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## THE WAVELENGTH CONVERSION IN WDM NETWORKS

In this paper we deal with the problem of wavelength conversion in WDM (wavelength division multiplex) networks. In all-optical networks the data are transmitted through optical networks transparently. It means that the data still remain in the optical domain between the source and end node. The data transmission between two nodes can be without wavelength conversion or with wavelength conversion (with full wavelength conversion or limited wavelength conversion). We want to give a comprehensive paper about recent and new forms of wavelength conversion.

### 1. Introduction

The WDM network is an optical network to employ the wavelength division multiplex WDM technology. This technology provides transmission of data on different optical wavelengths through the same optical fiber. We will concentrate on WDM network only, where each wavelength corresponds to a data communication channel. Moreover, we deal with all-optical networks. In these networks, the optical signal still remains in the optical domain from the source node to the destination node.

An optical fiber can carry several simultaneous wavelength channels. Each wavelength has to be different in the same fiber. The number of wavelengths that each fiber can carry is limited by the physical characteristic of the fiber and the state of optical technology, which is used to combine these wavelengths onto to the fiber and isolate them off the fiber. Today the third low loss optical window (about 1550 nm) is used for the transmission, which can support about tenths wavelengths. However, it is expected to grow rapidly in the next ten years [1].

### 2. Wavelength Conversion

In the case that in the networks a signal is transmitted through physical links and if the signal has to use the same wavelength, then it is called transmission without wavelength conversion. The networks, which do not enable wavelength conversion, are called the networks without conversion or the non-conversion networks. If it is possible to change a wavelength to other wavelength in the

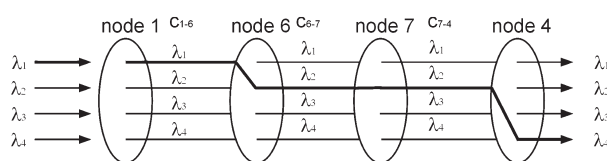


Fig. 1 Wavelength path

network nodes, then those networks are called networks with conversion or the conversion networks.

When we use the wavelength to routed data then it is referred to as wavelength routing. A network that employs this technique is called a wavelength-routed network. A wavelength routing network consists of two types of nodes [2]:

- optical cross-connects (OXC), which connect the fibers in the networks,
- end nodes (access or edge nodes), which provide the interface between non-optical end systems and the optical systems.

The OXC provides the switching and routing functions in order to establish the connection between edge nodes. The OXC can include wavelength converters for supporting wavelength conversion.

The wavelength conversion means the change of incoming wavelength to other wavelength. We know several types of wavelength conversion. In general, any incoming wavelength can be switched to any outgoing wavelength. The number of possible outgoing wavelength on which the incoming wavelength can be switched is  $k$ , and the number of all outgoing wavelength is  $W$  at the node. In dependence on  $k$ , we know the following types of wavelength conversion [3]:

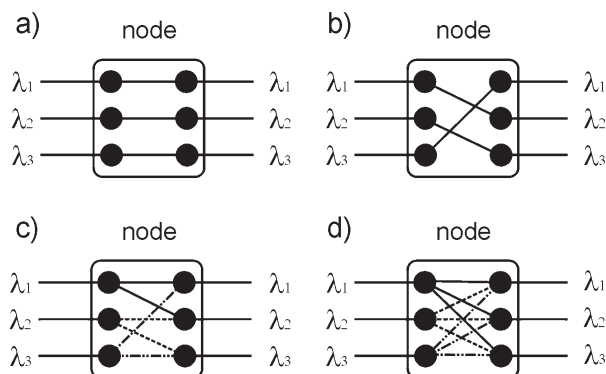


Fig. 2 Types of wavelength conversion

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- *no-wavelength conversion*: if the  $k = 1$ , where each incoming wavelength is converted only to itself (any incoming wavelength is switched to the same outgoing wavelength) (Fig. 2.a),
- *fixed wavelength conversion*: if the  $k = 1$ , where each incoming wavelength can be converted to other outgoing wavelength, but this outgoing wavelength is well-known (it is still the same) (Fig. 2.b),
- *limited wavelength conversion*: if the  $1 < k < W$ , where each input wavelength can be converted to any wavelength from a specific limited set of wavelengths (Fig. 2.c),
- *full wavelength conversion*: if the  $k = W$ , where any incoming wavelength can be converted to any outgoing wavelength (Fig. 2.d).

### 3. Network without wavelength conversion

In the networks without wavelength conversion the optical signal is transmitted from the source node to end node through all links on the same wavelength along a physical path. The session has to use the same wavelength on every fiber-hop (links). This requirement is also known as the wavelength continuity constrain.

Before the session is set up, the wavelengths, which are not occupied on all the links of the path, are found. After that we choose a wavelength out of these free wavelengths by some wavelength assignment methods. This wavelength is the same on all the links of the path. If no such a wavelength is available on all the links then the new call is blocked and, consequently, is lost. A call is accepted on a route if there exists at least one wavelength, which is simultaneously idle on all the links of that route. This means that an arrival call can be blocked if there are free wavelengths on all the links but it is not the same.

We can suppose without any mathematical analysis that the networks without wavelength conversion have the worst behavior of other networks (with full or limited wavelength conversion). The blocking probability is measured of the throughput of network and is the highest in the network with no conversion. However, the very good network routing and wavelength assignment algorithm can slightly decrease blocking probability. But these algorithms are more complicated and their complexity is significant.

In these networks the utilization of wavelengths is very small due to the wavelength continuity constrain if we want to keep the low blocking probability. If we want to increase the wavelength utilization the blocking probability will be increased very dramatically. Moreover, the blocking probability is very increased with a number of hops on a path. Therefore, we have to achieve sufficiently low utilization, for example usually about  $0.1 \div 0.2$  for 10 hops and 15 wavelengths. Barry and Humblet [4] have proposed the model for evaluation wavelength utilization as a function of a number of wavelengths for the certain number of hops. There are very interesting results for the networks without wavelength conversion.

### 4. Network with limited wavelength conversion

The limited wavelength conversion is wavelength conversion in some node where each input wavelength can be converted to any wavelength from a specific limited set of wavelengths. We know different ways of limited wavelength conversion, which are described in next chapters.

#### 4.1 Symmetrical limited wavelength conversion with conversion degree d

A limited range symmetrical wavelength conversion with conversion degree  $d$  is the conversion of the wavelength of the optical signal at the switch, which can convert any incoming wavelength to  $d$  adjacent wavelengths on the output side from the wavelength plane of the spectrum, as well as to the input wavelength itself (the same wavelength) [5]. The wavelength plan is an order of all outgoing wavelength. We choose the same outgoing wavelength or from  $d$  outgoing wavelength on the left or on the right side from wavelength plane. The possible outgoing wavelengths are symmetrically distributed.

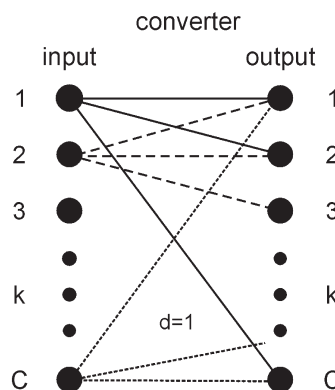


Fig. 3 The symmetrical limited wavelength conversion with conversion degree  $d = 1$

This means that any wavelength can be converted to  $k = 2d + 1$  outgoing wavelengths (Fig. 2). In general, if the incoming wavelength is  $\lambda_i$ , then this wavelength can be switched to any outgoing wavelength  $\lambda_{i-d}, \dots, \lambda_i, \dots, \lambda_{i+d}$ , where  $\lambda_i$ , for  $i = 1, 2, 3, \dots, n$  are possible outgoing wavelengths for the conversion degree  $d$ .

If  $d = 0$  then it is the case without wavelength conversion. Otherwise, if  $d$  is very high it is the full wavelength conversion case. Usually  $d = 1$  or  $d = 2$ .

This case of limited wavelength conversion is the best for the wavelength converter technology. The time needed to set up the switching elements is shorter than in other cases. It means that the technological requirements are no so complex.

#### 4.2 Non-symmetrical limited wavelength conversion with conversion degree $d$

In this case, the input wavelength can be converted to the same wavelength or to one on the left side (the right side) from the wavelength plan. It means that it is possible to switch any input wavelength to  $k = d + 1$  output wavelengths.

For example, if the incoming wavelength is  $\lambda_i$ , then the wavelength can be switched to the following set of wavelength  $\lambda_{i-d}, \dots, \lambda_i$ , in the case “conversion on the left side” (Fig. 4.a), or  $\lambda_i, \dots, \lambda_{i+d}$ , in the case “conversion on the right side” (Fig. 4.b).

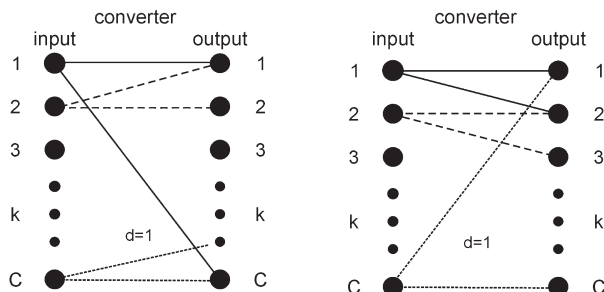


Fig. 4 The non-symmetrical limited wavelength conversion with conversion degree  $d = 1$   
a) “on the left side” b) “on the right side”

#### 4.3 Random limited wavelength conversion

The random limited wavelength conversion is generalization of limited wavelength conversion when any input wavelength is converted to the limited set of wavelengths, which is well-known. However, the selection of wavelengths for any set of wavelength is random from the wavelength plan.

#### 4.4 Partial limited wavelength conversion

In the standard architecture, at first, each wavelength is switched in space. Then, if possible, it is converted to the same or another wavelength. However, in networks with conversion each output port has its converter (Fig. 5).

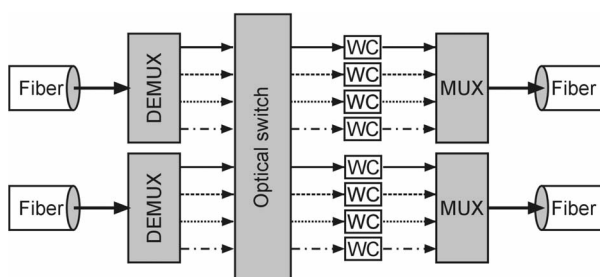


Fig. 5 Non-partial wavelength conversion

In this case, the limited number of wavelengths can use wavelength converters at the same time. There is a set of wavelength converters, which are shared by all the output ports. These converters are ordered to a converter bank. The idea of this architecture is to save the number of used wavelength converters. Therefore only the wavelengths requesting wavelength conversion are transported through the converter bank. Each wavelength converter can provide full or limited wavelength conversion.

We know different architectures of partial limited wavelength conversion [6]:

- share-per-node wavelength-convertible switch architecture: The converter bank is shared for all the output wavelengths of any fiber. However, it means that we need the second space optical switch, which is smaller (Fig. 6).
- share-per-link wavelength-convertible switch architecture: The converter bank is shared for all output wavelengths of the fiber link. However, it means that we need more converter banks (Fig. 7).

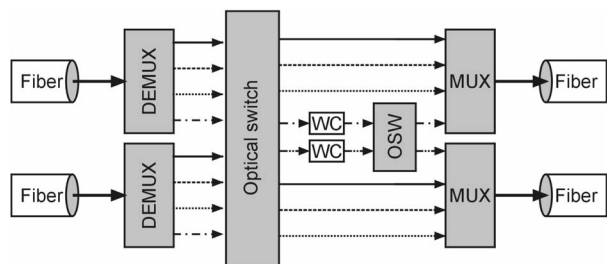


Fig. 6 Share-per-node wavelength-convertible switch architecture

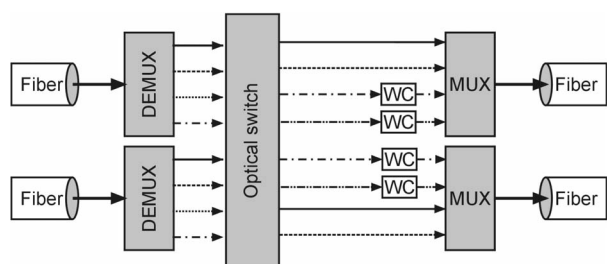


Fig. 7 Share-per-link wavelength-convertible switch architecture

#### 4.5 Sparse limited wavelength conversion

If some nodes of the network have a wavelength converter, but not all, then it is called sparse limited wavelength conversion (Fig. 8) [7]. And the wavelength converter can provide either full or limited wavelength conversion.

A lightpath has to use the same wavelength along several links in a segment between two nodes, which are equipped with converters. However, it is possible to use a different wavelength for a lightpath along the different segment of links.

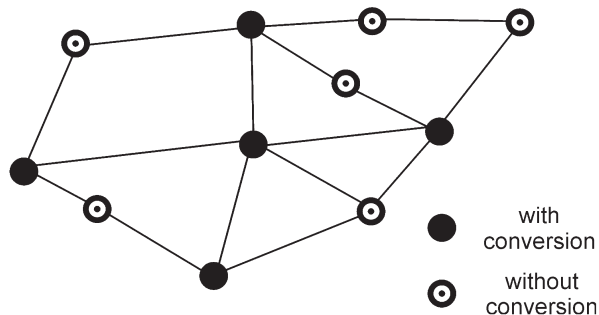


Fig. 8 Sparse wavelength conversion network

#### 4.6 The different ways for building the networks with limited conversion

The networks with limited wavelength conversion do not enable full conversion but the conversion with some restriction is possible. This restriction can be realized at the node, where any input wavelength can be connected to a limited set of output wavelengths. This case is called the node limited wavelength conversion. Otherwise, the next restriction at the node is partial wavelength conversion. The other restriction is the limited number of nodes enabling wavelength conversion. All other nodes do not enable wavelength conversion. It is called sparse wavelength conversion.

The all-optical networks with limited wavelength conversion can be divided to the following cases:

- limited wavelength conversion due to restriction at the node:
  - all nodes of WDM network use converters only with limited wavelength conversion,
  - all nodes of WDM network use converters only with partial wavelength conversion,
- sparse (limited) wavelength conversion due to restriction in the network:
  - only a few nodes employ wavelength converters with limited wavelength conversion (other nodes employ either without or full wavelength conversion),
  - only a few nodes employ wavelength converters with full wavelength conversion, other nodes do not enable wavelength conversion,
- in the case of multi-fiber WDM networks, the network do not enable wavelength, but the same wavelength can be employed on the different fiber on the same link.

Further, the network with limited wavelength conversion can originate as a combination of the limited wavelength conversion due to restriction at node with sparse wavelength conversion due to restriction in the network.

#### 5. Network with full wavelength conversion

In networks with full conversion, a full conversion is enabled to all nodes. It means that any incoming wavelength can be changed to any outgoing wavelength in all switches.

In that case we choose a wavelength out of the free wavelengths on the first hop by some wavelength assignment algorithm. This is repeated on the subsequent hops of the path. In case there is no free wavelength on some link of the path the arrival call is blocked and lost [8].

It is clear that these networks are the most flexible of other cases and these networks have the lowest loss. However, full conversion networks are the most technologically difficult because optical switches have to enable to switch any input with every output. This switching has to be very fast and it is still a complex problem today.

It is clear that the networks with full wavelength conversion have the best performance. However, it has been found that good routing policy in network without wavelength conversion can decrease the blocking probability. And moreover, the network with limited wavelength conversion has the blocking probability very close to blocking probability of network with full wavelength conversion. The network with the sparse wavelength conversion uses far less converters than the networks with full wavelength conversion. But if we use good placement algorithms for location converters the performance of sparse wavelength conversion is similar to the one in the case of networks with conventional wavelength conversion.

#### 6. Conclusion

We presented different possibilities of wavelength conversion in WDM network. We wanted to provide you with an overview of the current state and new promising technology in this area. Moreover, we want to indicate how blocking probability depends on the wavelength conversion and which case is the best in term of blocking probability. But which is also important is effectiveness and value.

The present state of technology does not provide the full wavelength conversion in the real networks because it is very expensive. The networks with limited wavelength are very popular and probably they will become more used in the future. There are many possibilities how to apply the limited wavelength conversion into the real networks. If the sparse wavelength conversion is used, it is not necessary to equip each node of the network with the wavelength converter. And if the partial wavelength conversion is used, it is not necessary to place as many converters into node as in case of the full conversion. Both approaches mentioned save the wavelength converter as the most expensive part of WDM switch. And if the limited wavelength conversion is used in the node, we do not need so complicated wavelength converters. It means that all the restrictions mentioned save financial resources.

In future, we will study the limited wavelength conversion in more detail and we will design the network model for computing blocking probability in WDM networks. Moreover, we want to determine the optimal placement for the wavelength converters in networks with sparse limited wavelength conversion.

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