

공유형 혹은 아웃풋 광 지연 선로 버퍼를 갖는 비동기 광패킷 스위칭 시스템 설계를 위해 필요한 가변 파장 변환기 및 내부 파장 개수의 도출

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Deduction of TWCs and Internal Wavelengths Needed for a Design of Asynchronous OPS System with Shared or Output FDL Buffer

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요 약

광 패킷 스위칭은 미래 광 인터넷을 위한 스위칭 기술로 고려되고 있다. 광 패킷 스위칭 내부의 경합 해결을 위해 파장 변환 기법이 광 지연 선로 버퍼와 함께 일반적으로 사용되어 진다. 본 논문에서는 공유형 혹은 아웃풋 광 지연 선로 버퍼를 갖는 비동기 광 패킷 스위칭 시스템의 비용 효율적인 설계를 위해 가변 파장 변환기를 공유함으로써 필요한 파장변환기 개수의 감소를 도출한다. 비동기 가변길이 패킷들을 비용 효율적 설계를 위해 고려하였고, 그러한 광 패킷 스위칭 시스템 내부에 필요한 가변 파장 변환기 개수를 도출하기 위해 출력 단의 채널뿐 아니라 유용 가능한 가변 파장 변환기와 내부 파장 또한 찾아 주는 스케줄링 알고리즘을 제안한다. 제안된 알고리즘을 공유형 혹은 아웃풋 광 지연 선로 버퍼를 갖는 비동기 광 패킷 스위칭 시스템에 적용하여 비용 효율적 설계를 위해 필요한 가변 파장 변환기 및 내부 파장 개수를 도출하였다.

Key Words : Optical packet switching (OPS), tunable wavelength converters (TWCs), shared FDL buffer, output FDL buffer, asynchronous OPS architecture, internal wavelengths.

ABSTRACT

Optical packet switching (OPS) is being considered as one of the switching technologies for a future optical internet. For contention resolution in an optical packet switching (OPS) system, the wavelength dimension is generally used in combination with a fiber delay line (FDL) buffer. In this article, we propose a method to reduce the number of tunable wavelength converters (TWCs) by sharing TWCs for a cost-effective design of an asynchronous OPS system with a shared or an output FDL buffer. Asynchronous and variable-length packets are considered in the OPS system design. To investigate the number of TWCs needed for the OPS system, an algorithm is proposed, which searches for an available TWC and an unused internal wavelength, as well as an outgoing channel. This algorithm is applied to an OPS system with a shared or an output FDL buffer. Also, the number of internal wavelengths (i.e., the conversion range of the TWC) needed for an asynchronous OPS system is presented for cost reduction of the OPS system.

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I. Introduction

Optical packet switching (OPS) is being considered as one of switching technologies for a future optical Internet and it is the most flexible and powerful switching technology to accommodate heterogeneous service traffic^[1-4]. Several studies on contention resolution of asynchronous and variable-length packets in an OPS system have been presented^[5-9]. Two techniques are mainly used for contention resolution in an optical packet switch: fiber delay line (FDL) buffering and wavelength conversion.

FDLs are the most representative way to buffer a packet in the optical domain. Contending packets are sent through a FDL and are thus delayed for a specific amount of time. However, for variable-length packets, an FDL buffer generates inevitable voids in the output line due to its discrete step delay^[8,10]. For this reason, efforts are required to increase buffer capacity in an optical packet switch with a limited number of FDLs^[7-14]. For asynchronous and variable-length packets, scheduling algorithms without void filling as well as those with void filling can be used to allocate incoming packets in each output channel using an FDL buffer^[15-20].

The wavelength dimension can also be used in combination with an FDL buffer for contention resolution of incoming packets in an OPS. Tunable wavelength convertors (TWCs) in an OPS provide various number of internal wavelengths (L) for each incoming packet and enable exploitation of L WDM channels in the FDL buffer^[8,11,13]. The number of internal wavelengths (L) in an optical packet switch is determined by the conversion range of the TWC.

Most studies on contention resolution of asynchronous and variable-length packets have fully assumed the use of switch resources such as TWCs and internal wavelengths, while a number of OPS architectures to share FDLs and wavelength converters have been addressed for synchronous and fixed length packets^[16-20]. However, the number of TWCs in an asynchronous optical packet or burst switch is a factor in the system cost, and the number

of internal wavelengths is related to the conversion range of the TWC and is also a factor in the system cost^[8,21-23]. Therefore, the reduction of TWCs and internal wavelengths to guarantee minimum packet loss is inevitably required to prevent resource waste and to reduce design cost of an asynchronous OPS or OBS system^[8,21-23]. Although TWCs, optical gates and internal wavelengths (i.e., conversion range of TWC) needed for an asynchronous optical packet switch system without an optical buffer have been evaluated^[21,22], TWCs and internal wavelengths needed for an asynchronous OPS system with an FDL buffer remains an unresolved issue in terms of cost-effective design.

In this article the reduced number of TWCs for a cost-effective design of an asynchronous OPS system with a shared or an output FDL buffer is investigated. The number of internal wavelengths (i.e., the conversion range of the TWC) needed for an asynchronous OPS system with a shared or an output FDL buffer is also evaluated. A scheduling algorithm is proposed for the asynchronous OPS with reduced TWCs and internal wavelengths, which searches for an available TWC, an unused internal wavelength in an FDL buffer, as well as an outgoing channel.

II. FDL Buffering and Wavelength Conversion on Contention Resolution

2.1 FDL Buffering

The simplest way to resolve contention is to buffer contending packets. However, optical RAM does not exist. FDLs are the only way to buffer a packet in the optical domain. Contending packets are sent to travel through an FDL and are thus delayed for a specific amount of time. In general, FDLs based optical buffers can be divided into two categories^[13,14]: traveling (feed-forward) type and re-circulating (feedback) type. Although the feedback type buffer has finer granularity compared to the traveling type buffer, the traveling type buffer is more general in an OPS due to the defect of low signal quality of the feed-back type buffer.

2.2 Wavelength Conversion

The wavelength dimension can be used in combination with the FDL buffer. By using TWCs to assign packets to unused wavelengths in the FDL buffers, the number of FDLs in an optical packet switch is reduced^[3,8]. If two packets having the same wavelength need to be buffered simultaneously, then one of them can be converted to another wavelength. Then, both packets can be stored in the same FDL, as shown in Fig. 1(a). If n internal wavelengths in the FDL exist, n packets can be simultaneously stored in the same FDL. When two packets with the same wavelength need to be buffered simultaneously without tunable wavelength conversion, two FDLs are needed to store the packets, as shown in Fig. 1(b).

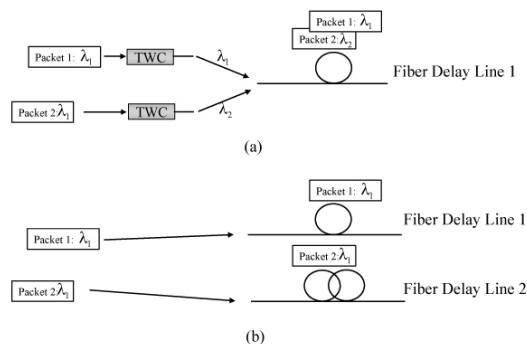


Fig. 1. Allocation of packets to FDLs: (a) with the use of TWCs, (b) without the use of TWC.

III. Optical Packet Switch with Shared TWCs for Shared or Output FDL Buffer

In this section, two general OPS architectures are intended to investigate the number of TWCs and internal wavelengths needed. One is an OPS with a shared FDL buffer, and the other is an OPS with an output FDL buffer. They have an advantage of reducing the number of TWCs and internal wavelengths, in a general asynchronous OPS with an optical buffer. A traveling type buffer is considered for the shared and output FDL buffers, due to the low signal quality of a feedback type buffer. The number of TWCs and internal wavelengths needed

for the two general OPS architectures will be investigated in Section V.

3.1 Optical Packet Switch with a Shared FDL Buffer

An OPS with a limited number of TWCs and internal wavelengths for the shared FDL buffer consists of the input section, the shared FDL buffer, the output section, and the switch control unit, as shown in Fig. 2.

Fully shared TWCs with a conversion range of $\{\lambda_1, \lambda_2, \dots, \lambda_L\}$ in the input section are employed to provide L internal wavelengths for each incoming packet, which enable each incoming packet to exploit one of L WDM channels in the FDL buffer^[21]. Although more TWCs can decrease the packet loss further for a fixed buffer size, the number of TWCs needed in an OPS should be investigated to prevent resource wastage connected with switch cost^[8,21]. $N \times n$ TWCs are required to design a non-blocking OPS system before investigating the number of TWCs needed for a cost-effective design of an OPS system.

The shared FDL buffer has a set of FDLs (1, 2, ..., $B - 1$, B) where the i th FDL represents the fiber delay line with the length D_i corresponding to i times the delay line length D of the FDL buffer, $1 \leq i \leq B$. By default, it is assumed there is a FDL with zero delay time denoted by D_0 . Also, the number of internal wavelengths needed for the shared FDL buffer is evaluated in Section V. $N \times n$ internal wavelengths are needed to design a non-blocking OPS system before investigating the number of

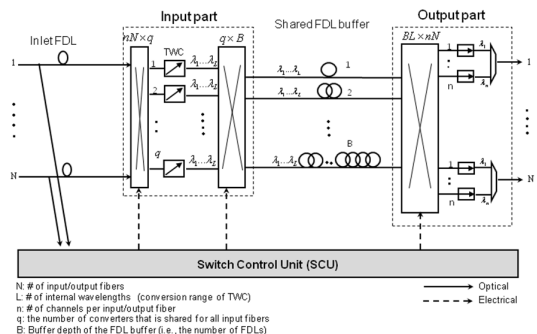


Fig. 2. OPS system architecture with shared TWCs for shared FDL buffer.

internal wavelengths needed for a cost-effective design of an OPS system.

Fixed-wavelength converters (FWCs) in the output section perform wavelength conversion to a scheduled channel in an output fiber for each buffered packet. Spatial switches in the input and the output parts are used to forward an incoming packet to determined paths (i.e., a determined TWC, a determined FDL, and a destination output fiber), after an incoming packet is scheduled. Inlet FDLs are used to provide Switch Control Unit (SCU) processing delays for incoming packets. By default, it is assumed that all spatial switches in the OPS have direct zero-delay paths. The SCU controls each switching element for switch reconfiguration after packet scheduling.

3.2 Optical Packet Switch with an Output FDL Buffer

An OPS with a limited number of TWCs for the output FDL buffer consists of the input section, the output FDL buffer, the output section, and the switch control unit, as shown in Fig. 3. Although the output FDL buffer makes the switch bulky, it leads to accommodate more incoming packets due to B FDLs dedicated for each output compared to the shared FDL buffer with B FDLs shared for all outputs, assuming that the number of channels in a FDL is same for both buffer architectures.

The fully shared TWCs with a conversion range of $\{\lambda_1, \lambda_2, \dots, \lambda_L\}$ are also employed to provide L internal wavelengths for each incoming packet. Before investigating the number of TWCs needed for a cost-effective design of an OPS system, $N \times n$ TWCs should be reflected in the design of a non-blocking OPS system.

The output FDL buffer has a set of FDLs $(1_j, 2_j, \dots, (B-1)_j, B_j)$ where ij FDL represents the FDL having the length D_i corresponding to I times the delay line length D for the j th output fiber, $1 \leq i \leq B$ and $1 \leq j \leq N$. Before investigating the number of internal wavelengths needed for a cost-effective design of an OPS system, n internal wavelengths should be reflected in the design of a non-blocking OPS system. By default, it is assumed that all

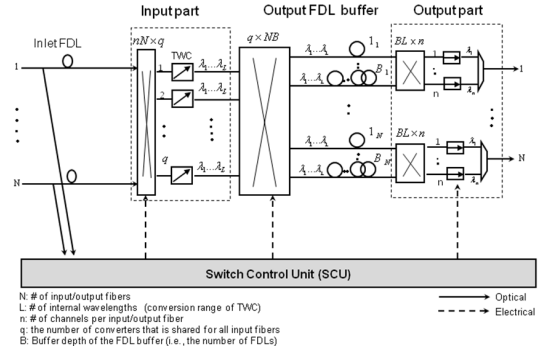


Fig. 3. OPS system architecture with shared TWCs for output FDL buffer.

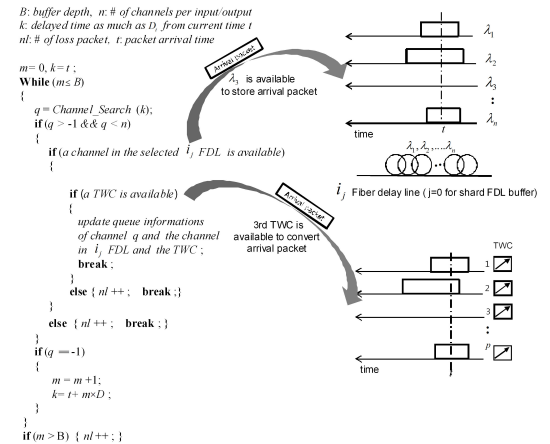


Fig. 4. Pseudo code of the proposed scheduling algorithm and an illustrative example depicting the selection of an unused internal wavelength and an available TWC.

spatial switches in the OPS have direct zero-delay paths.

IV. Proposed Algorithm for a Limited Number of TWCs and Internal Wavelengths

Scheduling algorithms for asynchronous and variable-length packets consist of two categories: scheduling algorithms without void filling^[15-17,20] and scheduling algorithms with void filling^[16-20]. However these algorithms in literatures haven't addressed both limited number of TWCs and internal wavelengths in their switch design.

If an OPS has limited number of TWCs and internal wavelengths, a scheduling algorithm is

required to find an available TWC and an unused internal wavelength in the FDL buffer as well as to find an outgoing channel. Thus, we propose a scheduling algorithm for an OPS with limited number of TWCs and internal wavelengths. A pseudo code of the proposed algorithm is shown in Fig. 4. Let t be the packet arrival time to the switch. First, the function $ChannelSearch(k)$ is used for finding an outgoing channel q using the FDL buffer. The LAUC (Latest Available Unused Channel) and the LAUC-VF (Latest Available Unused Channel with Void Filling) algorithms with the outstanding performance for variable length packets will be selected as a scheduler for the $ChannelSearch(k)$ in the proposed algorithm. If an available outgoing channel q is found at a delayed time $k=t+D_i$, it is checked whether a channel in the selected ij FDL (i th FDL in j th output buffer of the output FDL buffer and i th FDL in the shared FDL buffer ($j=0$)) is available. If a channel in the selected ij FDL is available, it is checked whether a TWC is available for converting the wavelength of the arrival packet to an unused channel in it. Otherwise the arrival packet is lost. If a TWC is available, then packet queue information of the selected outgoing channel q , the selected channel in the ij FDL, and the selected TWC is updated. Otherwise the arrival packet is lost. An available channel in the ij FDL and an available TWC are selected in a FIFO manner.

V. Reduction in TWCs and Internal Wavelengths Achieved for Shared and Output FDL Buffers

5.1 Simulation Environments

The optical packet switch systems with a shared FDL buffer or an output FDL buffer described in Section III were considered for simulation. To model asynchronous and variable-length packets, we used self-similar aggregate traffic to consider the superposition of many on/off sources. The length T of each period in the self-similar aggregate traffic is modeled according to the Pareto heavy-tail

distribution. The on and off periods are represented as $T_{on} = \lfloor b_{on} / U^{1/\alpha_{on}} \rfloor$ and $T_{off} = \lfloor b_{off} / U^{1/\alpha_{off}} \rfloor$, respectively, where U is a uniform random variable on $(0,1]$ ^[8]. The on and off periods represent bursts of packets and inter-arrival times, respectively. Each burst of packets corresponding to an on period was treated as a single entity and was uniformly distributed to the output fibers^[8]. The Hurst parameter H represents the measure of self-similarity and is related to the α parameter ($H=(3-\alpha)/2$, $1 < \alpha < 2$). In this study, b_{on} was determined as 400 bytes to represent the minimum burst length^[8].

5.2 TWCs and Internal Wavelengths Needed for Shared and Output FDL buffers

Figure 5 shows packet loss probability as a function of q (the number of TWCs shared for all input fibers). Since the optimum delay line length to obtain minimum packet loss for variable-length packets is a function of the number of internal wavelengths (L)^[8], we simulated the packet loss probability as a function of delay line length for the number of internal wavelengths (L). As a result, the optimum delay line length (D) for each L was as follows: ($L=32$, $D=150$ bytes) and ($L=64$, $D=450$ bytes) with the LAUC for the shared buffer; ($L=12$, $D=400$ bytes) and ($L=16$, $D=450$ bytes) with the LAUC for the output buffer; ($L=32$, $D=200$ bytes) and ($L=64$, $D=1000$ bytes) with the LAUC-VF for the shared buffer; ($L=12$, $D=150$ bytes) and ($L=16$, $D=1000$ bytes) with the LAUC-VF for the output buffer.

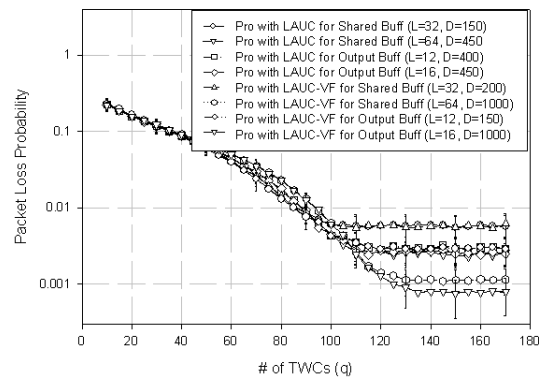


Fig. 5. Packet loss probability as a function of the number of TWCs (q) for shared and output FDL buffers, with confidence intervals at 95% confidence level ($N=16$, $n=16$, $B=15$, $\rho = 0.8$, $\alpha_{on}=\alpha_{off}=1.4$).

D=150bytes) and (L=16, D=1000bytes) with the LAUC-VF for the output buffer. For the proposed algorithm with the LAUC for the shared or the output FDL buffer, packet loss probability was almost saturated at $q=110$, with more than 32 internal wavelengths (L) for the shared FDL buffer and more than 12 internal wavelengths (L) for the output FDL buffer. This result implies that 110 TWCs were sufficient to guarantee minimum packet loss when the number of channels per input/output (n), buffer depth (B), and load (ρ) are 16, 15, and 0.8, respectively. For the proposed algorithm with the LAUC-VF for the shared FDL buffer, only 110 and 130 TWCs were required to guarantee minimum packet loss when the number of internal wavelengths (L) was 32 and 64, respectively. For the proposed algorithm with the LAUC-VF for the output FDL buffer, only 115 and 135 TWCs were sufficient to guarantee minimum packet loss when the number of internal wavelengths (L) was 12 and 16, respectively. Since the LAUC-VF algorithm could reduce packet loss further due to void filling in the output lines compared to the LAUC algorithm, more TWCs (q) were required to achieve lower packet loss with an increase in the number of internal wavelengths (L). The LAUC-VF could not reduce packet loss as much as the LAUC due to the lack of the number of internal wavelengths under the specific number of internal wavelengths (L=32 for the shared FDL buffer and L=12 for the output FDL buffer), even though it has more chances to fill voids in the output fibers and to lower packet loss.

Figure 6 shows packet loss probability as a function of the number of internal wavelengths (L) for the shared or the output FDL buffer. For the minimum number of TWCs (q) deduced from Fig. 5, packet loss probability was simulated for an increased number of internal wavelengths (L). For the proposed algorithm with the LAUC, only 48 internal wavelengths (L) for the shared buffer and 12 internal wavelengths (L) for the output buffer were required to accommodate arrival packets and achieve minimum packet loss, with 110 TWCs (q) and 400 bytes of delay line length (D), as an example. For the proposed algorithm with the

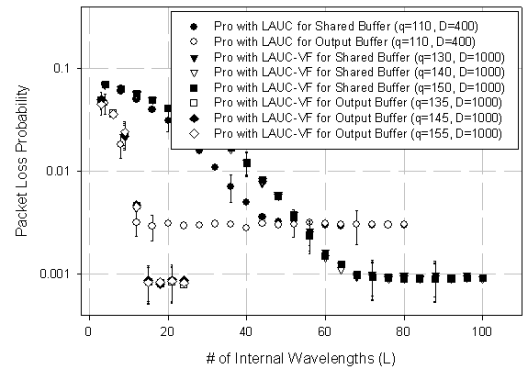


Fig. 6. Packet loss probability as a function of the number of internal wavelengths (L) for shared and output FDL buffers, with confidence intervals at 95 % confidence level (N=16, n=16, B =15, $\rho = 0.8$, $\alpha_{on}=\alpha_{off}=1.4$).

LAUC-VF for the shared FDL buffer, 68 internal wavelengths (L) were required to achieve minimum packet loss, with more than 130 TWCs ($q \geq 130$) and 1000 bytes of delay line lengths (D), as an example. On the other hand, 15 internal wavelengths (L) could guarantee minimum packet loss, with more than 135 TWCs ($q \geq 135$) and 1000 bytes of delay line length (D), for the proposed algorithm with the LAUC-VF for the output FDL buffer. Since the LAUC-VF algorithm could reduce packet loss further due to void filling in the output lines compared to the LAUC algorithm, more internal wavelengths (L) were required to accommodate more arrival packets, together with an increase in the minimum number of TWCs (q).

Figure 7 shows packet loss probability as a function of q for each FDL buffer when the number of channels per input/output(n), buffer depth (B) and load (ρ) were 8, 15, and 0.8, respectively. For the proposed algorithm with the LAUC for the shared or the output FDL buffer, packet loss probability was almost saturated at $q=75$, with more than 16 internal wavelengths (L) for the shared buffer and more than 6 internal wavelengths (L) for the output buffer. This result implies that only 75 of TWCs were required to guarantee minimum packet loss for each FDL buffer. For the proposed algorithm with the LAUC-VF for the shared FDL buffer, only 75 and 85 of TWCs were required to support minimum packet loss when the number of internal wavelengths

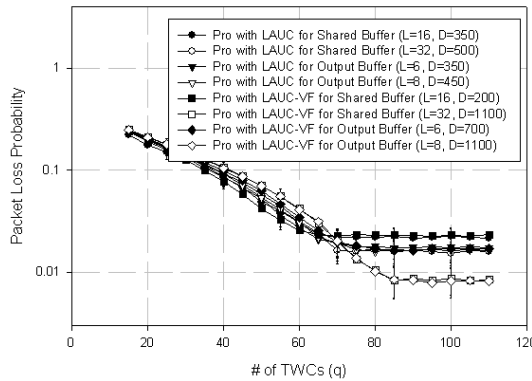


Fig. 7. Packet loss probability as a function of the number of TWCs (q) for shared and output FDL buffers, with confidence intervals at 95% confidence level (N=16, n=8, B=15, $\rho = 0.8$, $\alpha_{on}=\alpha_{off}=1.4$).

(L) was 16 and 32, respectively. For the proposed algorithm with the LAUC-VF for the output FDL buffer, only 75 and 85 of TWCs (q) were required to guarantee minimum packet loss when the number of internal wavelengths (L) was 6 and 8, respectively.

Figure 8 shows packet loss probability as a function of the number of internal wavelengths (L) for the shared and the output FDL buffer when the number of channels per input/output(n), buffer depth (B) and load (ρ) were 8, 15, and 0.8, respectively. For the minimum number of TWCs (q) deduced from Fig. 7, packet loss probability was simulated with an increase in the number of internal wavelengths (L). For the proposed algorithm with

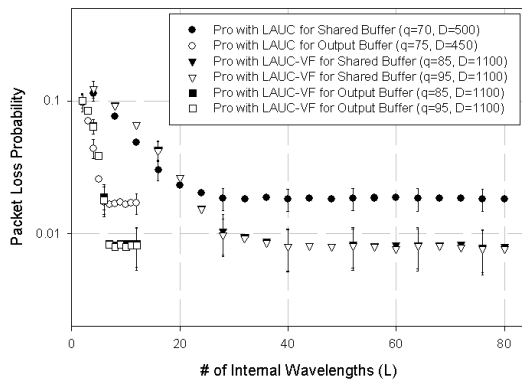


Fig. 8. Packet loss probability as a function of the number of internal wavelengths (L) for shared and output FDL buffers, with confidence intervals at 95% confidence level (N=16, n=8, B=15, $\rho = 0.8$, $\alpha_{on}=\alpha_{off}=1.4$).

the LAUC, only 28 internal wavelengths for the shared buffer and 6 internal wavelengths for the output buffer were required to accommodate arrival packets and to guarantee minimum packet loss, with 75 TWCs (q). For the proposed algorithm with LAUC-VF for the shared FDL buffer, 40 internal wavelengths were required to achieve minimum packet loss with more than 85 TWCs ($q \geq 85$). For the proposed algorithm with the LAUC-VF for the output FDL buffer, 7 internal wavelengths (L) were required to accommodate arrival packets with more than 85 TWCs ($q \geq 85$).

Finally, Table I summarizes the reductions in the number of TWCs and internal wavelengths from above results. The design of a non-blocking OPS system with the shared FDL buffer requires 256 TWCs and 256 internal wavelengths when the number of input/output fibers (N) and the number of channels per inputs/outputs (n) are 16 and 16, respectively. After investigation of 130 TWCs and 68 internal wavelengths needed for an OPS system with the shared FDL buffer, with the proposed algorithm, we found that 126 TWCs and 188 internal wavelengths can be saved for a cost-effective design of an asynchronous OPS system with the same minimum packet loss probability. On the other hand, 121 TWCs and 1 internal wavelength could be saved for the output FDL buffer when buffer depth (B), load(ρ), and the number of channels per inputs/outputs (n) were 15, 0.8, and 16, respectively.

TABLE 1. Reductions in the Number of TWCs and Internal Wavelengths (IW) (B = 15, $\rho = 0.8$).

Asynchronous OPS System	(TWCs, IWs) Before Investigation	(TWCs, IWs) After Investigation	Savings of (TWCs, IWs)	n
With sharedbuffer	(128, 128)	(85, 40)	(43, 88)	8
With outputbuffer	(128, 8)	(85, 7)	(43, 1)	8
With sharedbuffer	(256, 256)	(130, 68)	(126, 188)	16
With outputbuffer	(256, 16)	(135, 15)	(121, 1)	16

VI. Conclusions

The number of TWCs needed for the shared or the output FDL buffer in an asynchronous OPS architecture was investigated by the proposed algorithm. Also, the number of internal wavelengths needed for an asynchronous OPS architecture was evaluated for the shared and the output FDL buffers. Asynchronous and variable length packets were considered for evaluation of TWCs and internal wavelengths needed for a cost effective design of an OPS system. The proposed algorithm finds an available TWC and an unused internal wavelength in the FDL buffer, as well as an outgoing channel, to prevent resource wastage. The proposed algorithm with the LAUC-VF for the shared or the output FDL buffer could lead to extreme reductions in the number of TWCs and internal wavelengths (their conversion range) for a cost-effective design of an asynchronous OPS system.

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