International Journal of Advanced Smart Convergence Vol.8 No.1 35-43 (2019)
http://dx.doi.org/10.7236/IJASC.2019.8.1.35

IJASC 19-1-5

Design Issues on a Metropolitan WDM Ring Network

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Abstract

A metro ring network using WDM technology requires many issues to be considered even though its transmission distance is shorter and its transmission capacity is lower than a long-haul WDM system. Unlike a long-haul WDM system, which is basically point-to-point configuration, a metro ring network usually equips with capabilty of wavelength reconfiguration. Therefore network performance considering crosstalk within OADM and the network behavior when the ring network is closed should be analyzed before implemented. We discussed some of results analyzed for the issues. Furthermore we proposed a novel method to design a dispersion map for a ring network, and demonstrated the methodology with an exemplary 8-node ring network of 399km circumference.

Keywords: *WDM, Ring network, Metropolitan network,Wavelength reconfiguration*

1. Introduction

Nowadays, many metropolitan core networks utilize existing WDM systems engineered for the long-haul network[1]. Wideband long-haul networks are essentially a collection of point-to-point links. The primary goal of the long-haul netwotks is to have a high transmission capacity(i.e. high bit rate and high channel number). Therefore it is required that various componets should meet high performance requirements such as wideband amplifibers covering (C+L) bands, strict control of wavelengths over temperature variation, nonliearity management etc. However, WDM systems for metropolitan networks require different aspects of the network even though the transmission distances are shorter and the transmission capacity is much lower. While point-to-point topology is predominantly used for long-haul WDM networks, ring topology is particularly used for metropolitan WDM networks because SONET/SDH are usually configured as a ring architecture [2]. In addition, metropolitan WDM networks should allocate wavelengths dynamically at nodes for efficient usage. Reconfigurability refers to the ability to select the desired wavelengths to be dropped and added on the fly, as opposed to having to plan ahead and deploy appropriate equipment. This allows carriers to be flexible when planning their network and allows lightpaths to be set up and taken down dynamically as needed in the network. Optical add/drop multiplexers(OADM) are often used in metropolitan WDM networks to provide a cost

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Manuscript Received: Jan. 7, 2019 / Revised: Jan. 13, 2019 / Accepted: Jan. 20, 2019
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effective means for wavelength reconfigurability. Fig. 1 shows a typical structure of a node capable of wavelength reconfiguration. Any wavelength can be dropped, and can also be added at the node while remaining optical channels will pass through the node.

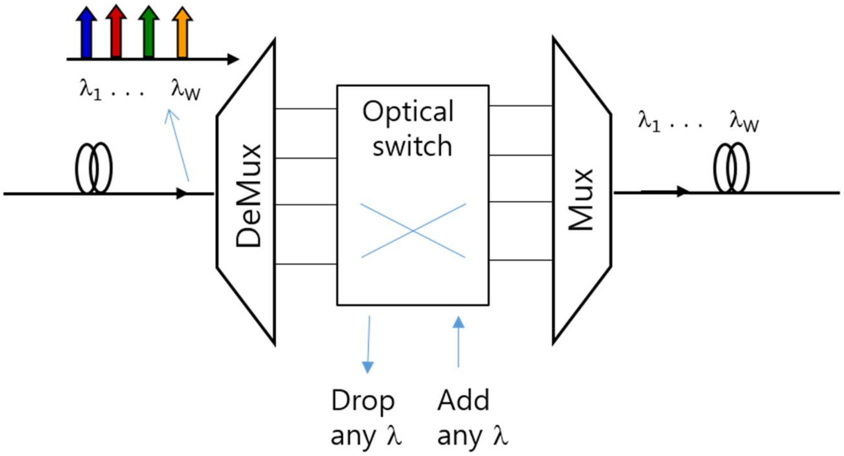


Figure 1. Typical node with capability of wavelength reconfiguration

Ring topology with wavelength reconfigurability makes us consider various design issues for a metropolitan WDM networks which are not expected to occur in a long-haul WDM network. In this paper we are going to review three important design issues in ametropolitan WDM networks and some of research results are summarized.

2. Crosstalk Analysis

Due to the reconfigurability, optical devices in a node with OADM should select certain channels. Ideally there should be no interferences between add channel and drop channel. However, during the add/drop process in a OADM, a certain amount of crosstalk between the two channels is inevitable. There are 3 different cases of crosstalk which is summarized in Table 1. The worst-case crosstalk may occur when a wavelength is dropped but then added back by a same optical device.

Table 1. Catagory of Crosstalk

	Crosstalk type
Case 1	Same wavelength, different information bits (IntraBand)
Case 2	Same wavelength, same information bits (IntraBand)
Case 3	Different wavelength, different information bits (InterBand)

Consider first a scenario when a certain wavelength is dropped at a node, and then a new signal is modulated by the same wavelength and added back to the node. In this case, the two modulated signals are completely uncorrelated, and their relative bit phase will be uniformly distributed within a bit period. To remove the effect of the receiver parameters such as the electrical filter shape, bandwidth, and thermal noise on the penalty due to crosstalk, let us consider *eye opening penalty* which is more adequate to assess power penalties due to deterministic impairments such as crosstalk. Eye opening penalty(EOP) is defined by [4]

$$\mathrm{EOP[dB]} = 10\log\left(\frac{\text{Eye opeing}_{\text{No crosstalk}}}{\text{Eye opeing}_{\text{With crosstalk}}}\right) \tag{1}$$

Fig. 2 shows eye closure penalty with eye pattern at –20dB crosstalk. An ideal photo-detector is assumed, and Table 2 summarizes a maximum allowable crosstalk level at a given power penalty. The results apply to both of 2.5G/s and 10G/s systems.

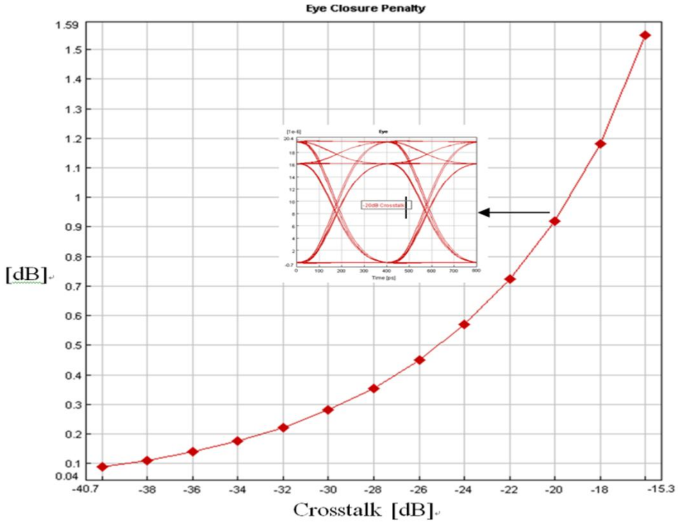


Figure 2. Eye Opening Penalty due to Intraband Crosstalk

Table 2. Case 1: Allowable crosstalk at a given penalty

EOP[dB]	Allowable Crosstalk [dB]
0.5	-25
1	-20
1.5	-17.5

Some of add/drop device can drop a certain wavelength, and add back. In that situation, the interfering signal (residual dropped channel) will carry same information bits by the same wavelength, but with time delay, Δt. In Eq. (2), the recovered signal at the receiver is expressed, in which Δt is the time delay between the two paths and ε is the power ratio.

$$\begin{aligned} I(t)/R &= \left|E_1(t)+\sqrt{\varepsilon}E_1(t+\Delta t)\right|^2 \\ &= P_1 d_1^2(t)+\varepsilon P_1 d_1^2(t+\Delta t)+2\sqrt{\varepsilon}P_1 d_1(t) d_1(t+\Delta t)\cos(\phi(t+\Delta t)-\phi(t)) \end{aligned} \tag{2}$$

Under the assumption of the worst case which will occur when the phase difference, $\phi(t+\Delta t)-\phi(t)$ equals to 180°, ‘Case2’ is identical to ‘Case1’.

Now consider crosstalk due to to neighboring channels, and it depends on channel isolation capability of optical filters (optical Mux/DeMux). Unlike intraband crosstalk, interband crosstalk signals have different center wavelengths. However, a post-detection filter at the receiver has a much smaller bandwidth than channel spacing. (The bandwidth of a post-detection filter is usually in the range of 0.6×bit rate to 0.9×bit rate.)

Therefore we can expect that crosstalk penalty due to inter-band crosstalk is much smaller than penalty due to intra-band crosstalks (Case1 and 2). Fig. 3 shows simulation results when channel spacing is 100GHz. With crosstalk < -16.5dB, inter-channel crosstalk penalty is less than 0.1dB which is indeed much smaller than the worst case of 'Case 1' and 'Case 2'.

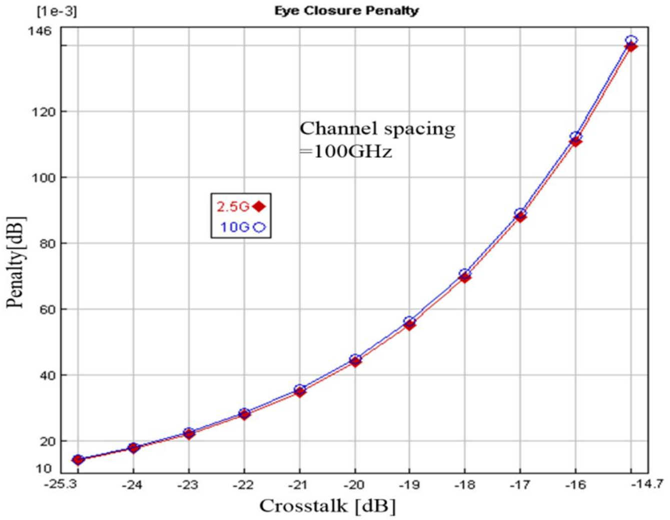


Figure 3. Inter-Channel Crosstalk penalty (Channel Spacing = 100GHz)

Crosstalk penalties are studied numerically for 3 different cases. While inter-channel crosstalks cause negligible penalties for both 2.5Gb/s and 10Gb/s systems, intra-band crosstalk can cause significant system performance degradation while an optical signal travels through many nodes in the metropolitan WDM networks with optical add/drop devices.

3. Path Loss Design

Optical amplifiers such as EDFA should be used at every nodes to compensate not only the fiber attenuation but also the power loss due to various optical devices such as optical multiplexers/demultiplexers and optical cross connectors. However, in a WDM ring network, an optical path can be closed without termination. In that case, a lightpath is infinite. In such case, the closed loop of amplified system can be modeled by an infinite series of amplifier chain as shown in Fig. 4.

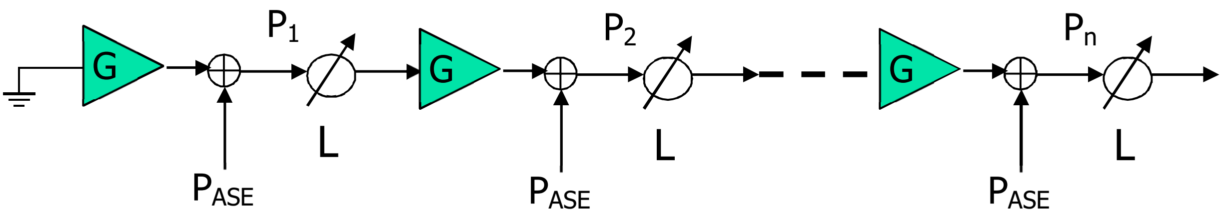


Figure 4. Infinite chain of amplifiers (G = amplifier gain, L = path loss, P_{ASE}= ASE noise power)

By assuming there is no input signal at the input of the first amplifier, we can derive output power of EDFA at each stage such as [4]

$$P_1 = P_{ASE} = 2n_{sp}(G-1)h\upsilon B_o$$

$$P_2 = P_1 GL + P_{ASE} = P_{ASE}(1+GL)$$

$$P_3 = P_2 GL + P_{ASE} = P_{ASE}(1+GL)GL + P_{ASE} = P_{ASE}\left[1 + GL + (GL)^2\right]$$

$$\vdots$$

$$P_n = P_{ASE}\left[1 + GL + (GL)^2 + \cdots + (GL)^{n-1}\right] \tag{3}$$

The product, GL, should be at least smaller than 1 to make output power of EDFA chain converge. When GL < 1, the converged output power of EDFAs will be as in Eq. (4).

$$\lim_{n\to\infty} P_n = \lim_{n\to\infty} P_{ASE}\frac{1-(GL)^n}{1-GL} = P_{ASE}\frac{1}{1-GL} \tag{4}$$

Then , $L_{critical}$, the required path loss to suppress EDFA output below $P_{critical}$ in the closed loop, is given by

$$L_{critical} = \frac{1}{G}\left(1 - \frac{P_{ASE}}{P_{critical}}\right) \tag{5}$$

where $P_{critical}$ = design parameter (maximum allowable power level (< P_{sat})).

So far it is assumed that there is no input signal other than ASE noise. Let’s consider when a burst noise signal is present at the input of EDFA. (P_{burst} at the input of the first EDFA in Fig. 4.) Eq.(6) shows the converged output power of EDFAs including the burst noise.

$$\begin{aligned} P_n &= P_{ASE}\left[1 + GL + (GL)^2 + \cdots + (GL)^{n-1}\right] + P_{burst}G(GL)^{n-1} \\ &= P_{ASE}\frac{1-(GL)^{n-1}}{1-GL} + P_{burst}G(GL)^{n-1} \qquad\qquad \text{if } GL < 1 \\ &= P_{ASE}\frac{1}{1-GL} \qquad\qquad n \to \infty \end{aligned} \tag{6}$$

When n increases, the burst noise signal dies out and the result converges to the previous case. Therefore sporadic occurrence of burst noise in a closed loop may not be as of concern as ASE noise. Fig. 5 shows the simulation result when the path loss (L[dB]) is 1 dB larger than the amplifier gain. After 20 loops, the noise power due to EDFA ASE converges to 0.26mW while burst noise having the same ASE power of a single EDFA dies out.

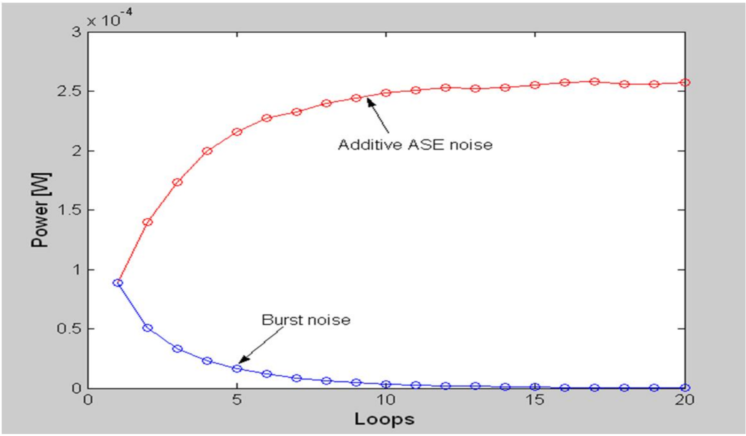
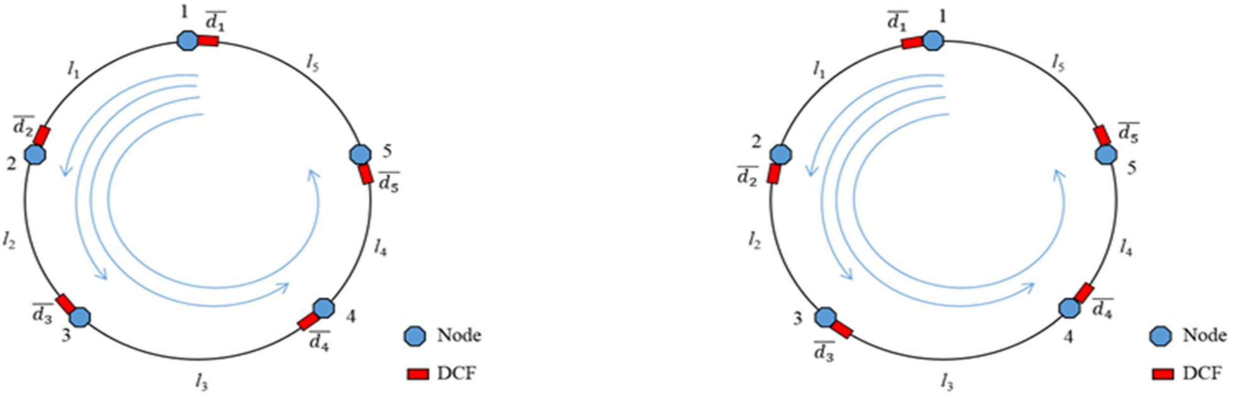


Figure 5. Noise power evolution in an otically closed loop

In an optically closed loop, the burst noise signal dies out as the number of nodes traveled is increased. Therefore sporadic occurrence of burst noise in a closed loop may not be as of concern as ASE noise. That is, the required path loss to suppress the burst noise in the closed loop is same as Eq. (5). If we allow the accumulated noise in a closed loop is 10 times greater than ASE noise of a single amplifier, the path loss between the neighboring two EDFAs should be around 0.5dB larger than the amplifier gain, G[dB].

4. Dispersion Map Design for a WDM Ring Network

Regardless of the network topology, dispersion is one of the major impairments in a WDM transmission system, especially at 10Gb/s or higher bit rate. In a long haul WDM system, it is relatively easy to design a dispersion map because the signal transmission distance (i.e. fiber length) is fixed. Therefore DCFs can be placed with a periodic way [5-7]. However, in a metro ring network with capability of wavelength reconfiguration, the dispersion map design can be a more challenging task because distances(i.e. fiber lengths) between each node are inevitably irregular, which makes it impossible to place DCFs in a regular pattern. Furthermore, if there are N nodes in the network, we need to consider $N\times(N-1)$ dispersion maps because a wavelength path starting at a node can terminates at any one of the remaining $(N-1)$ nodes. Basically there are two configurations to compensate fiber dispersion, namely, postcompensation (Figure 6(a)) and precompensation (Figure 6(b)). If we ignore the fiber nonlinearities, the two configurations will make no differences in signal quality because chromatic dispersion in fiber is a linear phenomenon [8].



(a) (b)

Figure 6. 5-node ring network with counterclockwise traffic (a)postcompensation (b)precompensation

Let's consider a signal traveled farthest starting from each node. The accumulated dispersions should meet the following conditions.

$$\begin{gathered} d_{loop} - D_N l_N + \bar{d}_{DCFs} - \bar{d}_1 \leq d_{tol} \\ d_{loop} - D_1 l_1 + \bar{d}_{DCFs} - \bar{d}_2 \leq d_{tol} \\ \vdots \\ d_{loop} - D_{N-1} l_{N-1} + \bar{d}_{DCFs} - \bar{d}_N \leq d_{tol} \end{gathered} \tag{7}$$

Then the minimum requirement of each DCFs can be obtained. That is,

$$\begin{gathered} (-\bar{d}_1)_{min} = -\frac{1}{N-1} d_{tol} + D_N l_N \\ (-\bar{d}_2)_{min} = -\frac{1}{N-1} d_{tol} + D_1 l_1 \\ \vdots \\ (-\bar{d}_N)_{min} = -\tfrac{1}{N-1} d_{tol} + D_{N-1} l_{N-1} \end{gathered} \tag{8}$$

where $\bar{d}_{DCFs} \leq -d_{loop} + N d_{tol}$, where $\bar{d}_{DCFs} = \sum_{i=1}^{N} \bar{d}_i$ is the total dispersion of DCFs in the network, $d_{loop} = \sum_{i=1}^{N} D_i l_i$ is the total dispersion in the network due to link fibers.

However, most commercial DCFs are provided in the granular form to compensate dispersion of 20km, 40km.… 100km length of a standard single mode fiber(G.652), and let's denote them DCM20, DCM40, ..., DCM100. Dispersion compensation modules(DCMs) based on the fiber Bragg grating technology are also provided in a similar way. Therefore we can only have a DCM at the i_{th} node of which dispersion is in the form of

$$\bar{d_i} = k_i DCM_{min} \tag{9}$$

where $(-DCM_{min})$ is the minimum dispersion of a DCM set available and k_i is an integer.

Now finding an optimum set of DCMs is to find a set of integers $\{k_i\}_{i=1,\ldots,N}$ which will satisfy (7). First, we can estimate k_i as

$$\widetilde{k_i} = \text{round}\left(\frac{(-\bar{d_i})_{min}}{-DCM_{min}}\right) \tag{10}$$

where round(x) means the nearest integer to x and $(-\bar{d}_i)_{min}$ is given by (8).

To demonstrate the methodology explained in the previous section, let's consider an exemplary 8-node ring network with postcompensation configuration(Figure 7).

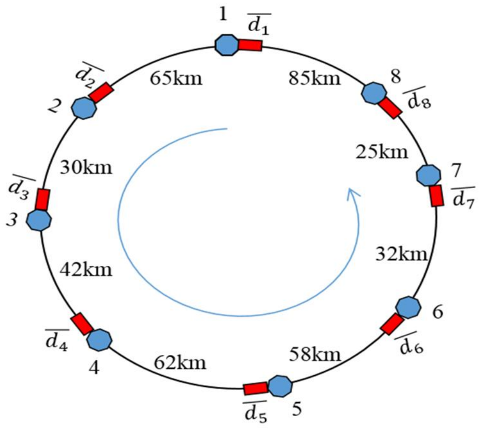
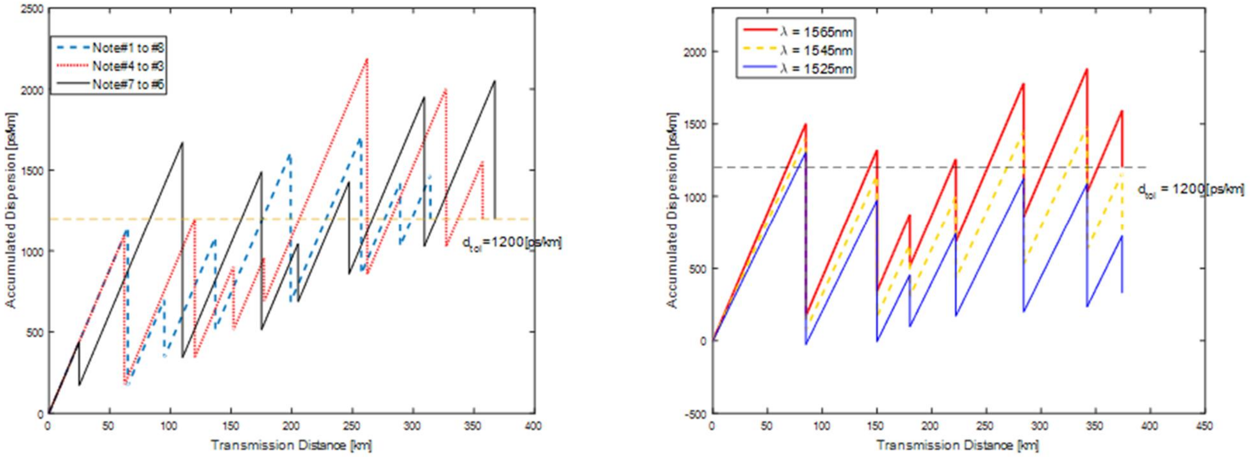


Figure 7. Exemplary 8-node ring network

Link lengths are arbitrary chosen and the circumference of the ring is 399km. Fig. 8(a) shows three exemplary dispersion maps, and Fig. 8(b) shows the wavelength dependence of the dispersion map from node#8 to node #7 which has the longest path. As expected, the residual dispersion at ecah node does not exceed the allowed residual dispersion in the network, d_{tol}[ps/nm].



(a) (b)

Figure 8. Dispersion maps using ideal compensation d_{tol}=1200[ps/nm] (a) 3 maps @λ=1565nm (b) maps from node#8 →node#7 at three different wavelengths

5. Conclusions

Wideband long-haul WDM networks require the stringent performance specifications. In a metro network, which is usually configured in a ring architecture, the transmission distances are shorter and the transmission capacity is much lower compared to a wideband long-haul WDM network. However, the ring configuration with capability of wavelength reconfiguration requires many other issues to be considered. We reviewed the most important design issues in a metro network, and anaylized those issues and discussed their impacts on performance of the network. However, other requirements unique to metro networks still remains to study further, including degree of connectivity, modular and flexible transmission platform.

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