Wavelength pre-assignment collision schedule for wavelength-routed optical networks

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A novel wavelength assignment scheme called the wavelength pre-assignment collision schedule (WPCS) is proposed for wavelength-routed networks. The WPCS pre-assigns the wavelength at the forward detection phase, and schedules the potential collision by priority. The potential collision is scheduled at the forward detection phase and the blocking of the wavelength assignment is reduced. Simulation is conducted with several other existing schemes. The numerical results show that WPCS performs better than other schemes in blocking probability under various traffic conditions.

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The introduction of generalized multi-protocol label switching (GMPLS) in wavelength-routed networks has made it possible to support distributed lightpath provisioning through signaling protocols, such as resource reservation protocol-traffic engineering (RSVP-TE). In the absence of wavelength conversion, the same wavelength must be assigned on every hop along a route; this is known as the wavelength continuity constraint[1]. Under the constraint, the aim of wavelength assignment is to optimize the network resource utilization, and to select a wavelength to avoid collision such that a wavelength is reserved by two or more connections simultaneously.

Recently, wavelength assignment schemes in wavelength-routed networks have been studied extensively[1−6]. Wavelength assignment also remains a problem for all-optical networks, such as optical burst switching (OBS) and optical packet switching (OPS), etc.[7−9]. In this letter, we focus on wavelength assignment in wavelength-routed optical networks, especially dynamic GMPLS networks with distributed control planes and without wavelength converters. We consider forward assignment allocation and backward resource assignment as a peering phase, and propose a potential collision schedule scheme. We design a test-bed of wavelength-routed optical networks, and analyze the performance of different assignment schemes.

In previous studies, the basic wavelength assignment schemes were source-initiated reservation (SIR) and destination-initiated reservation (DIR)[1]. DIR can be expanded as first fit (FF)[1], random fit (RF)[1], contention detection (CD)[2], collision-aware first fit (CAFF)[3], and circular wavelength-list (CWL)[6], etc.

In SIR, a reservation request (PROBE) message is sent from source to destination, reserving one or more wavelengths along the route as it proceeds towards the destination. The destination node selects one of the reserved wavelength channels and sends a confirmation (RESV) back to the source, informing it the selected wavelength and releasing the other reserved wavelengths.

In DIR, a reservation request (PROBE) message is forwarded from the source to the destination collecting the wavelength availability information along the route. Based on this information, the destination node selects an available wavelength and sends a reservation (RESV) message back to the source node to reserve the selected wavelength. For FF and RF, the destination selects the first/random wavelength in the available wavelength set to reserve, and sends a reservation request back to the source node to reserve the first wavelength. CD detects possible resource potential collisions in the forward detection phase by adding a CD bit in the control message, and the destination chooses the wavelength selection strategy (FF or RF) accordingly. CAFF assigns a weight to each wavelength of the network links such that the destination can select a wavelength according to the weight collected in the forward detection phase. In CWL, the intermediate node forecasts which wavelength will be selected by the incoming PROBE message.

Blocking can be sorted as forward blocking and backward blocking. Forward blocking occurs when the wavelength continuity constraint is not satisfied along the path, while backward blocking occurs when the wavelength has been assigned by another wavelength. In the above schemes, SIR has high forward blocking due to the lack of resources, but experiences low backward blocking. DIR has lower forward blocking but higher backward blocking than SIR. Comparisons between SIR and DIR have been performed in some studies[4,5]. The proposed WPCS scheme in this letter is also a DIR scheme. And we focus on the comparison among some DIR schemes; SIR is out of the scope of this letter. FF has lower forward blocking probability but higher backward blocking probability than RF, and FF obtains better network resource utilization than RF[3]. CD can mitigate backward blocking, thus reducing overall blocking[2]. CAFF has slightly more forward blocking than FF, but keeps the backward blocking comparable to RF such that CAFF can achieve better performance in total blocking[3]. CWL forecasts the future assigned wavelength of the following wavelengths at the detection phase to reduce overall blocking[6]. The above DIR schemes try to avoid potential collision using different wavelength selection strategies at the destination node, but collision remains an occurrence.

In wavelength-routed optical networks, the wavelength assignment consists of two phases: forward detection phase and backward reservation phase. We propose a wavelength pre-assignment collision schedule (WPCS) scheme that assigns wavelengths at both forward and backward phases. Compared with other schemes, this scheme combines SIR and DIR, and uniquely schedules the potential collision of pre-assigned wavelengths at the forward detection phase to minimize the potential collision without additional resource costs.

To compare the blocking performance of WPCS with other schemes, we group potential collision into two classifications: same direction collision (SDC) and opposite direction collision (ODC). SDC occurs when two same direction connection reservation (RESV) messages simultaneously reserve the same wavelength of a link. ODC occurs when two opposite direction connection reservation (RESV) messages simultaneously reserve the same wavelength of a link.

The time chart representing SDC and ODC is shown in Fig. 1. In a distributed network, the reservation of a wavelength of a link means that at the two end nodes of the link, the same wavelength should be reserved by one connection. Because of processing and propagation delay, the wavelength of two end nodes cannot be probed or reserved at the same time. This is the reason behind SDC and ODC. SDC and ODC occur at the backward reservation phase, but the reason behind these can be found at the forward detection phase. The corresponding two PROBE messages of the later collision connections (PROBE1 and PROBE2 in Fig. 1) are not aware of each other when they pass the link (A, Z) where collision later occurs. To probe the wavelength availability of link (A, Z), the PROBE message must check the wavelength availability of node A and node Z when it reaches the two nodes, respectively. When reserving a wavelength of a link, the RESV message also needs to reserve the wavelength at both nodes of the link. To state the question more clearly, we call the two nodes of a link as the near-end node and the far-end node. They are the two nodes of a link which the PROBE or RESV message passes first and later. In Fig. 1 we can see that in SDC, collision occurs at the near-end node of RESV2, and in ODC, collision occurs at the far-end node of both RESV1 and RESV2.

In WPCS, SDC can be resolved by the wavelength pre-assignment in the forward detection phase. The PROBE message carries not only the available wavelength set but also the preferred wavelength (PW) which is the wavelength that the PROBE pre-assigns along the links of the route at the forward detection phase. If a wavelength of a link is pre-assigned by a PROBE message, it will not be pre-assigned with other later arrivals in the same direction by the PROBE messages. When the PROBE message reaches the destination node, a RESV message is generated and sent back through the route. The PW of the links along the route is formally assigned.

In WPCS, ODC can also be resolved by the wavelength pre-assignment in the forward detection phase. Opposite direction PROBE messages may have ODC with one another, as shown in Fig. 2. PROBE1 and PROBE2 pre-assign λ_1 at nodes A and Z, respectively. But λ_1 of the far-end node is pre-assigned by the PROBE message from the opposite direction. In WPCS, a priority-based solution for PROBE ODC scheme is proposed. Any priority judgment, which can compare the priority of the two PROBE messages, can be applied in this scheme. In this example, the IP addresses (IPv4 or IPv6) of the PROBE messages' near-end node and far-end node are compared. We assume that if the IP address of the near-end node is smaller than that of the far-end node, the PROBE has a higher priority. We also assume that node A has a smaller IP than node Z. When PROBE1 reaches node Z and encounters PROBE ODC, it compares the IP address of the near-end node (A) and the far-end node (Z). Because the IP address of node A is smaller than that of node Z, PROBE1 has a higher priority than its opposite direction counterpart, PROBE2. Thus, PROBE1 grabs and pre-assigns λ_1. At the same time, PROBE2 at node A finds that it has a lower priority; hence it pre-assigns another available wavelength λ_2, and sends a PROBE message with the new PW λ_2 forward. At the same time, a message called NACK is sent back along the route to the source node to tell the passing nodes that the pre-assigned wavelength by PROBE2 has been changed to λ_2.

The PROBE message's PW can be changed under some conditions. One condition is that the PW of the near-end node has been pre-assigned or formally assigned by another connection when the PROBE message reaches the near-end node. The other condition is PROBE ODC. The PROBE with the lower priority changes the PW.

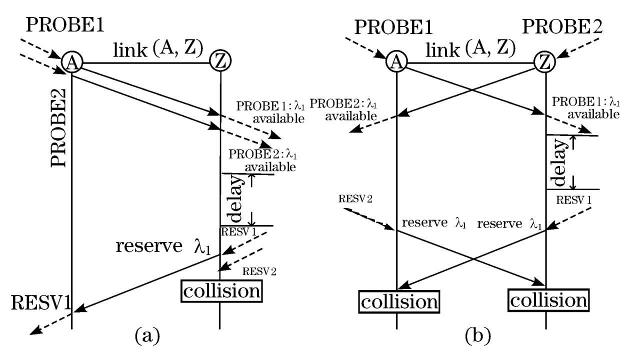

Fig. 1. Time charts of (a) SDC and (b) ODC.

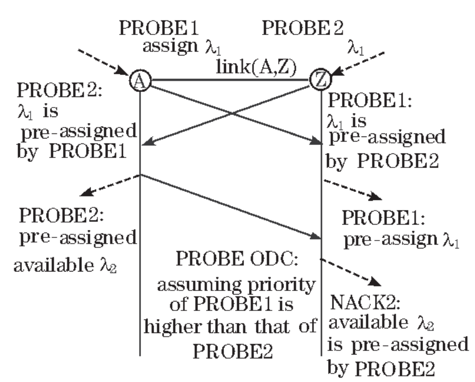

Fig. 2. Priority-based solution for PROBE ODC.

By sending a NACK message along the route back to the source node, the pre-assigned wavelength of the passing nodes is changed to the new PW.

The description of WPCS schemes is as follows.

In a given network, M is the maximum number of wavelengths among all the links in the network; $w_{k,mn}$ is the wavelength k of network link (m,n); $s(w_{k,mn})$ is the status of wavelength k of network link (m,n); $W_{m,n}[M]$ is an array with the length of M, denoting the wavelength status of network link (m,n), and it is stored in node n; $A_{c,n}[M]$ is an array with the length of M, denoting the wavelength status of passing by links from source node s to node n by connection request c, and it is carried by the reservation request message; $w_{c,p}$ is the PW carried by the PROBE message of connection request c; $(s, m_x, m_{x-1}, \cdots, m_2, m_1, m, n, o, o_1, o_2, \cdots, o_{y-1}, o_y, d)$ is the route of connection request c.

In the WPCS, we assign a status $s(w_{k,mn})$ to the wavelength k of the network link (m,n), which is stored in the local resource table of node n and with the initial value 0. The local resource table of node n is composed of some arrays $W_{m,n}[M]$. $s(w_{k,mn})$ is an array element of $W_{m,n}[M]$. When the wavelength k is pre-assigned by a PROBE message, $s(w_{k,mn})$ is set to 1; when the wavelength k is reserved by a RESV message, $s(w_{k,mn})$ is set to infinity; when the wavelength k is released during the teardown process of connection, or when the pre-assigned wavelength k is out of time, $s(w_{k,mn})$ is reset to 0. The PROBE message is extended to carry the status of available wavelength set $A_{c,n}[M]$ and the PW $w_{c,p}$.

At the source node s, PROBE message's status of available wavelength set $A_{c,s}[M]$ is initialized by the wavelength status of the first link, $A_{c,s}[M] = W_{m_x,s}[M]$. When the PROBE message of connection c arrives at the intermediate node m, it wants to pre-assign PW in link (n,m). The status of the available wavelength set $A_{c,m}[M]$ should be refreshed firstly. The refreshment is the combination of the status of the previous wavelength set $A_{c,m}[M]$ and the status of the next hop link $W_{n,m}[M]$,

$$A_{c,m}[M] = A_{c,m}[M] + W_{n,m}[M], \quad \text{for} \quad i = 0;\ i < M;\ i++. \tag{1}$$

Because the elements of $A_{c,m}[M]$ and $W_{n,m}[M]$ have only three values, 0, 1, and infinity, the combination should follow the rules of

$$A_{c,m}[i] = A_{c,m}[i] + W_{n,m}[i] = \begin{cases} 0, \text{ when } 0+0 \\ 1, \text{ when } 1+0,\ 0+1, \text{ or } 1+1 \\ \infty, \text{ other status} \end{cases}. \tag{2}$$

Then, the PROBE message's PW in $A_{c,m}[M]$ is checked whether it is available on the next link or not. We assume that PW is the kth wavelength; if the kth wavelength on link (n,m) is still available, i.e., $A_{c,m}[k] = 0$ or $s(w_{k,nm}) = 0$, it is pre-assigned at node m. The PROBE message of c is then sent to the far-end node n. If the kth wavelength on link (n,m) is assigned or pre-assigned by another connection, a new PW is selected in $A_{c,m}[M]$. According to a different wavelength selection strategy, a new PW can be selected as FF or RF:

$$PW = \begin{cases} w_i \text{ when } \min\limits_i(A_{c,m}[i] = 0), \text{ FF} \\ w_i \text{ when } \operatorname{rand}\limits_i(A_{c,m}[i] = 0), \text{ RF} \end{cases}. \tag{3}$$

If the new PW is available, the PROBE message with the new PW is sent to node n. At the same time, a NACK message is sent back to the source node along the route $(m, m_1, m_2, \cdots, m_{x-1}, m_x, s)$ to notify the nodes that the pre-assigned wavelength has been changed to a new PW. If the new PW is not available, the connection setup fails and the pre-assigned wavelength is released.

When the PROBE message of connection c arrives at the far-end node n, it wants to pre-assign PW in link (n,m). The status of the available wavelength set $A_{c,m}[M]$ should be refreshed as $A_{c,n}[M]$. The refreshment is

$$A_{c,n}[M] = A_{c,m}[M] + W_{m,n}[M]. \tag{4}$$

Then, the PROBE's PW is checked in $A_{c,n}[M]$ regarding its availability on link (m,n). If the PW is available, it is pre-assigned on link (m,n) at node n. If the PW is pre-assigned by another connection, the PROBE ODC problem occurs. We use the priority based solution for PROBE ODC scheme to solve the problem. After the solution, if connection c has a higher priority, the PW is prep-assigned at node n on the next hop link (o,n), and the PROBE is sent to node o. Otherwise, connection c fails and so does the pre-assigned wavelength along the route $(m, m_1, m_2, \cdots, m_{x-1}, m_x, s)$.

The hardware platform of the wavelength-routed network test-bed consists of up to 18 interconnected node servers, a network management server, and an INTERWATCH 95000 protocol tester as client. Every node server is equipped with GMPLS protocol suites, which are secondary developments of the Linux zebra-0.93b software. INTERWATCH 95000 can simulate many clients for node servers via the optical user-network interface (UNI). The architecture of the wavelength-routed network test-bed is shown in Fig. 3. During the test, GMPLS packets were exchanged between node servers. In this experiment, a backbone topology containing 14 nodes and 21 bi-directional links was constructed. Each link carried 32 wavelengths, as shown in Fig. 3. INTERWATCH 95000 simulated a client for each node. Connection requests were dynamically generated by the clients according to the Poisson process and uniformly distributed among the node pairs.

Due to the PW selection strategy, WPCS can also be described as FF (WPCS-FF) and RF (WPCS-RF). Six schemes were compared in the experiment: WPCS-FF, WPCS-RF, FF, RF, CD, and CWL. CAFF was not introduced in the experiment because it is very complicated and difficult[3] for the platform to realize. However, we are able to compare WPCS and CAFF by theoretical analysis. CAFF assigns a weight to each wavelength of the network links, which denote the concurrent reservation probability. Thus, the destination is able to select a wavelength with less collision probability according to weight. CAFF cannot solve the SDC and ODC problems, but can alleviate them. The more similar the two routes are, the more probable the two connections choose the same wavelength to reserve. WPCS is able to solve the SDC using the pre-assigned wavelength and solve the ODC problem using a priority-based solution for the PROBE ODC scheme. Thus, WPCS performs better than CAFF in blocking probability.

In a previous study[3], two basic blocking types of DIR have been shown: 1) blocking occurs in the forward detection phase due to insufficient network capacity, and is reflected by forward blocking probability (FBP); 2) blocking occurs in the backward reservation phase due to outdated information, and is reflected by backward blocking probability (BBP). In a distributed network, there is the propagation delay between nodes, thus the information collected by a PROBE message may be different from the current link state, and this information may be outdated. FBP and BBP are shown in Figs. 4 and Fig. 5.

In the FBP, WPCS-FF performed better than WPCS-RF because the FF strategy reduced the discontinuous wavelength fragmentation better than RF. FF/RF performed better but close to WPCS-FF/WPCS-RF in FBP because the pre-assigned wavelength was not accounted for in the available set in WPCS-FF/WPCS-RF. The FBP of CD was similar to that of FF/RF because CD did not pre-assign the wavelength in the forward detection phase. The FBP of CWL was similar to that of WPCS-FF/WPCS-RF because CWL pre-assigned the wavelength in the forward detection phase. When the traffic intensity increased, more wavelengths were pre-assigned, and available wavelengths of CWL/WPCS-FF/WPCS-RF were less than those of CD/FF/RF. More connections in CWL/WPCS-FF/WPCS-RF were rejected because available sets were not enough. Collision happened because of wavelength assignment occurring simultaneously in the FBPs of CWL/WPCS-FF/WPCS-RF and in CD/FF/RF, and the latter received much lower blocking probability.

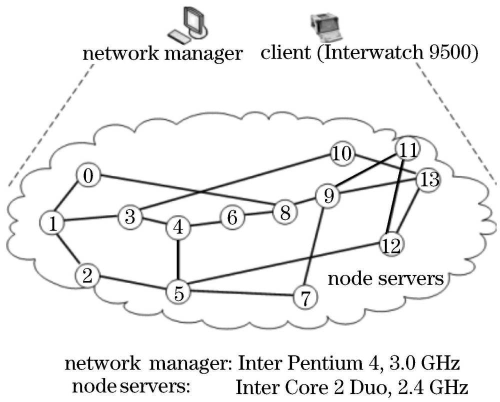

Fig. 3. Test-bed architecture.

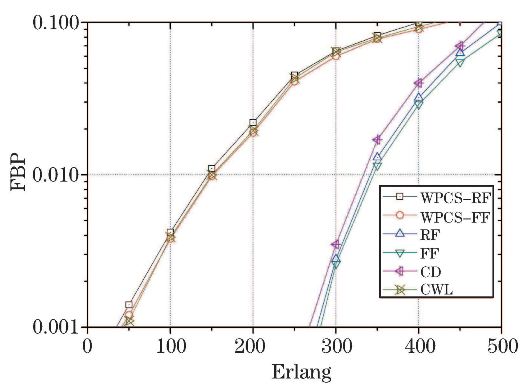

Fig. 4. FBP comparison for the six schemes.

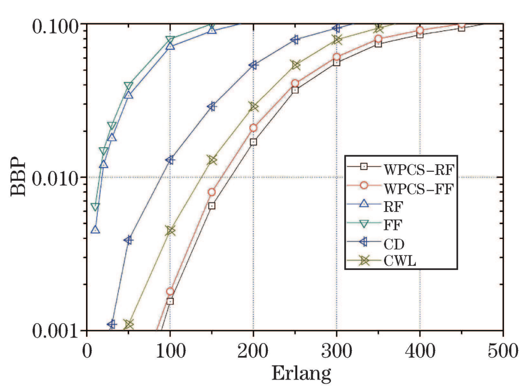

Fig. 5. BBP comparison for the six schemes.

In the BBP, WPCS-RF performed better than WPCS-FF because the RF strategy reduced the probability that the same wavelength was chosen compared with FF. In the backward reservation phase, the BBP of FF/RF was the highest, and the BBP of CD was lower than that of FF/RF, the BBP of CWL was lower than that of CD, and the BBP of WPCS-FF/WPCS-RF was the lowest. Because the wavelength of CWL/WPCS-FF/WPCS-RF was pre-assigned in the forward detection phase, the BBPs of these three schemes were much lower than those of CD/FF/RF, which did not have wavelength pre-assignment schemes.

Total blocking probability (TBP) is the combination of FBP and BBP. The TBPs of the six schemes are shown in Fig. 6. In the TBP, RF had slightly lower TBP than FF; so did WPCS-RF and WPCS-FF. WPCS-FF/WPCS-RF had lower TBP than FF/RF because the BBP gained more weight in the TBP and WPCS-FF/WPCS-RF performed much better than FF/RF. In the TBP, we can see that WPCS performs better than CD. In the CD scheme, a CD bit was used to distinguish potential collisions. The CD bit was initiated at 0. If potential collision happened, the CD bit of a later coming PROBE was set to 1. Different wavelength selection strategies were used for different CD bits. For example, when the CD bit was 0, FF was used and the first available wavelength was preserved. When the CD bit was 1, RF was used. CD solved the SDC of two connections. But having only one CD bit meant that in the SDC of three or more collisions, at least two connections had the same wavelength selection strategy. Thus, CD cannot solve the SDC of more than two connections. In the ODC of two connections, both connections changed the CD bit and had the same wavelength selection strategy. Thus, CD cannot solve the ODC. WPCS can solve SDC of more connections using wavelength pre-assignment and scheduling, and can also solve ODC; thus WPCS performs better than CD in blocking probability.

In the TBP, we can see that WPCS performs better than CWL. In CWL schemes, a wavelength list was carried by the PROBE message and the list was similar to the available wavelength set in WPCS. The wavelength selection window in CWL was similar to the PW in WPCS. In the CWL, the PROBE also pre-assigned wavelength, and the pre-assigned wavelength was called the "undesirable" one, which cannot be used by other PROBE messages. Thus, the CWL was similar to the WPCS-FF in the wavelength assignment method. Similar to WPCS, CWL can solve the SDC of more than two collisions. However, CWL cannot solve the ODC because it does not have the solution to solve the PROBE ODC. In this situation, the two opposite-direction connections have to get back to the source node and reroute and re-setup. The process is called the crankback in GMPLS. However, because the wavelength strategy was not changed, the PROBE ODC may have again occurred if the same route in the crankback was followed. WPCS has the scheme called the priority-based solution for PROBE ODC as shown in Fig. 3; thus, WPCS can solve the ODC problem.

The average time of connection setup (ATCS) is shown in Fig. 7. In the experiment, if the connection setup was not successful, every connection had two chances to reroute and re-establish the connection. The re-route and re-establishment of the connection in GMPLS is called the crankback. The ATCSs of FF and RF are nearly the same as one another; this is also true for WPCS-RF and WPCS-FF. The ATCS of CD is a bit higher than that of FF/RF because CD is a bit more complex than FF/RF. The ATCS of CWL is a bit higher than that of WPCS-FF/WPCS-RF because CWL uses a circular list and WPCS-FF/WPCS-RF uses a much easily fixed length array. The ATCSs of the six schemes mainly slightly increase when the traffic increases, but when the traffic is high, the ACTS of FF/RF slightly decreases. This is because the TBP of FF/RF is very high under a high traffic environment, and many connections are rejected and the setup time of these connections are not taken into account of the total ATCS. The ACTS of WPCS-FF/WPCS-RF/CWL is longer than that of FF/RF/CD. Moreover, because WPCS-FF/WPCS-RF/CWL assigns wavelength in the forward phase and backward phase, the increased process complexity in the WPCS-FF/WPCS-RF/CWL consumes extra time, which is the cost lower than the TBP of the new schemes.

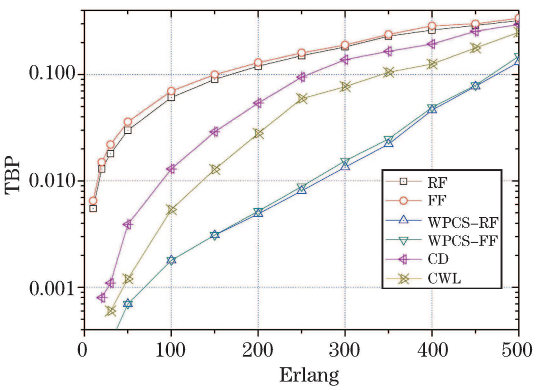

Fig. 6. TBP comparison for the six schemes.

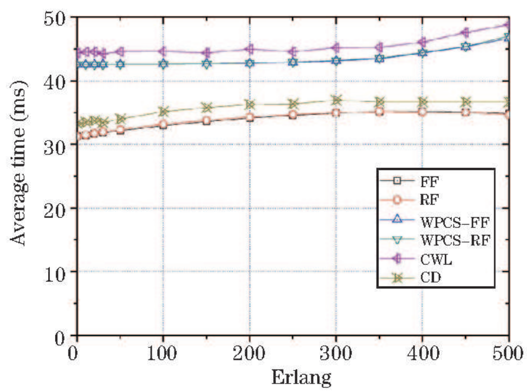

Fig. 7. Average time of connection setup.

In conclusion, a collision-schedule wavelength assignment scheme called WPCS is proposed for a GMPLS-based wavelength-routed network. By pre-assigning wavelength and scheduling potential collision in the forward detection phase, WPCS can alleviate potential collision to a low extent. We compared WPCS with existing wavelength assignment schemes (FF, RF, CD, CAFF, CWL), and analyzed their advantages and limits. Our experiment results show that WPCS has more, but close forward blocking than FF/RF, while receives much lower backward blocking. Nonetheless, total blocking is lowered at a cost of greater connection setup time. Our theoretical analysis and experiment results show that WPCS performs better than CD/CAFF/CWL. Thus, WPCS is a suitable wavelength assignment scheme in wavelength-routed networks under various conditions.

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