Evaluation of the Flexibility of Switching Node Architectures for Spaced Division Multiplexed Elastic Optical Network

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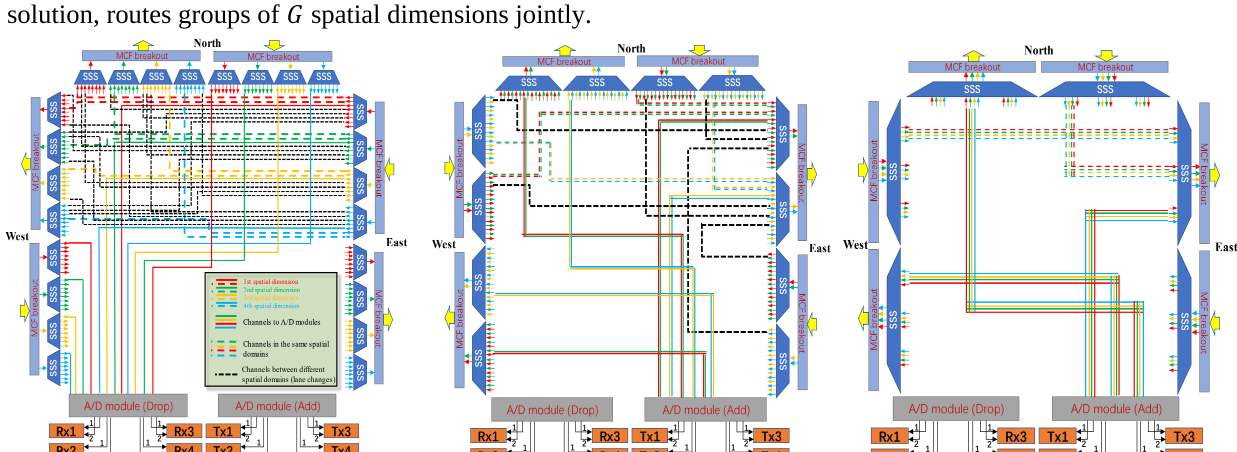
Abstract: We present a flexibility model for quantitatively evaluating switching node architectures in terms of switching strategies, function and required components in SDM-EON, revealing designs with the most switching flexibility.

1. Introduction

Traditional elastic optical networks (EON) have fulfilled the demand of disparate traffic granularity, raising the utilization of spectral resources and network capacity. By exploiting fiber capacity to the full, space division multiplexing (SDM) over multi-core or multi-mode fiber would allow the optical transport network to keep pace with traffic growth beyond the petabit per second level [1], which would be a promising technology for the future bandwidth-hungry applications. In the meantime, colorless, directionless and contentionless (CDC) operation of reconfigurable optical add/drop multiplexers (ROADMs) has become a commercial reality for EON. Such switching node architectures can also be upgraded to route signals between different spectral and spatial dimensions in SDM-EON.

In order of decreasing flexibility and increasing hardware efficiency, three SDM switching strategies have been proposed and evaluated [1][2][3]: independent switching (InS), fractional joint switching (FrJoS), and joint switching (JoS), as it is shown in Fig. 1. Spatial super-channels (SChs), i.e., data streams transported as groups of sub-channels occupying the same spectral slots across different spatial transmission media [2], have been achieved in these switching strategies. Therefore, multi-core fiber (MCF) fan-out [4] is needed to separate multiple cores into groups of spatial channels. Spectrum selective switches (SSS) have replaced fixed-grid wavelength selective switches (WSS) to support elastic spectrum allocation for finer granularity. More ports provided by SSSs enable the ability to establish connections between different spatial domains, which is also known as "lane changes" (LC) [3].

Fig. 1 shows switching node architectures based on route-and-select (R&S) architecture with three nodal degrees ($D = 3$) in SDM network with four spatial dimensions ($S = 4$). The spatial dimensions are fiber cores here. Note that only connectivity from "East" is shown. SSSs switch spatial super-channels as groups of G spatial dimensions' sub-channels, where G is a divisor of S. The three switching strategies can be defined as cases where G takes different values, i.e., $G = 1$ for InS strategy and $G = S$ for JoS strategy [2]. In Fig. 1(a), each spatial dimension is routed independently whereas all spatial dimensions are routed together in Fig. 1(c). FrJoS, as an intermediate solution, routes groups of G spatial dimensions jointly.



(a) InS (G=1) (b) FrJoS (G=2) (c) JoS (G=4)

Fig.1 R&S-based switching node architectures

However, binding a group of channels will limit the switching flexibility of the system [5]. A flexibility measurement approach based on entropy maximization has been proposed to quantitatively evaluate switching flexibility of the optical components in EON [7]. Nevertheless, a detailed study analyzing switching flexibility quantitatively in SDM-EON, while considering the influence of lane changes and spatial super-channels, is missing from the literature. In this paper, we propose a switching flexibility model based on entropy maximization for comparing switching node architectures enabling InS, FrJoS and JoS strategies. We find that less coupled spatial super-channels (i.e., lower G), the introduce of lane changes, more connections in A/D modules and finer spectrum granularity in SSSs will result in better switching flexibility, and the effect of any aspect can be evaluated quantitatively.

2. Flexibility measurement approach and flexibility analysis

By referring to [5] that has proposed an approach to measure flexibility in the context of EON, we consider the influence of some features introduced by SDM, e.g., lane changes and spatial super-channels, and refine the measurement approach to implement it in SDM-EON.

Consider the problem of switch a signal from any input to any output in Fig. 1 (a). Note that switching flexibility is the ability of a system to map inputs to outputs in different ways and across different dimensions, e.g., frequency, time and space [5]. The number of mapping ways is finite. One can associate each distinct map with a different state s_i of the switching node. Let $S = \{s_1, s_2, s_3, \dots, s_M\}$ be the set of all possible states. Suppose that for each state s_i there exists a stable value at any instant in time, regardless of the initial conditions, i.e., the system is ergodic. Thus, the system can be modeled as a discrete Markoff process with alphabet S and associated probability $P = \{p_1, p_2, p_3, \dots, p_M\}$. Therefore, the entropy of the system can be calculated [6] in (1):

$$H(S,P) = -\sum_{i=1}^{M} p_i \log(p_i) \tag{1}$$

The state probabilities of a device p_i are determined by factors such as traffic load, traffic requirements. However, there is a maximum limit to the entropy set by the properties of the devices itself. We call this maximum entropy the flexibility of the device [5]. Thus, we have (2)

$$F(S) = \max\,[\,H(S,P)\,]. \tag{2}$$

Obviously, $H(S,P)$ is maximum when all the states are equiprobable, i.e., $p_i = 1/M$, where M is the number of different states (also known as the cardinality of S). Put p_i into (1), we get

$$F(S) = \log(M). \tag{3}$$

By going back to the definition of entropy [6], if two components a and b with flexibilities F_a and F_b are connected together to form a subsystem (a,b), then

$$F_{(a,b)} \leq F_a + F_b, \tag{4}$$

with equality only if the components can work independently from one another.

Review the switching node architecture in Fig. 1. Switching flexibility is provided in this architecture and hereby calculated. SSS devices at each output may block spectral slots or pass them from one of the inputs or from the A/D module. Determined by the features of SSS devices, a signal cannot be switched simultaneously to several outputs or dropped, i.e., multicasting is not supported. Suppose that the spectral granularity factor of SSSs is k. Therefore, the switching flexibility of R&S-based node architecture excluding A/D modules is (5) and (6), which supports and does not support lane changes, respectively.

$$F(S)_{RS-LC} = k \log\left[\sum_{i=0}^{\frac{S}{G}D} \binom{\frac{S}{G}D}{i} 2^i \binom{\frac{S}{G}D}{\frac{S}{G}D - i} \left(\frac{S}{G}D - i\right)!\right] \tag{5}$$

$$F(S)_{RS-nLC} = k \frac{S}{G} \log\left[\sum_{i=0}^{D} \binom{D}{i} 2^i \binom{D}{D-i} (D-i)!\right] \tag{6}$$

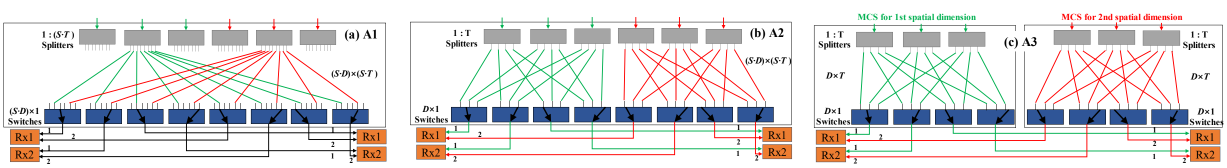


Fig.2 Three MCS-based A/D module architectures. Only ‘Drop’ MCS are shown.

The A/D modules are implemented with multicast switches (MCS) considering 2 spatial dimensions as shown in Fig. 2 (only the drop modules). T is the number of transceivers (TRx) connected to the A/D ports. The architecture shown in Fig. 2(a) supports full CDC switching between all common ports and A/D ports and is required in the case of single-channel TRxs, while in Fig. 2(b) and (c) connectivity is simplified to provide CDC operation per spatial dimension [2]. The simplification also leads to loss of flexibility to some extent. Note that the splitter can switch a signal to multiple switches simultaneously, i.e., multicast is supported. Thus, the switching flexibility of MCS-based A/D modules A1, A2 and A3 is (7), (8) and (9), respectively.

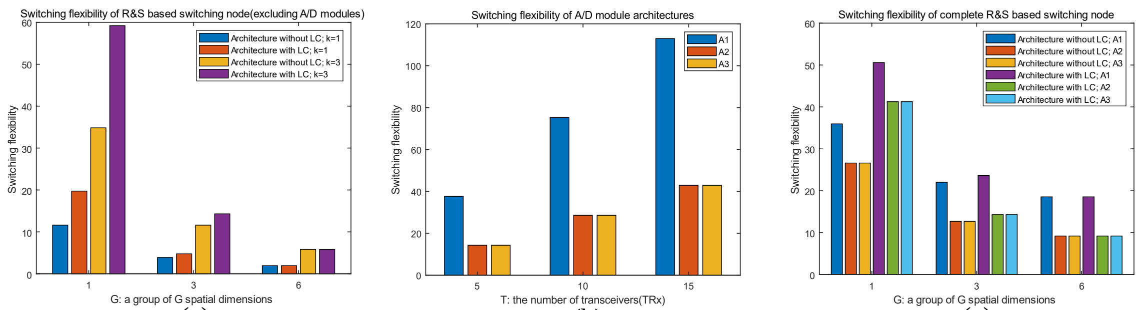
$$F(S)_{A/D-A1} = ST\log(SD) \quad (7) \qquad F(S)_{A/D-A2} = ST\log(D) \quad (8)$$

$$F(S)_{A/D-A3} = ST\log(D) \quad (9) \qquad F(S)_{total} = \alpha F(S)_{RS} + \beta F(S)_{A/D} \quad (10)$$

Going back to inequation (4), since the switching part of the node works independently with the A/D modules, we add the flexibility of the switching part and the A/D modules to calculate the total switching flexibility of the node in (10).α and β are the weight of the switching part and the A/D modules determined by their influence on the whole system in specific applications.

3. Discussions on the flexibility of R&S based switching node architectures

Based on the flexibility model described previously, we calculate the total switching flexibility of each R&S based switching node architecture. A degree-3 ($D = 3$) switching node for an SDM-EON network with 6 spatial dimensions ($S = 6$) is considered for the calculations.



(a) (b) (c)

Fig.3 Switching flexibility of different architecture implementations

Fig. 3(a) shows the most flexible R&S-based switching node architecture excluding A/D modules is the one which i) supports lane changes, ii) implements InS strategy ($G = 1$), iii) uses SSSs with highest spectral granularity ($k = 3$). The effect of introducing lane changes on switching flexibility is dramatic when implementing InS strategy, while with the increase of G the effect decreases dramatically. Conversely, the influence of using SSSs with higher spectral granularity is stable regardless of switching strategy. Fig. 3(b) shows that A1 provides the most switching flexibility in MCS-based A/D modules, which we can attribute to the redundant connections between the splitters and the switches. With the number of transceivers increasing, more switching flexibility is required to switch signals to different transceivers. Since there is no big difference between switching architectures of A2 and A3, they provide the same flexibility in any case. Fig. 3(c) shows the switching flexibility of complete R&S based switching node in the case that $k = 3$, $T = 5$, $\alpha = 0.6$ and $\beta = 0.4$. The node architecture providing the most switching flexibility is the one which implements InS strategy, supports lane changes and applies A/D module design A1. By referring to the cost model in [2], this architecture maximizes the switching flexibility at the expense of the highest total relative cost. In a practical system, the flexibility should be balanced against its cost depending on the specific application.

4. Conclusions

We proposed a flexibility measurement approach in SDM-EON to quantitatively evaluate the switching flexibility of node architectures. By calculating the flexibility of each architecture, we found that an architecture introducing lane changes, implementing InS strategy and maximizing the number of A/D ports and the spectral granularity, achieves the best switching flexibility performance. On this basis, we will consider quantitatively trading off the cost against the system flexibility depending on the specific network in the future.

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