Performance of Dynamic Optical Path Networks with Large-scale WBSS-based Optical Cross-connects

Le Hai Chau*, Le Anh Ngoc, Pham Thi Viet Huong and Dao Thanh Hai

Abstract—In this paper, we have proposed a generalized large-scale optical cross-connect (OXC) architecture utilizing waveband selective switches (WBSS) for realizing future cost-effective, bandwidth-abundant and flexible optical networks. The developed architecture implements multiple WBSSs for each incoming fiber and small size wavelength selective switches (WSSs) for dropping optical paths while simply deploying 1×2 WSSs or 1×2 optical couplers for realizing the adding function. Thanks to the use of WBSSs, which are more cost-effective and simpler devices, the developed architecture enables a significant hardware scale reduction. The WBSS-based OXC, however, suffers from a limited routing capability, which relies on the inner node parameter (i.e., the WBSS number per input fiber) and the waveband granularity of WBSSs. We, therefore, evaluate the hardware scale requirement of our developed architecture in comparison with that of conventional WSS-based OXC. It is verified that a substantial hardware scale reduction can be achieved by using the proposed architecture, especially for high port count OXCs or when applying coarser granular WBSSs. Moreover, we also assess the performance of dynamic optical networks based on the proposed OXC. Numerical simulations show that the network offers a substantial necessary hardware scale reduction at the cost of a small performance offset comparing to that of the network using conventional WSS-based OXC.

Index Terms—optical network, optical cross-connect, wavelength selective switch, network control algorithm.

1. Introduction

INTERNET traffic is growing at incredible rates due to the demands of high-performance applications such as video-oriented services as well as cloud and grid computing [1] [2] [3]. New applications and services require even more ubiquity, higher mobility/flexibility, and heterogeneous bandwidths [4] [5]. This traffic growth places the requirements for optical networks to support an extremely large data capacity. Therefore, the need for cost-effective and bandwidth-abundant flexible optical networks has become more and more critical [6] [7] [8]. In addition, the development of cost-effective and large-scale reconfigurable optical add/drop multiplexers (ROADMs) or optical cross-connects (OXCs) also becomes a crucial issue [9] [10] [11] [12] [13] [14] [15].

Recent researches on optical transmission and networking technologies are oriented forward more efficient, flexible, and scalable optical network solutions [4] [6] [7] [8] [9] [10]. One of the most attractive approaches to improve optical switch's capacity cost-effectively and scalably is the use of coarse granular optical path switching [4] [11] that can be realizable with optical selective switching technologies [18] [19] [20] [21] [22]. Optical selective switches are available with multiple granularities including wavelength and waveband levels. Wavelength selective switch (WSS) can deal with wavelength individually while waveband selective switch (WBSS) can only switch waveband, which is a group of wavelength paths, where all wavelengths of a waveband are simultaneously routed as one entity [4] [19]. At present, most existing optical switching systems such as ROADMs and OXCs are implemented with WSSs. For constructing large scale ROADMs/OXCs, multiple WSSs can be cascaded to create the larger port count WSSs due to the limitation of commercially available WSS port count, which is currently 20+ and unlikely, can be substantially enhanced cost-effectively in the near future. WSS-based ROADM/OXC systems can switch optical paths at wavelength level. However, wavelength selective switches are now still costly and complicated devices. A notable alternative switching technology, waveband selective switch, is more cost-effective and simpler. Unlike conventional WSSs, WBSSs can selectively switch wavelength groups only. Optical cross-connect systems which use WBSSs instead of WSSs in conventional architectures are capable of reducing the total hardware scale with a slight performance penalty due to a coarse granular routing limitation [4]. Previous studies proposed an ROADM/OXC architecture that is based on WBSSs by simply replacing WSSs with WBSSs in conventional architecture [20] [21] [22] [23]. The effectiveness of the developed architecture

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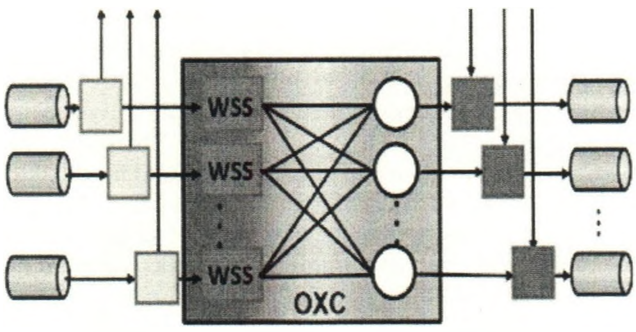
Manuscript received November 17, 2020; revised April 14, 2021; accepted May 05, 2021.

Digital Object Identifier 10.31130/ict-ud.2021.124

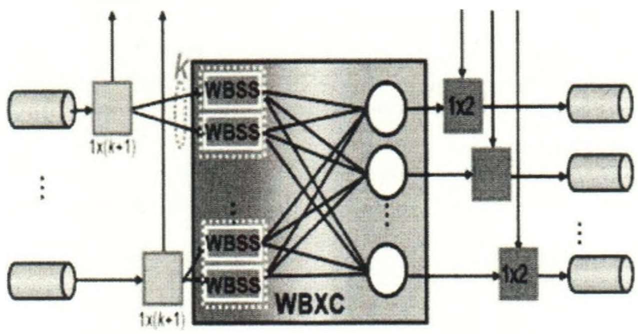
is also verified [20] [21]. However, this architecture suffers from a limited routing flexibility, which can only be improved by applying finer granular (i.e., a smaller number of wavelengths per waveband) WB-SSs. Depending on the waveband granularity applied, a notable hardware reduction can be attained at the cost of small link resource increment. Unfortunately, this routing limitation may severely affect the network performance, especially in the case of dynamic wave-length path provision, and therefore, it is desirable to enhance the node routing flexibility while still keeping the hardware reduction as large as possible. A simple approach is to lessen the number of wavelength paths per waveband, i.e., to apply a finer waveband granularity. However, this may cause an explosion of total necessary hardware scale [24] and consequently limits the advantage of the WBSS-based architecture. Hence, in order to fully exploit WBSS technology for building cost-effective large-scale OXCs, a new OXC architecture is necessary. Based on that, in this paper, we have developed a generalized optical cross-connect architecture to realize cost-effective, scalable high-port count OXCs for building bandwidth-abundant flexible optical transport networks. The proposed architecture deploys multiple WBSSs and small size WSSs to drop optical paths for each input fiber and uses simple 1×2 WSSs or 1×2 optical couplers for adding optical paths. Although the proposed architecture exploiting WBSS technology is able to reduce the necessary hardware scale significantly, its routing flexibility is restricted by inner node parameter, i.e., the WBSS number per input fiber, and waveband granularity. In order to verify the efficiency of the proposed node architecture, we evaluate and compare the total switch scale and the dynamic network performance obtained by the developed OXC architecture to those of appropriate conventional WSS-based OXCs. Numerical evaluations show that the developed architecture can provide a substantial hardware scale decrease at the cost of a slight performance offset.

2. Proposed generalized Optical Cross-connect Architecture with WBSSs

In order to further exploit coarse granular optical path routing and the use of WBSSs while relaxing the coarse granular routing restriction, we propose a generalized optical cross-connect architecture that employs multiple WBSSs for each incoming fiber. The difference between our proposed architecture and the conventional WSS-based OXC are shown in Figure 1). Both architectures use small scale WSSs for dropping wavelength paths (adding wavelength paths can be done by 1×2 WSSs or simply by 1×2 optical couplers). However, the proposed architecture deploys k WBSSs ($k \geq 1$), in replacement of only one WSS (or WBSS) as in conventional OXCs (or grouped routing OXCs), to serve each incoming fiber. Here, the number of WBSSs equipped per fiber, k, is an inner node parameter and it is pre-determined. Obviously, this parameter should be as small as possible to minimize the switch scale. Figure 2) illustrates the routing principle of the considered OXC architecture. Wavelength paths of a waveband can be flexibly added/dropped at any intermediate node along the waveband path. Unlike the flexible wavelength path routing of conventional WSS-based OXCs, wavelength paths within a waveband from an incoming fiber of the architecture can be separated individually and routed to no-more-than k different output fibers due to the coarse granular routing restriction of WBSSs. As multiple WBSSs is used in combination with a small size WSS for each incoming fiber, routing process of the developed OXC architecture is composed of two stages; the first stage using WSSs, is to divide a waveband into different wavebands and send to the corresponding WBSSs and then, at the second stage, these wavebands will be directed to the appropriate output fibers. It means that the node routing flexibility relies on the routing flexibility of WBSSs at the second stage and the inner parameter, k. The WBSS routing flexibility is determined by the waveband granularity, which is the number of wavelengths per waveband (group); using finer granular WBSSs or deploying more WBSSs per incoming fiber (i.e., greater k) is able to improve the node routing flexibility. However, applying more or finer granular WBSSs may result in a significant cost/hardware-scale increment. Hence, the parameters that are the inner parameter (k) and the waveband granularity must be carefully considered in order to take the advantages of the generalized WBSS-based OXC architecture.



(a) Conventional WSS-based OXC architecture



(b) Generalized WBSS-based OXC architecture

Fig. 1: Conventional WSS-based and Generalized WBSS-based OXC architectures.

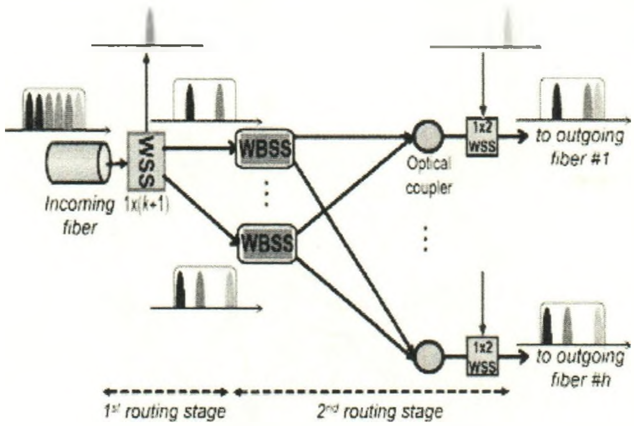


Fig. 2: Routing principle of the generalized WBSS-based OXC.

3. Performance Evaluation of The proposed WBSS-based OXC Architecture

In this section, we evaluate the switch scale of the proposed node architecture and compared to that of the conventional WSS-based OXCs. To clarify the efficiency of the developed architecture, the switch scale reduction offered by the proposed architecture is estimated with respects to various waveband granularities and different inner node parameter. Finally, we verify the performance offset of dynamic optical networks employing the proposed OXC architecture. The impact of key network and node parameters such as traffic load, inner node parameter on the network performance is also analyzed.

3.1. Switch Scale Reduction

To realize wavelength/waveband selective switches, several mature optical technologies such as planar lightwave circuit (PLC) switch, 2-D and 3-D micro-electro mechanical systems (MEMS) and liquid crystal (LC)/liquid crystal on silicon (LCoS) switches are applicable. Comparing to WSSs, WBSSs are simpler (smaller switch size, footprint, ...) and more cost-effective devices. Among available optical switch technologies for implementing WSS and WBSS systems, MEMS-based systems are known as one of the most popular and widely adopted technologies in current ROADM/OXC systems. Therefore, in order to estimate the efficiency of the proposed node architecture versus conventional WSS-based ones, for simplicity, we only consider MEMS-based WSSs/WBSSs whose scale is mainly determined by the number of necessary elemental MEMS mirrors. Adding/dropping portions are also neglected. The switch scale of ROADM/OXC systems, consequently, is quantified by the total MEMS mirrors required by WSS/WBSS components. Practically, the cost and the control complexity of WSS/WBSS-based systems rely strongly on the switch scale (i.e. mirrors of MEMS-based systems). Hence, switch scale minimization plays a key role in creating cost-effective large-scale WSS/WBSS-based ROADMs/OXCs.

Let W denote the waveband granularity, the number of wavelengths per waveband, and L denote the total number of wavelengths that is carried by a fiber. Here, $1 \leq W \leq L$ and L is divisible by W; $B = L/W$ $(1 \leq B \leq L)$ is the number of wavebands per fiber. Because, in MEMS-based selective switches, each mirror is dedicated to a wavelength (or waveband) and therefore, each WSS (WBSS) requires L (B) mirrors. Note that mirrors of WBSSs are to switch a group of wavelengths (waveband); all wavelengths of a waveband are simultaneously switched by a mirror. Hence, the sum of necessary mirrors in each WBSS is less than that of a WSS ($B \leq L$) or in other words, using WBSSs instead of WSSs will help to reduce the switch scale of OXC systems.

TABLE 1: Switch Scale Calculation

OXC Architecture	Switching component: *Switch element*	Switching component: *Total number*	Switch scale *(Mirror count)*
Conventional	WSS	$n\left(1+\lceil\frac{n-1}{M}\rceil\right)$	$nL\left(1+\lceil\frac{n-1}{M}\rceil\right)$
Proposed	WBSS	$kn\left(1+\lceil\frac{n-1}{M}\rceil\right)$	$\frac{knL}{W}\left(1+\lceil\frac{n-1}{M}\rceil\right)$

Table 1 summarizes the switch scale calculation of the proposed OXC and a conventional architecture. If we assume that the input/output fiber number is n $(n > 0)$ and the maximal selective switch size, i.e., the number of port counts, is M, the number of WSSs required for conventional OXC architecture is $1 + \lceil\frac{n-1}{M}\rceil$ while that of WBSSs needed in the proposed architecture is $k\left(1 + \lceil\frac{n-1}{M}\rceil\right)$ where k is the number of WBSSs equipped for each input fiber. Based on that, the total mirror numbers of the proposed node and the conventional one are respectively calculated as $\frac{knL}{W}\left(1 + \lceil\frac{n-1}{M}\rceil\right)$ and $\frac{nL}{W}\left(1 + \lceil\frac{n-1}{M}\rceil\right)$. Hence, the switch scale ratio of $1 \times M$ WBSS-based optical cross-connect to the corresponding WSS-based OXC is given by, $R = k/W$. The obtained ratio doesn't rely on both the maximum size of WSSs/WBSSs applied (M) and the input fiber number (n). It strongly depends on the inner node parameter, k, and the waveband granularity used. Figures 3 and 4 describe the switch scale comparison between the proposed architecture and the conventional OXC with L of 80, M of 16 and various k values. Figure 3 shows that the switch scale of both our developed architecture and the conventional OXC dramatically increases as the number of input fibers becomes greater. Our architecture requires significantly less number of switching elements (MEMS mirrors) than the conventional WSS-based OXC, its switch scale is determined proportionally by the inner node parameter, k, and the waveband granularity (see Figure 4). A greater switch scale reduction can be achieved by applying our developed architecture with smaller inner node parameter or finer waveband granularity. However, smaller inner node parameter will cause a severe limitation on routing flexibility while finer waveband granularity may result in an increment of the control complexity and the cost of the devices.

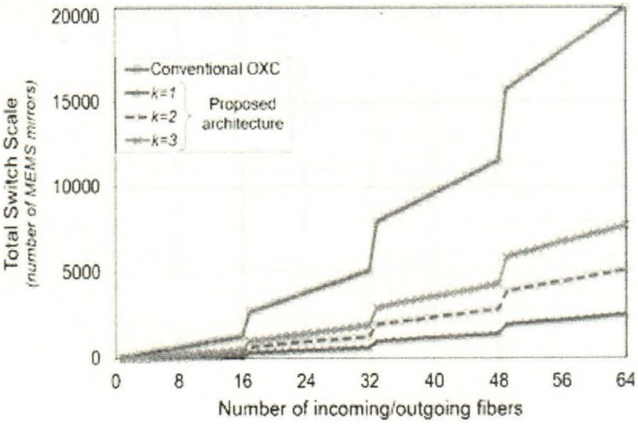


Fig. 3: Switch scale comparison.

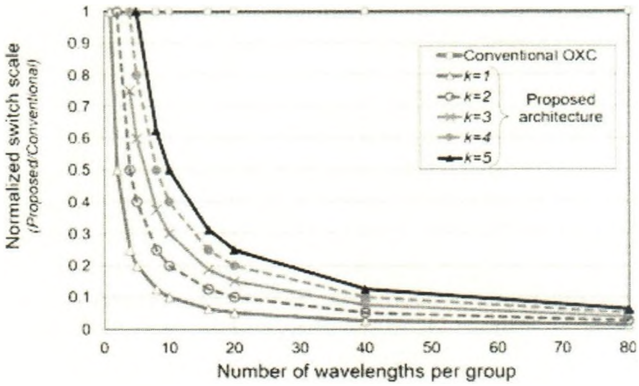


Fig. 4: Impact of waveband granularity on the switch scale.

3.2. Performance offset of dynamic lightpath provisioning network utilizing the developed node architecture

In this part, we assess the performance of a dynamic lightpath provisioning network that employs the developed WBSS-based node architecture. Numerical simulations were performed by using the following parameters. The tested network topology is a pan-European optical network, COST266 that consists of 26 nodes and 51 bi-directional links (see Figure 5) [25]. We assume that lightpaths are dynamically and flexibly set up and released by user requests. A fiber can carry up to 80 wavelengths and no wavelength conversion is taken into account. Traffic intensity, the average number of lightpaths requested between node pairs, is assumed to be 12. The arrival of lightpath setup requests follows a Poisson process while the connection holding time is distributed by a negative exponential process where the average arrival rate of lightpath set-up requests is λ (requests per time unit) and the mean hold time is $1/\mu$ (time units). Moreover, we also use an equivalent conventional network that uses traditional WSS-based OXCs and is installed with the same fiber configuration as the benchmark. The number of established fibers on links of both comparative networks is determined by employing the static network design for the conventional network to accommodate the given traffic intensity.

Fig. 5: Experimental physical network topology, COST266.

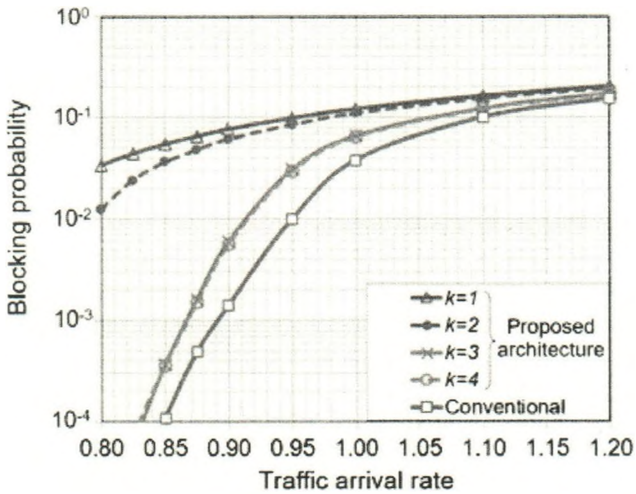


Fig. 6: Blocking probability with five wavelengths per group.

Figure 6 illustrates the performance comparison of the developed generalized WBSS-based OXC network and that of conventional WSS-based OXCs. The comparison was done with the waveband granularity of 5, inner-node parameter k between 1 and 4, mean holding time (MHT) of 1000 time units and various traffic arrival rate from 0.8 to 1.2 (traffic load between 800 and 1200 Erlangs). The obtained results demonstrate that the network using the proposed architecture suffers from a small performance offset, i.e. blocking probability, compared to the conventional network. The performance penalty strongly depends on the inner node parameter, k. That is due to the routing flexibility restriction of the proposed OXC architecture. It is also confirmed that the performance offset is reduced significantly as the inner-node parameter, k, becomes greater. This thanks to applying more WBSSs per fiber enhances the routing flexibility and as a result, helps to improve the network performance. However, when k is great enough, the network performance enhancement becomes slight. The reason is that, with such k values, the inner node routing is flexible enough to satisfy the lightpath routing requirement in overall network.

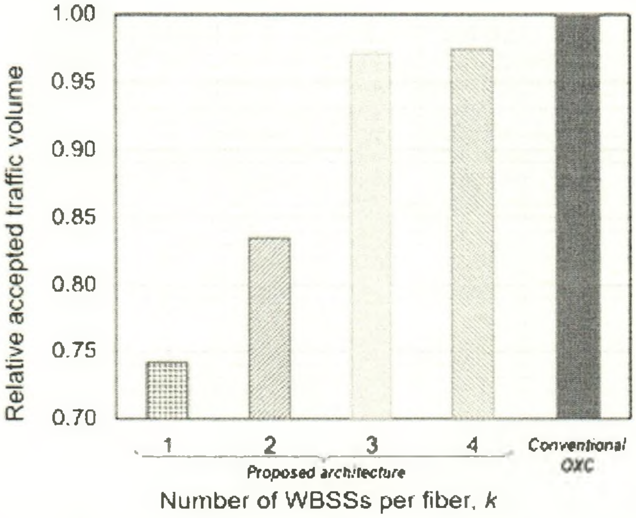


Fig. 7: Accepted traffic volume versus the inner node parameter, k.

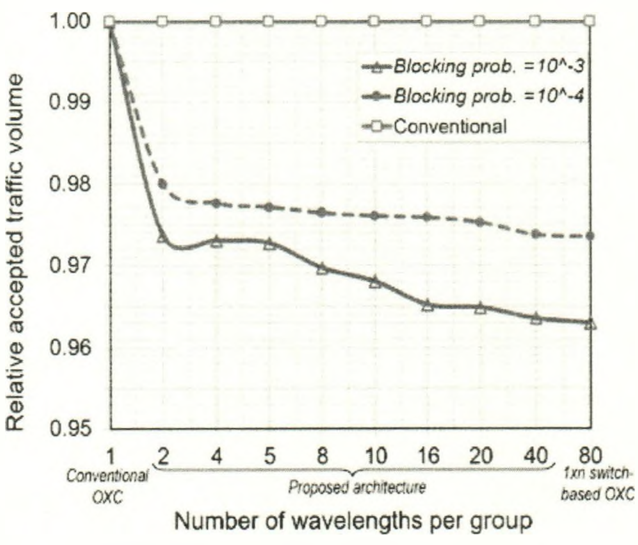


Fig. 8: Relative accepted traffic volume versus W.

Furthermore, we have verified the impact of key node parameters including the inner node parameter and the waveband granularity, on the network performance in terms of total accommodated traffic. Numerical results are shown in Figures 7 and 8. In this evaluation, the obtained total accommodated traffic volume of the proposed networks are normalized by that given by the corresponding traditional optical network based on WSS-based OXCs. That is the reason why the relative accepted traffic volume of the conventional network is always 1.0 (the benchmarking). Obviously, as demonstrated in Figure 7 with the blocking probability of 10^{-3}, our proposed network can also provide better performance compared to simple WBSS-based OXC network ($k = 1$) while it suffers from a slight performance offset comparing to the conventional WSS-based OXC network. Again, it is verified that when greater k is applied, higher relative accepted traffic volume is attained. The proposed network offers less than 3% performance offset comparing to the conventional one as k is more than 2. Note that the inner node parameter, k, should be kept as small as possible as discussed above. Hence, selecting suitable k value plays a key role in dealing with the trade-off between the switch scale reduction and the overall network performance to exploit the proposed OXC architecture. Similarly, as shown in Figure 8, applying finer waveband granularity is an alternative way to improve the proposed network performance. However, the network performance just slightly relies on the number of wavelengths per group (waveband granularity); the performance fluctuation is less than 2% as the waveband granularity changes from 2 to 40 at the inner node parameter of 3. It means that, in dynamic optical networks, the routing flexibility is hardly enhanced further with a finer waveband granularity if k is large enough, says 3. Remember that using finer waveband granularity dramatically increases the switch scale and may result in a hardware cost explosion.

4. Conclusion

In this paper, we have proposed a generalized optical cross-connect architecture that equips each incoming fiber with multiple WBSSs for realizing large capacity bandwidth-flexible optical cross-connects required in future bandwidth-abundant optical transport networks. Our proposed architecture utilizes small size WSSs for dropping optical paths while simply deploying 1×2 WSSs or 1×2 optical couplers for realizing the adding function. Thanks to the use of WBSSs which are more cost-effective and simpler devices, the developed architecture enables a significant hardware scale reduction. However, it suffers from a limited routing flexibility which relies on the inner node parameter (the WBSS number per input fiber) and the waveband granularity of WBSSs. We have then evaluated the hardware scale requirement of our developed architecture in comparison with that of conventional WSS-based OXC. It is verified that a substantial hardware scale reduction can be achieved, especially with higher port count OXCs or applying coarser granular WBSSs. Moreover, we have also assessed the performance of dynamic optical networks using our proposed architecture. Numerical simulations show that the developed architecture reduce the necessary hardware scale substantially at the cost of a small performance offset comparing to conventional WSS-based OXC architecture.

Acknowledgment

This research is funded by Vietnam National Foundation for Science and Technology Development (NAFOSTED) under grant number 102.02–2018.09.

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