Utilization of Optical Fibre WDM Channel in Wavelength Routed Networks using Sparse Partial Limited Wavelength Conversion

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Abstract—in the previous 20 years, wavelength conversion has received a considerable attention due to its strong influence on the blocking performance of wavelength-routed WDM networks. In a wavelength-routed WDM network, end users communicate with one another via all-optical WDM channels. In all-optical WDM channels optical fibre is used. Optical fibre is a single, hair-fine filament drawn from molten silica glass. These fibre are replacing metal wire as the transmission medium in high-speed, high-capacity communications systems that convert information into light, which is then transmitted via fibre optic cable. Wavelength converters help to reduce the blocking probability of the network and enhance the fibre utilization. Most of the related works focus on only one aspect of wavelength conversion, i.e., sparse or partial or limited wavelength conversion. This paper will recommend the use of sparse-partial-limited wavelength conversion (SPLWC) integrating all approaches i.e. sparse or partial or limited wavelength conversion. For minimizing the wavelength conversion cost (WCC) a converter placement problem is considered to meet the constraint on the blocking probability. A novel analytical model will be presented for accounting the two sources of call blocking in wavelength conversion: a range blocking from the limited conversion range of a wavelength converter; and a capacity blocking from the limited number of wavelength converters. A converter placement algorithm will also be presented which can be applicable to any wavelength conversion schemes. The MATLAB/SIMULINK Communication tool box is used for implement the proposed model.

Keywords—Blocking probability, converter placement, wavelength converters, wavelength routing, optical fibre cable and wavelength division multiplexing (WDM) networks

I. INTRODUCTION

WDM (wavelength division multiplexing) allows several optical channels (wavelength) to be allocated simultaneously in an optical fibre, improving its transmission capacity. Present status of WDM technology provides transmission rates in the order of terabit per second (Tbps) in a single fibre. Besides, WDM channels can be modulated independently, allowing different rates and transmission formats through the same fibre. In an optical network, a lightpath interconnects two optical nodes, establishing a communication path formed by one or more concatenated links between them. In the absence of wavelength converters, a lightpath must use the same wavelength from the source to the destination. This propriety is known as wavelength continuity constraint. On the other hand, a wavelength-routed WDM network allows overcoming such restriction by using Wavelength Converters - WC. WCs are devices located at optical network nodes, with the purpose of converting an input wavelength into a different output wavelength. Therefore, using WCs, a lightpath may be formed by different wavelengths, in different links. In WDM networks of this type, a node with wavelength conversion capability is called a Wavelength Convertible Router - WCR [2] [3]. Although recent improvements in wavelength converters technology, its costs still remain very high. Therefore, many works has focused its efforts on wavelength conversion architectures where just a few numbers of WCs are available. Those architectures have been proposed with the goal of achieving performance close to full-complete wavelength conversion using a lower number of WCs and decreasing equipment costs.

Complete wavelength conversion: Fig. 1 shows an example of a WCR with Complete Wavelength Conversion capability, where each output port of the optical switch is associated with a dedicated wavelength converter. This kind of ideal WCR is assumed to be able to convert all the input wavelengths to any other wavelengths simultaneously without any limitation. Note that the number of converters is equal to the number of the fibre links multiplied by the number of wavelengths per fibre. Since the number of wavelengths on each fibre could be hundreds or even more, the number of converters inside a WCR will be very large and the cost of such architecture can be prohibitively high.

Partial wavelength conversion: It has been shown that a WCR with a limited number of converters can achieve very close performance to Complete Wavelength Conversion. This is referred to as Partial Wavelength Conversion. Fig. 2 shows the architecture of a WCR with share-per-node partial wavelength conversion. There is a pool of wavelength converters which are shared by all the output ports. This architecture requires much less number of wavelength converters. Hon-ever, it is more complex than a wavelength router without wavelength conversion, because it needs an addition small optical switch (OSW). In addition, it remains unknown how many converters should be equipped in a WCR in order to achieve satisfactory performance. If all the
wavelength routers in the network support wavelength conversion (either completes conversion or partial conversion). We call it Full wavelength conversion. On the other hand, it’s only a small part of the wavelength routers can perform wavelength conversion. The network is called with sparse wavelength conversion [4]. The latter has received much attention recently, because it can significantly save the number of WCRs. It also offers a flexible solution for the network carriers to upgrade their network gradually to support wavelength conversion. To date, most of existing studies simply assume that, the WCRs in a Sparse Wavelength Conversion networks all have the capability of Complete Wavelength Conversion, which however is very costly and inefficient in practice.

Fig. 1. A wavelength converter with full wavelength conversion

Fig. 2. A wavelength converter with partial wavelength conversion

The midway-point works in [5]-[8] outperform the FWC, they focus on only a part of wavelength conversion, i.e., sparse [5] or partial [7] or limited [8] wavelength conversion. As a result, it is very difficult to quantitatively compare the performance of different approaches. Furthermore, it is not clear which wavelength conversion scheme leads to the optimal performance of WDM networks. To address these limitations, an alternative wavelength conversion problem will be introduced that determines the placement of wavelength converters to minimize the wavelength conversion cost (Min WCC) while satisfying the constraint on the blocking probability; here, the WCC is defined as the sum of conversion ranges over all wavelength converters in the network. To address the Min WCC problem the use of sparse-partial-limited wavelength conversion (SPLWC) would be advocated that encompasses all existing wavelength conversion approaches. More specifically, a new analytical model is presented that can precisely estimate the blocking probability of WDM networks with SPLWC. Based on this model, a converter placement algorithm will also be presented that would achieve an optimal WCC performance regardless of the wavelength conversion schemes. The accuracy of the analytical model would be validated by showing that the blocking performance of the analysis closely matches with that of the simulation. It will also be shown that SPLWC can achieve an outstanding WCC performance when compared with that of the existing schemes.

II. NETWORK MODEL AND ANALYSIS

A wavelength-routed WDM network consisting of N nodes and L links is considered. Each link has a single fibre carrying W wavelengths, labelled from 0 to W − 1. A node can be either wavelength-selective or wavelength-convertible depending on the capability of wavelength conversion. A wavelength selective node (WSN) connects an input wavelength to the same output wavelength, whereas a wavelength-convertible node (WCN) can switch an input wavelength to a set of adjacent output wavelengths. Each WCN has a wavelength converter pool (WCP) shared by all wavelength ports. To maximize the sharing of the WCP, shared-per node architecture is assumed. The WCP consists of n wavelength converters whose conversion range is d. Assuming the dynamic-traffic scenario, a call is dynamically established or torn down at random time points. A call request arrives at path r according to the Poisson process with rate \( \lambda_r \), and has exponential holding time with unit mean. Thus, the traffic load of path r is equal to \( \lambda_r \). Fig. 3 shows an H-hop path r and the corresponding notations. Path r is defined as an ordered set of \((H + 1)\) nodes and L links, where \( r = \{v_0, e_1, v_1, e_2, \ldots, v_{i+1}, \ldots, v_H\} \) denote by \( V_r \) the ordered subset of path r, consisting of nodes only, where \( V_r = \{v_0, v_1, \ldots, v_H\} \). \( V_r \) is further partitioned into the set of end nodes denoted by \( V_{\text{r}E} \), and the set of intermediate nodes denoted by \( V_{\text{r}I} \), where \( V_{\text{r}E} = \{v_0, v_H\} \) and \( V_{\text{r}I} = \{v_1, v_2, \ldots, v_{H-1}\} \). The ordered subset of path r is also denoted by \( E_r = \{e_0, e_1, e_2, \ldots, e_{H-1}\} \), comprising of links only, where link \( e_i \) connects node \( v_i \) to node \( v_{i+1} \). A segment of path r is defined as an ordered subset of path r consisting of consecutive nodes and links. The segment from element \( v_i \) to element \( v_j \) is denoted by \( (x_i \rightarrow x_j) \), where \( x_i \) and \( x_j \) are either a node or a link.
Most of the existing converter placement algorithms focus on the minimization of the blocking probability for a given number of wavelength converters [3], [4]. However, these works consider only one aspect of wavelength conversion technology; as a result, it is very hard to fairly compare different wavelength conversion approaches in a unified manner. To address these limitations, an alternative definition of converter placement problem is introduced, which is called the MinWCC problem that determines the placement of wavelength converters to minimize the WCC with a constraint on the blocking probability BWCC. Here, the WCC is defined as the sum of the number of wavelength converters in the network multiplied by its conversion range, i.e.,

$$ WCC = \sum_{x=1}^{n(x)} n(x) \times d $$

The blocking probability BWCC can be any points between the lower bound BFWC and the upper bound BNWC, i.e.

$$ B_{WCC} = (B_{FWC})^{\alpha} (B_{NWC})^{1-\alpha} $$

Where BFWC and BNWC are the blocking probability of FWC and NWC, respectively and \( \alpha \) is traffic load of shortest path. As the parameter \( \alpha \) increases from zero to one, B_{WCC} decreases from B_{NWC} to B_{FWC} in a geometrical progression.

\( \alpha_j(m) \) is the total offered load of link \( e_j \) when \( X_j = m \), can be obtained by aggregating all contributions of such paths, i.e.

$$ \alpha_j(m) = \sum_{\forall r : x_j \in e_r} \alpha_r (1 - B_{FWC})_{x_j = m} $$

Where \( B_{FWC} \) is link conditional blocking probability, the partition of path \( r \) into three independent segments: the left segment \( (v_0 \rightarrow v_j) \), link \( e_j \), and the right segment \( (v_{j+1} \rightarrow v_y) \). It is denoted by \( x \) and \( y \), the number of free wavelengths of the left segment and the right segment respectively. The number of wavelengths commonly free between the left and the right segment is denoted by \( z \). In order for path \( r \) to be blocked, there should be no common wavelength in all three segments.\[ i.e. \]

$$ B_{FWC}^m = \sum_{x=0}^{W} V_j - (x) \sum_{y=0}^{W} V_j(y) \sum_{z=0}^{\min(x,y)} R(z|x,y)R(0|z,m) $$

The network-wide blocking probability can be represented in terms of the end-to-end blocking probabilities, i.e.

$$ B = \sum_{r \in R} \alpha_r B_r $$

A sequential converter placement algorithm (SCPA) is presented to solve the MinWCC problem based on the analytical model. The SCPA first determines the minimum conversion range of wavelength converters, denoted by \( d_{min} \), to meet the constraint on the blocking probability (STEP I). Under the assumption of LWC, the SCPA starts with \( d_{min} = 1 \), and then increases \( d_{min} \) one by one until the blocking probability is less than or equal to B_{WCC}. Once the value of \( d_{min} \) is determined, the SCPA starts with a SPLWC WDM network without any wavelength converters (STEP II). The key idea of the SCPA is to sequentially add a wavelength converter to a node which results in the maximum amount of traffic blocking in the network, until the blocking probability is less than or equal to B_{WCC} (STEP III and STEP IV). In this procedure, the traffic blocking of a WSN is represented by the range blocking \( (\delta_{min}) \), whereas that of a WCN is contributed by the capacity blocking \( (\beta_s) \). Below, a brief description of the SCPA is also presented where \( n(x) \) stands for the number of wavelength converters at node \( x \).

**Converter Placement Algorithm**

**STEP I** Assuming LWC, find the smallest conversion range \( d_{min} \) in which the blocking probability is less than or equal to the constrained blocking probability, i.e.

$$ B \leq B_{WCC} $$

**STEP II** Assuming SPLWC, start with a WDM network without any wavelength converters, i.e.

$$ n(x) = 0 $$

**STEP III** Based on the analytical model, compare the computed Blocking probability \( B \) and the constrained blocking probability \( B_{WCC} \). Terminate this algorithm, if \( B \leq B_{WCC} \); otherwise, go to STEP IV.

**STEP IV** Compute the amount of traffic blocking at each node.

If a node is a WSN, calculate the range blocking \( (\delta_{min}) \); otherwise, calculate the capacity blocking \( (\beta_s) \). Find the node yielding the maximum traffic blocking, denoted by \( x^* \). Add a wavelength converter to the corresponding WCP, i.e. \( n(x^*) = n(x^*) + 1 \), and then go to STEP III.

Here, two sources of call blocking at the WCP i a WCN:

- Range blocking due to the limited conversion range of a wavelength converter.
- Capacity blocking due to the limited number of wavelength converters.

The SCPA considers the most general case of wavelength conversion, i.e. SPLWC; thus, it can be easily applicable to any special case of SPLWC, such as SWC, PWC, and LWC. For example, two simple modifications of
SCPAs will suffice for the case of SWC: 1) the algorithm predetermines the conversion range \( d_{\text{max}} = W \) in STEP I; and 2) the algorithm increases \( n(x') \) by \( D(x') \times W \) in STEP IV, where \( D(x) \) is the number of outgoing links directly connected to node \( x \).

NSFnet: We consider NSFNET with 14 nodes and 21 edges, depicted in Fig. 3. The routes are the shortest paths in terms of number of hops and the traffic are converted into the probabilities of call arrivals accordingly. We assume that the traffic load is uniformly distributed to all the node pairs.

III. EXPECTED OUTCOME

In this section, the accuracy of analytical model is verified and compared the WCC performance of SPLWC with that of existing schemes. All results taken from the experiments will be well-known network topologies of NSFNet.

At present assuming that an incoming call at a node is uniformly destined to \( (N - 1) \) other nodes. Firstly the accuracy of our analytical model is validated & then compares the WCC performance of the wavelength conversion schemes. As expected, the WCC of the FWC is always equal to one. Three basic solutions, i.e. SWC, PWC, and LWC, can satisfy the constrained blocking probability with much smaller WCC. Among these schemes, the PWC (SWC) scheme shows the lowest (highest) WCC. Two combined solutions, i.e. SLWC and SPWC, show a better WCC performance than then the basic solutions, but the improvement of the WCC is marginal. We also observe that SPLWC has the outstanding WCC performance compared with all existing wavelength conversion schemes, regardless of \( a \). From these results, we conclude that SPLWC outperforms the existing wavelength conversion approaches in terms of the WCC.

IV. CONCLUSION

In this paper, an alternative wavelength conversion problem is studied to find the placement of wavelength converters in order to minimize the wavelength conversion cost under the constraint on the blocking probability. The use of SPLWC is advocated that encompasses all existing wavelength conversion approaches, i.e., SWC, PWC, and LWC. An analytical model is presented to estimate the blocking probability of WDM networks with SPLWC. This model is the first one taking into account the two sources of call blocking in WCNs: a range blocking and a capacity blocking. Based on this model, a sequential converter placement algorithm is also presented that is applicable to any wavelength conversion schemes considered in this paper.

REFERENCES


