Impact of PMD on Hybrid WDM/OCDM Networks

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Abstract—In this work, we investigated the impact of polarization-mode dispersion (PMD) in optical networks using the hybrid technology of wavelength-division multiplexing and optical code-division multiplexing. In these networks, virtual paths based on code/wavelength channels (VCP/VWP) are dynamically established to attend the traffic demand. We use a routing channel assignment based on genetic algorithm to establish the VCP/VWPs. The main results show that the network blocking probability caused by PMD depends on parameters of optical orthogonal codes like weight and length.

Index Terms—Optical orthogonal codes (OOCs), polarization-mode dispersion (PMD), wavelength-division multiplexing and optical code-division multiplexing (WDM/OCDM).

I. INTRODUCTION

HYBRID wavelength-division multiplexing and optical code-division multiplexing (WDM/OCDM) allow us to improve the capacity and scalability of optical networks enabling the scaling number of usable channels in two dimensions: code and wavelength. These networks, known as transparent virtual optical code/wavelength path network [1], utilize multiplexing methods to establish virtual paths based on wavelength and code. The research emphasis on OCDM has expanded from low rate short-range networks to include high-capacity and medium/large range code/wavelength routed networks [2]. Further, the interest in OCDM/WDM applications has increased mainly in networks that use code and wavelength as labels like those proposed in [3] and [4]. These approaches support intelligent optical routing and switching, and are compatible with generalized multiprotocol label switching [2]. The performance of such networks was analyzed in [2], [4], and [5], however, any physical impairment has been considered. In this letter, we will analyze the effects of polarization-mode dispersion (PMD) on the blocking probability performance of such networks, because different from chromatic dispersion, it is difficult to accurately determine and compensate PMD due its dynamic nature [5]. We use a routing channel assignment (RCA) based on genetic algorithm (GA) to solve the problem of dynamically allocating wavelengths and codes in a hybrid WDM/OCDM network. This letter is organized as follows. Section II briefly presents the concepts of PMD constraint. Section III describes the techniques and methodology applied. Section IV shows the numerical results. Finally, Section V concludes this letter.

II. PMD CONSTRAINT IN WDM/OCDM NETWORKS

PMD impairment establishes an upper bound on the length of the optical segment due to fiber dispersion which causes the temporal spreading of optical pulses. In WDM/OCDM, the upper link distance depends on the chip-rate distance product \((L \cdot L_0 \cdot B)\), where \(L_0\) is the link length, \(B\) is the bit rate and \(L\) is the code length. The minimum value of \(L\) for \(C\) different codes considering the code cardinality is given by [6]

\[ L \geq [C \cdot w \cdot (w - 1) + 1]. \]  

(1)

In particular, the PMD places an upper bound on code length limiting the number of distinct codes because the chip rate is \(L\) times the effective data rate due to spreading [7]. A route in an optical network consists of \(M\) fiber spans, where each span refers to a segment between two optical nodes. The main restriction of PMD shows that the average differential group delay of two orthogonal polarization states should be less than one fraction of bit duration, \(T = 1/B\). The relation between chip-rate distance product and optical orthogonal code (OOC) parameters adapted from [7] considering (1)

\[ B \cdot [C \cdot w \cdot (w - 1) + 1] \cdot \sqrt{\sum_{k=1}^{M} D_{PMD}(k)^2 \cdot L_0(k)} < a \]  

(2)

where \(w\) is the code weight, \(C\) is the number of OOCs, \(D_{PMD}(k)\) is the fiber PMD parameter measured in ps/\(\sqrt{\text{km}}\), \(L_0(k)\) is the length of the \(k\)th span, \(a\) is fraction of the bit duration, \(T = 1/B\). A typical value for \(a\) is 0.1. The PMD parameter for typical fiber ranges from 0.2 to 0.5 ps/\(\sqrt{\text{km}}\). However, new fibers can have PMD as low as 0.05 to 0.1 ps/\(\sqrt{\text{km}}\).

III. GENETIC ALGORITHM

The GAs are computationally simple yet powerful in their search for optimized solutions. GAs demand relatively few requirements for their application: a mapping between the search and the chromosomes spaces, a set of operators, and an evaluation function. The optimal or suboptimal solutions are obtained among resulting descendants of the best elements of previous generations in such a way that the attributes of the strongest individual tend to last for the following generations [8]. In the proposed model, a gene represents a codeword status, in the binary form, and the genes together form a chromosome. This represents the wavelength status of the link to a particular node. The set of all wavelengths composes an individual who represents an assignment policy. Hence, in a system with \(E\) unidirectional
links and $\lambda$ wavelengths with $C$ OOCs, each individual is denoted by an array of dimension $D = E \times \lambda \times C$, as shown in Table I.

The GA looks for a policy, a set of states of all lightpath, which optimizes the system processing. The proposed GA uses the standard genetic operators (selection, crossover, and mutation) together with random-immigrant mechanism, understood as inclusion of new individuals into the existing population.

### A. Fitness Function

The fitness function estimates the environmental adequacy of each individual with respect to the objective. The procedure for fitness calculation considers different variables involved in RCA aiming to establish the highest number of lightpaths, in an optimized form, considering the current state of the system. For the investigated system, the total fitness function is calculated as follows:

$$fit_{\text{tot}} = \sum_{i=1}^{E} \sum_{k=1}^{\lambda} fit(i, k, j)$$

where the fitness function of path $i$ is calculated by

$$fit(i, k) = n_1(k)r_1 + n_2(k)r_2 + n_3(k)r_3 + n_4(k)r_4 + n_5(k)r_5$$

where $n_1(k)$ is the number of idle codes in wavelength $k$ referring to link $i$; $n_2(k)$ is the number of links of path $i$ that are currently using wavelength $k$; $n_3(k)$ is the number of links of path $i$ that can not support the current $j$ request codes; $n_4(k)$ is the path length; $n_5(k)$ is the number of router nodes of path $i$; $r_1, r_2, r_3, r_4$, and $r_5$ are weight coefficients. The fitness function (3) estimates the $j$ codes assignment cost in a wavelength $k$ for each path $i$, i.e., (3) represents the cost associated to choose $j$ codes in a wavelength $k$ to serve the current request attempt in path $i$. Through simulations, we have adjusted the coefficients as $r_1 = +5$, $r_2 = -1$, $r_3 = -2$, $r_4 = -3$, $r_5 = -5$. The algorithm performance for a particular load can be evaluated by the measure of the blocking probability $P_b$ given by the number of request blocking per the number of new request arrivals.

### IV. RESULTS

In our study, we chose for computational simulations the high-speed South of Finland network topology [5] (see Fig. 1) consisting of 12 nodes and 19 bidirectional links. The number of wavelengths per link is assumed $\lambda = 8$. We use a dynamic traffic model in which each node requests connections to the destinations nodes according to a Poisson distribution. Each connection can request $j$ codes, where $1 \leq j \leq C$, chosen at random. However, the $j$ codes request cannot be divided in different wavelengths, and can use one established lightpath just if its route does not deviate from this path. The session holding time is assumed to be exponentially distributed with mean $1/\mu = 60$ s. We consider PMD impairment and study its impact on RCA optimization. If the length of the transparent segment exceeds the upper bound imposed by the PMD, then regeneration through a compensator either at intermediate node or along the path is required to recover the original signal. We consider full chromatic dispersion compensation is available for each channel as the links that exceed the maximum span length, assumed in this network as 62 km. The nodes have no ability of wavelength and code conversion.

Fig. 2 presents the effect of bit rate growing on network performance. This simulation considers PMD $= 0.1 \text{ ps}/\sqrt{\text{km}}$ and $w = 3$. Adding OOCs into network let better wavelength use to attain new connections. For the considered span length, the PMD does not affect bit rates lower than 2.5 Gb/s. However, if $B \geq 10 \text{ Gb/s}$, it does not allow any connection to establish.

### TABLE I

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<th>$\lambda_9$</th>
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<th>$\lambda_{19}$</th>
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<tbody>
<tr>
<td>$\gamma_1$</td>
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<td>$\gamma_9$</td>
<td>$\gamma_{10}$</td>
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Fig. 1. High-speed South of Finland network topology consisting of 12 nodes and 19 bidirectional links [5]. Distances in kilometers.

Fig. 2. Blocking probability versus number of OOC for South of Finland network as function of bit rate. $\lambda = 8$, $D_{\text{PMD}} = 0.2 \text{ ps/km}$, $B = 2.5 \text{ Gbps}$.
The variation of PMD value injures the network performance. Both simulations consider $B = 1.0$ Gb/s.

The variation of PMD value injures the network performance. We can see the impact of PMD in blocking probability for PMD higher than 0.3 ps/√km. In this case, the number of OOCs is limited to six. From results shown in Figs. 3 and 4, we observe the influence of OOC parameters when PMD effects are considered. In WDM/OCDM networks, the blocking probability decrease as the OOCs number increase, then the codes could be exploited to reduce blocking probability due to wavelength exhaust. However, the impact of PMD effects upon the codes limits the maximum number of OOCs per wavelength. This can be observed in Fig. 4 for OOCs > 6 with $w = 5$ and $D_{\text{PMD}} = 0.1$ ps/√km. We also observed that for both code weight values three and four, the PMD effects are negligible. That is due to the maximum span length adopted in this network. On the other hand, low code weight produces more errors in function of multiple access interference (MAI) [6]. Then, it is important to strike a compromise between the need in reducing PMD (short $L$) and avoid MAI (large $w$) with others OOCs.

V. Conclusion

In this work, we have analyzed the performance of WDM/OCDM networks including PMD as physical constraint. This further hybrid network technology possesses a huge degree of freedom (code and wavelength) that could be exploited to improve the network performance. However, there is a limit on this freedom imposed by PMD. This limit is bounded by path length, number of OOCs, and code weight. The challenge in WDM/OCDM networks design will be to adjust the OOC’s parameters to allow optical links with great span lengths. However, solving the constraint imposed by PMD will be hard. That is because higher code weight assures better optical signal quality increasing the OOC’s number permit more simultaneous connections and the networks tend to be world wide.

REFERENCES


