0→2) carries load from traffic flows for node pairs (0,3) and (1,2): load = 0.3+0.6=0.9;

Lightpath P2 (0→1) carries load from traffic flow for node pair (2,1) : load = 0.8;
Lightpath P3 (3→0) carries load from traffic flow for node pair (2,1) : load = 0.8;
Lightpath P4 (2→3) carries load from traffic flows for node pairs (0,3) and (2,1): load = 0.3+0.8=1.1;
Lightpath P5 (1→4) carries load from traffic flow for node pair (1,2) : load = 0.6;
Lightpath P6 (4→0) carries load from traffic flow for node pair (1,2) : load = 0.6;

Congestion $= Max(f_{i,j})$, for all i,j $= Max(0.9, 0.8, 0.8, 1.1, 0.6, 0.6) = 1.1.$
where $f_{i,j}$ is the load on the lightpath for node i to node j.

$$\text{Weighted number of hops} = \Sigma(h_{s,d}) \times t_{s,d}, \text{ for all s,d}$$

where $t_{s,d}$ is the estimated amount of traffic flow from node s to node d,
$h_{s,d}$ is the number of (virtual) hops, i.e. the number of lightpaths traversed by traffic flow $t_{s,d}$.

$$\text{Total traffic demand} = \Sigma t_{s,d}, \text{ for all s,d}$$

$$\textbf{Avg. weighted number of hops} = \frac{\text{Weighted number of hops}}{\text{Total traffic demand}} = \frac{0.3 \times 2 + 0.8 \times 3 + 0.6 \times 3}{0.3 + 0.8 + 0.6} \approx 2.8$$

The traffic routing table (Table 3) and traffic load for each lightpath (Table 4)are shown below.

Traffic flow	route	hop
0.3 (0,3)	0→2→3	2
0.8 (2,1)	2→3→0→1	3
0.6 (1,2)	1→4→0→2	3

Table 3: Traffic Routing

Lightpath P_i	Load
P_1	0.9
P_2	0.8
P_3	0.8
P_4	1.1
P_5	0.6
P_6	0.6

Table 4: Lightpath Load

Question 2

(a)

"Wavelength rerouting" migrates an **existing lightpath** from its **current wavelength** to a **new wavelength** without changing the physical path traversed by the existing lightpath. There might be a scenario wherein a new lightpath request cannot be set up due to wavelength continuity constraint, and wavelength rerouting could be helpful to create this new lightpath by migrating some existing lightpath(s) to a new wavelength. Consider a path network 1→2→3→4→5→6

→7 with two wavelengths w_0 and w_1 ,wherein **lightpath requests arrive dynamically one by one**, and they use 2-hop or 3-hop physical paths. Construct a scenario of dynamically arriving lightpath requests to illustrate the benefit of wavelength rerouting. Your example should be such that you are not able to create a new lightpath, but with wavelength rerouting you are able to create it. Illustrate your example using a figure showing the lightpaths with the wavelengths routed on the above path network. Assume fixed order wavelength assignment policy.

Solution:

Consider the original scenario (shown in Figure 4), let's assume the following wavelength assignments without rerouting:

LP1 (1→3) uses w0 on links 1→2→3.

LP2 (2→4) must use w1 due to the wavelength continuity constraint (since w0 is already occupied on link 2→3 by LP1).

LP3 (4→7) then claims w0 on links 4→5→6→7.

Now, when attempting to assign LP4 (3→6), we face a conflict :

1. On link 3→4, w1 is already used by LP2 (2→4).
2. On links 4→5→6, w0 is occupied by LP3 (4→7).

Thus, no wavelength (w0 or w1) is available for LP4 (3→4→5→6).

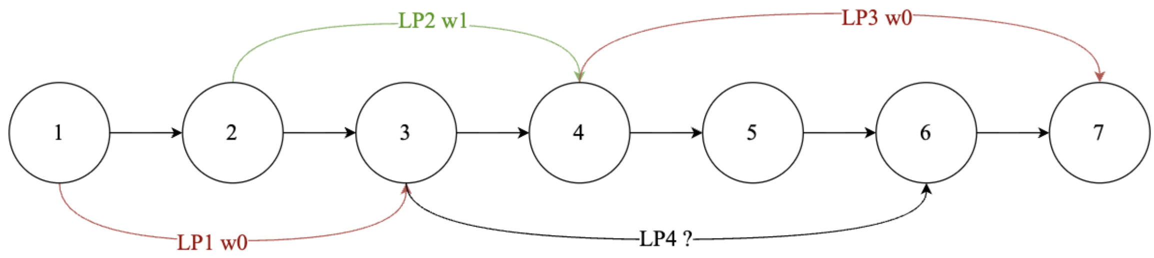


Figure 4: Scenario (unable to create LP4)

To resolve this, we reroute LP3 (4→7) from w0 to w1 (shown in Figure 5). This frees up w0 on links 4→5→6→7. Now, LP4 (3→6) can be successfully assigned w0 on its path 3→4→5→6:

1. Link 3→4: w0 is still used by LP1, but LP4's path starts at node 3, so no conflict.
2. Links 4→5→6: w0 is now available after rerouting LP3.

Rerouting LP3 breaks the wavelength continuity constraint only temporarily during reassignment. By shifting LP3 to w1, we create a "gap" in w0 that LP4 can exploit. This demonstrates how rerouting optimizes wavelength reuse in constrained scenarios.

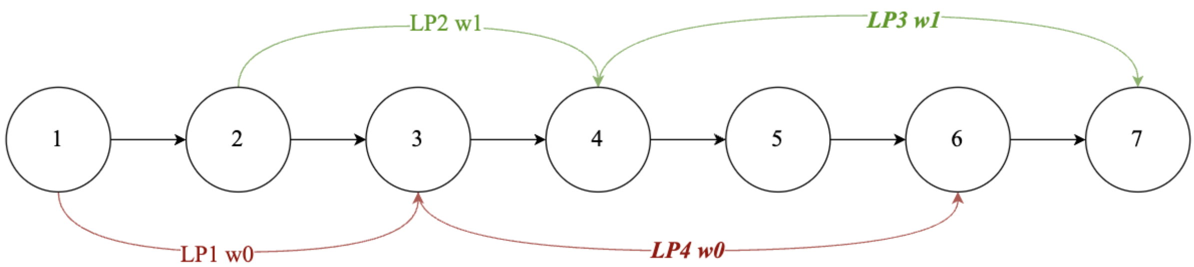


Figure 5: Scenario (rerouting LP3 from w0 to w1)

(b)

Is there any drawback or limitation of using "wavelength rerouting"? Briefly explain.
Solution: Yes, here are some drawbacks of wavelength rerouting:

1. Operational Complexity: Wavelength rerouting requires real-time coordination between network control systems and physical infrastructure. Dynamic path recalculation and wavelength reallocation increase signaling overhead, especially in large-scale networks[1]. This complexity may lead to delays or failures in rerouting decisions.

2. Service Disruption Risks: Even brief interruptions during wavelength switching (e.g., microsecond-level signal loss) can degrade performance for latency-sensitive applications like real-time communications or financial transactions[2].

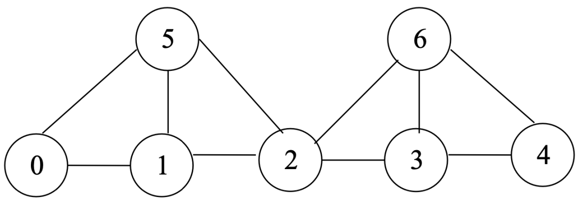
3. Wavelength Converter Dependency: Without wavelength converters, rerouting is constrained by the *wavelength continuity* rule, forcing lightpaths to reuse the same wavelength across all links. This limits flexibility and increases blocking probability for longer paths[2].

4. Cost and Compatibility Issues: Older network devices often lack support for advanced rerouting features (e.g., CDC-F components). Upgrading hardware to enable seamless wavelength switching incurs significant costs[1][2].

5. Potential Network Oscillation: Frequent rerouting may destabilize the network, causing loops or resource contention between lightpaths. For example, repeated adjustments to resolve conflicts could trigger cascading rerouting events[1].

Question 3

Consider a WDM network with 4 wavelengths per fiber as shown in Figure below. The wavelengths are labeled w_0 through w_3. The mean time to failure (MTTF) and mean time to repair (MTTR) of each link in the network are 9 and 1 unit, respectively. The MTTF and MTTR values are assumed to be independent for the links. Suppose that node 2 is provided with wavelength converters. Further suppose that only wavelength w_0 is available on links 0-5 and 5-2, no wavelength is available on links 2-6 and 6-4, and only w_2 is available on all other links.



(a)

Calculate the availability of a link.
Solution:
The availability per link i is:

$$A_i = \frac{\text{MTTF}}{\text{MTTF} + \text{MTTR}} = \frac{9}{9+1} = 0.9$$

(b)

Which path and wavelength are chosen if it is required to set up a lightpath from node 0 to node 4 without requiring any wavelength conversion?

Solution:

Consider a lightpath from node 0 to node 4 without using wavelength conversion, we should find the wavelength available through all the links. From node 2 to node 4, the only path available is 2-3-4 using w_2. From node 0 to node 2, w_2 is available on links 0-1 and 1-2, so the lightpath is **0-1-2-3-4** using wavelength $\mathbf{w_2}$.

(c)

What is the availability value for the path chosen in part Q3(b)?

Solution:

As we assumed MTTF and MTTR to be independent for the links, the availability for the path **0-1-2-3-4** can be simply calculated by:

$$A_{\text{path}} = \prod_{\text{link i}\in\text{path}} A_i = 0.9^4 \approx 0.66$$

where A_i is the availability of link i, A_{path} is the multiplication of availability values of it all links, since all links must work simultaneously.

(d)

It is possible to improve the availability of a path by protecting one or more links, or segments on a path. What are the **links and segments** that can be protected on the path chosen in part Q3(b) to improve the path availability? For **each** possible case of such protection, calculate the improved availability value.

Solution:

1. Consider link-based protection, there is only one link (0-1) can be protected by the segment (0-5-2-1), wherein links 0-5 and 5-2 use wavelength w_0, link 2-1 uses wavelength w_2. Node 2 must convert w_0 to w_2 to guarantee the segment 0-5-2-1 can be established from node 0 to 1. The segment 1-2-3-4 is retained.

For the protected link (0-1), the availability can be calculated by:

$$A_{\text{protected link}} = 1 - (1 - A_{\text{unprotected link}}) * (1 - A_{\text{backup}}) = 1 - (1 - 0.9)(1 - 0.9^3) = 0.9729$$

where $A_{backup} = \prod_i A_i$, meaning multiplication of the availability values of all links on the backup segment. $(1 - A_{\text{unprotected link}}) * (1 - A_{\text{backup}})$ means the primary link and backup segment fail simultaneously.

The segment 1-2-3-4 is still unprotected, so the new path availability after link 0-1 is protected is:

$$A'_{\text{path}} = A_{\text{protected link}} * \prod_{\text{unprotected link i}\in\text{path}} A_i = 0.9729 * 0.9^3 \approx 0.71 > 0.66$$

In the case of link-based protection, the availability is improved from 0.66 to 0.71 (a 7.6% relative increase).

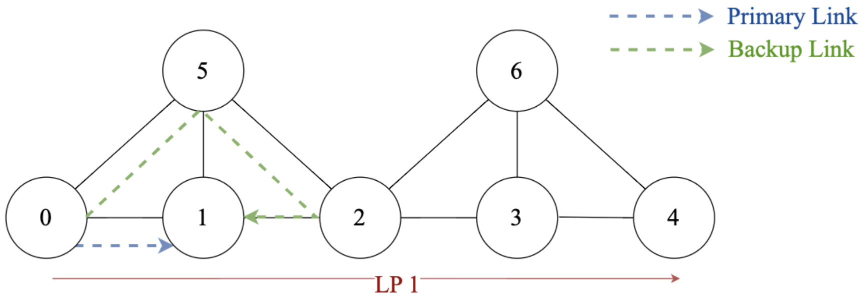


Figure 6: Link-Based Protection

2. Consider segment-based protection, there is only one segment (0-1-2) can be protected by another segment (0-5-2) using different wavelength w_0. Node 2 convert w_0 to w_2 to establish the lightpath from node 0 to node 4, and the segment 2-3-4 is retained.

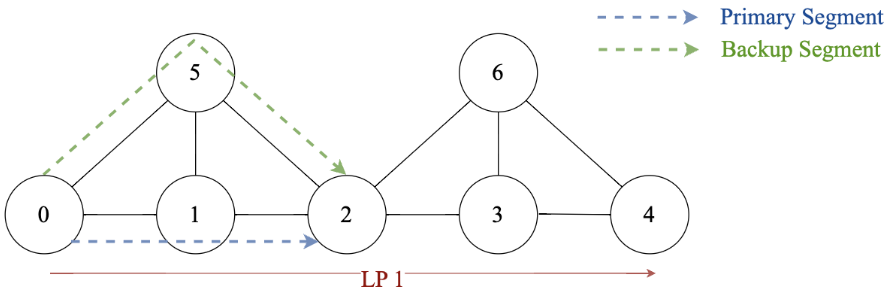


Figure 7: Segment-Based Protection

For the protected segment (0-1-2), the availability can be calculated by:

$$\begin{aligned} A_{\text{protected segment}} &= 1 - (1 - A_{\text{unprotected segment}}) * (1 - A_{\text{backup}}) \\ &= 1 - (1 - 0.9 * 0.9)(1 - 0.9 * 0.9) = 0.9639 \end{aligned}$$

where $A_{\text{backup}} = \prod_i A_i$, meaning multiplication of the availability values of all links on the backup segment.

The segment 2-3-4 is still unprotected, so the new path availability after segment 0-1-2 is protected is:

$$A'_{\text{path}} = A_{\text{protected segment}} * \prod_{\text{unprotected link i} \in \text{path}} A_i = 0.9639 * 0.9^2 \approx 0.78 > 0.66$$

In the case of segment-based protection, the availability is improved from 0.66 to 0.78 (a 18% relative increase).

In conclusion, segment-based protection is better than link-based protection in terms of the path availability metric based on this scenario.

Question 4

In an optical burst switching (OBS) network, usually, the bursts are scheduled (i.e. wavelength channels are chosen) on the outgoing link based on their arrival time and duration, at the time of arrival of their control packets. This might result in high burst loss probability, because at the time of scheduling, the pattern of bursts that arrive later is not known. One possible way to avoid such a scenario (to some extent) is to use *burst rescheduling* as discussed in the class. Another possible way to avoid such a scenario (to some extent) is to use *ordered scheduling* which schedules a burst just before its arrival time instead of making the scheduling decision at the time of arrival of the control packet.

(a)

Construct an example with **at most four bursts** to illustrate the advantage of burst rescheduling and ordered scheduling over the usual approach. Assume an OBS network link with **two wavelengths** and use the Latest Available Unscheduled Channel (LAUC) scheduling algorithm. Your example should be such that **burst rescheduling and ordered scheduling** (both are based on LAUC) **are able** to schedule all the bursts, but, the **usual approach** (LAUC) **fails** to schedule at least one burst. Use the following table format to give your **example**. Here, CA-T, BA-T, and BD represent control packet arrival time, burst arrival time and burst duration, respectively. Show the bursts scheduled on wavelengths as a timeline diagram (as discussed in the lecture)

Burst	CA-T	BA-T	BD
B1			
B2			
B3			
B4			

Solution:

Assume an OBS link with two wavelengths (w0 and w1). The following bursts arrive dynamically with the parameters below (Table 5):

Burst	CA-T	BA-T	BD
B1	0	1	1
B2	1	6	1
B3	2	3	2
B4	3	4	2

Table 5: Example 1

Consider usual approach (LAUC) scheduling first, a burst is scheduled at the time of arrival of the control packet. **Using LAUC Policy** means, at the time of control packet arrival (CA-T), we select the **latest available unscheduled channel** (wavelength) that can accommodate the burst. Steps are as following:
1. B1 arrives at t=0: BA-T=1, BD=1→ B1 occupies [1,2), w0 is free, assign B1 to w0, then update w0 unscheduled time = 2;
2. B2 arrives at t=1: BA-T=6, BD=1→B2 occupies [6,7), w0 unscheduled time=2 (earlier than BA-T=6), assign B2 to w0, update w0 unscheduled time=7;
3. B3 arrives at t=2: BA-T=3, BD=2→ B3 occupies [3,5), w0 unscheduled time=7 (later than BA-T=3 → conflict), w1 unscheduled time=0 (free), assign B3 to w1, update w1 unscheduled time=5;
4. B4 arrives at t=3: BA-T=4, BD=2 → Burst occupies [4, 6), w0 unscheduled time=7 (later than BA-T=4 → conflict), w1 unscheduled time=5 (later than BA-T=4 → conflict), no available

wavelength → **B4 is dropped**. (See Figure 8)

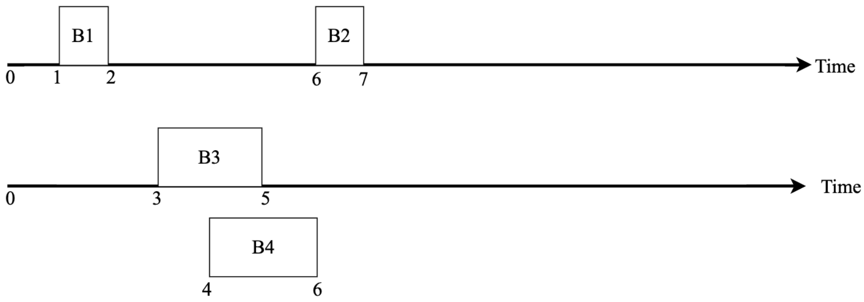


Figure 8: Usual Approach (B4 dropped)

Next, consider burst rescheduling, we could migrate the last burst B3 from w1 to w0, freeing w1[3,5) for B4. (See Figure 9)

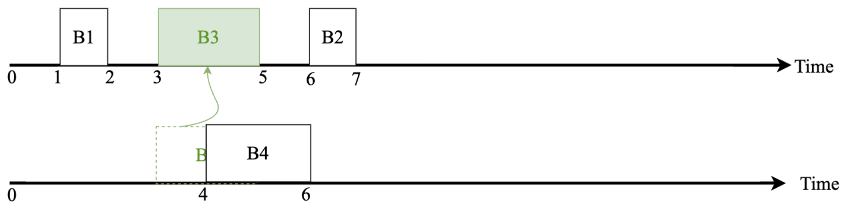


Figure 9: Burst Rescheduling (able to assign all bursts)

Finally, consider ordered scheduling, a burst is scheduled just before its arrival time rather than the arrival time of the control packet, which means, processing bursts in BA-T order. We would prioritize B3's scheduling at BA-T=3 before B4's BA-T=4, as shown in Figure 10. Wavelength w0 is available on time period [3,5), so B3 is assigned to w0, and then we assign B4 to w1, finally, B2 to w1 (w1 unscheduled time is later than w0, so LAUC will choose w1). This approach makes good use of wavelength and avoids conflicts B4 arrives.

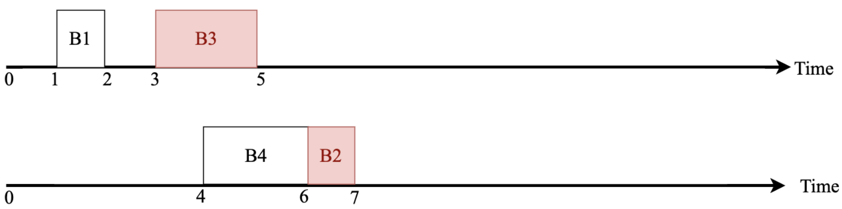


Figure 10: Ordered Scheduling (able to assign all bursts)

(b)

Same as part (i) above, but your example should be such that **ordered scheduling is able** to schedule all the bursts, but, the **usual approach (LAUC) and burst rescheduling fail** to

schedule at least one burst.
Solution:

Assume an OBS link with two wavelengths (w0 and w1). The following bursts arrive dynamically with the parameters below (Table 6):

Burst	CA-T	BA-T	BD
B1	0	5	2
B2	1	6	3
B3	2	8	2
B4	3	4	1

Table 6: Example 2

Consider usual approach (LAUC) scheduling first, steps are as following:
1. B1 arrives at t=0: BA-T=5, BD=2→ B1 occupies [5, 7), w0 is free, assign B1 to w0, then update w0 unscheduled time = 7;
2. B2 arrives at t=1: BA-T=6, BD=3→B2 occupies [6,9), w0 unscheduled time=7 (later than BA-T=6), assign B2 to w1, update w1 unscheduled time=9;
3. B3 arrives at t=2: BA-T=8, BD=2→ B3 occupies [8,10), w0 unscheduled time=7 (earlier than BA-T=8 → free), assign B3 to w0, update w0 unscheduled time=10;
4. B4 arrives at t=3: BA-T=4, BD=1 → Burst occupies [4, 5), w0 unscheduled time=10 (later than BA-T=4 → conflict), w1 unscheduled time=9 (later than BA-T=4 → conflict), no available wavelength → **B4 is dropped**. (See Figure 11)

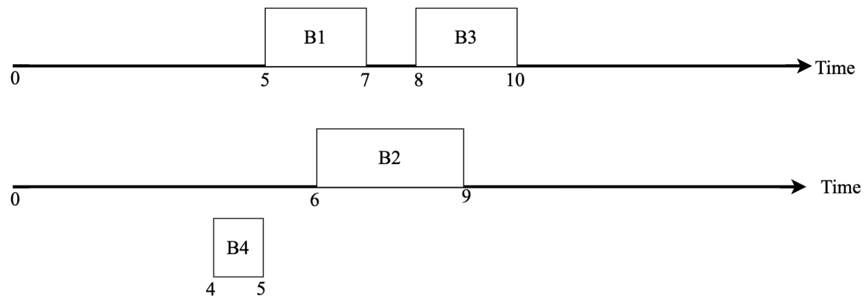


Figure 11: Usual Approach (B4 dropped)

Next, consider burst rescheduling, the last burst B3 is unable to be migrated, B4 is still **dropped**. (See Figure 12)

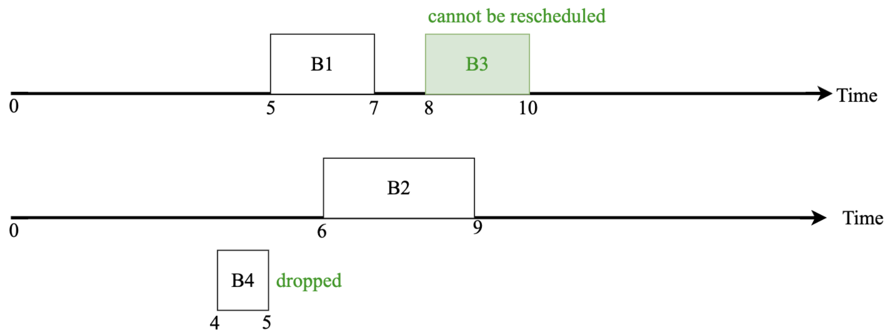


Figure 12: Burst Rescheduling (B4 dropped)

Finally, consider ordered scheduling, we should process bursts in BA-T order. We would prioritize B4's scheduling at BA-T=4 before the other burst, as shown in Figure 13. This approach makes good use of wavelength and we manage to schedule all the bursts.

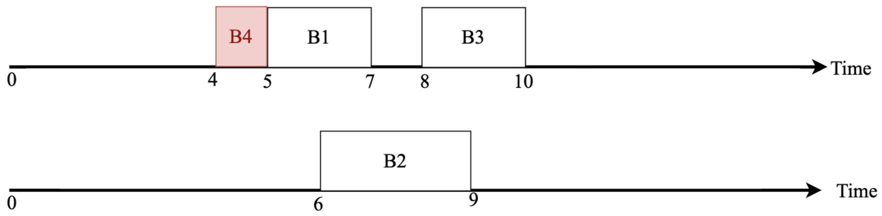


Figure 13: Ordered Scheduling (able to assign all bursts)

References

[1] C. V. Saradhi and C. R. Murthy, “Dynamic establishment of differentiated survivable lightpaths in wdm mesh networks,” *Computer Communications*, vol. 27, no. 3, pp. 273–294, 2004.

[2] K. Venugopal, M. Shiva Kumar, and P. Sreenivasa Kumar, “A heuristic for placement of limited range wavelength converters in all-optical networks,” *Computer Networks*, vol. 35, no. 2, pp. 143–163, 2001.