

Assessment of physical impairments in a DWDM ring network based on optical packet switching

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In this work, we study the physical effects over a multiple-access unidirectional ring network with a DWDM wavelength scheme based on optical packet switching. In our proposal, each node in the ring is identified by a combination of wavelength and numerical address and can transmit data in any wavelength, but receive data only in its assigned wavelength. Packets dropped by the node are routed using an optical switch according to their address, without optoelectronic conversion. We introduce physical impairments in this network, making the necessary modifications in the node design to minimize the restrictions they impose.

1. Introduction

Metropolitan networks have been attracting much attention as they impose a bandwidth bottleneck between the local access networks and the backbone. The deployed circuit-switched SONET/SDH rings are relatively inefficient for dynamic traffic and, although several approaches to adapt circuit-switched techniques to data traffic are in the standardization stage, many efforts are oriented to the design of packet-switched techniques combined to WDM to increase bandwidth. These later techniques are particularly promising, but they are still in an early stage. A complete classification and description of different proposals to WDM metropolitan rings can be found in [1]. Most of these approaches are based on wavelength sharing among different channels in a unidirectional all-optical fiber ring, while they differ in the node design, with either tunable transmitters or receivers and in the medium access control (MAC) protocols. In our approach, each node is equipped with a fixed receiver and a transmitter array to allow insertion in any of the rings wavelength, and with an optical switch. This later feature introduces true optical layer functionality into the ring architecture as there is no need for conversion to the electronic domain until it reaches its final destination, and it can be viable as commercial switching times have decreased up to 100ns [2]. In fact, recent results obtained from the simulation of a 10Gbps ring showed that this network is able to support high traffic loads and a great number of nodes [3].

However, the physical viability of the proposed network has not been assessed up to this point. Our node design requires optical components which impose power

losses, in addition to fiber attenuation. Fiber dispersion and non-linear effects can also be important in our design as high bit rates, high optical power and several wavelengths are involved in our WDM scheme. Therefore, we set out here to analyze the impact of physical impairments and we present a new practical node design intended to minimize them, which has been simulated using OptSim 4.0 from RSoft Inc., in order to introduce all the physical effects including noise.

The structure of the paper is as follows: In the first section, the ring architecture is described as well as the functional stages of the node and their implementation. In the following section, we discuss the influence of the different physical effects over the network, and present the results of the simulation for different configurations of the node. Finally, the conclusions are summarized in the last section.

2. Network Architecture

We propose a unidirectional ring network with a DWDM wavelength scheme, which uses 8 wavelengths in the C-band. Two of these wavelengths are destined exclusively to support traffic external to the MAN while the other six support traffic between nodes within the ring (which will be indicated from now on as external and internal wavelengths, respectively). The network contains two types of nodes or connection points: Access Points (AP) enable access of users connected to LANs to the metro ring; Point Of Presence (POP) nodes connect the ring to the wide area network. Each channel (wavelength) within the MAN ring transmit packets at a 10Gb/s bit rate, while the traffic from the LANs to the MAN ring is inserted at a bit rate of 1Gb/s. Packets have a fixed-size of 1500 bytes. Inter-node distance is supposed to be 2Km and POP nodes are equidistant in both directions. We assume that there is no synchronization between nodes, and that the network operates under an un-slotted approach. Figure 1 shows a simplified scheme of the network with 4 internal channels and only one internal channel.

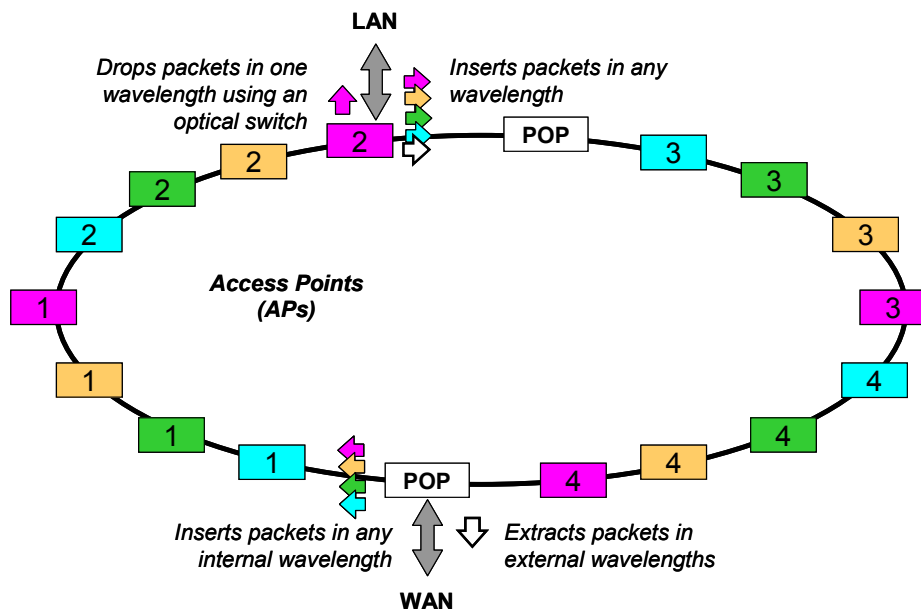


Figure 1: MAN ring architecture: Access Points (APs) manage packets conveyed by wavelengths supporting traffic internal to the MAN. Points of Presence (POPs) manage packets conveyed by wavelengths supporting traffic external to the MAN.

The group of AP nodes that share the same internal wavelength are able to extract packets from the ring only at this wavelength but, however, can insert packets into the ring at any of the network wavelengths. POP nodes insert packets in any of the internal wavelengths and extract packets in any of the external wavelengths. The exact design of the access points and the points of presence is described in what follows.

2.1 The Access Point

There are three functional stages in the AP: The *packet manager*, the *optical drop* and the *optical add*, shown in Figure 2.

Packet manager

An optical splitter is used to extract part of the power transmitted by the ring, necessary for the packet manager to perform a-priori channel inspection to detect channel occupancy, and to obtain the packet address. The packet manager consists on a de-multiplexer followed by a bank of receptors. The exact procedure to extract the packet address is not relevant here, but it is required a good signal to noise ratio and very low Bit Error Rate (BER) to avoid packet loss [4].

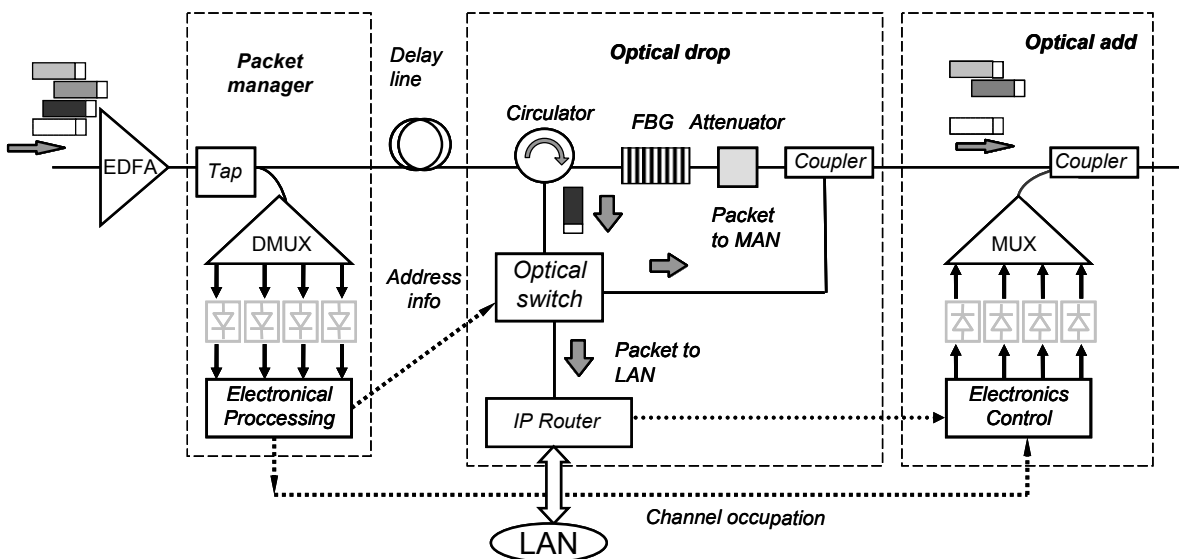


Figure 2: AP design: The packet manager extracts channel occupancy and packet address. The optical drop based on an FBG and an optical switch routes packets at the node's own wavelength. The optical add consists on a laser array, a MUX, and a coupler to insert packets into the ring.

Optical drop

The task of the optical drop is to extract packets with a destination address in the LAN connected to the node. This stage is composed of a circulator and a fiber Bragg grating (FBG) filter acting as a mirror for the node's own wavelength which directs all the packets at this wavelength towards the optical switch. The switch is controlled by the address information provided by the packet manager so that, if the packet is in the LAN connected to the node, it is definitely dropped. However, if its

destination is a LAN connected to a node downstream sharing the same wavelength, it is sent back to the ring by means of an optical 2x1 coupler. The key point of our proposal is that this stage is entirely realized in the optical domain, without optoelectronic conversion of dropped packets. Packets on a wavelength different from the node's own drop wavelength are transmitted throughout the node because the FBG is transparent to their wavelength. In our proposal most of the electronic processing, such as encapsulation of payload and address into fixed length packets, wavelength assignment to each packet based on its destination address, etc., is performed at the router level, making the node design much simpler.

Optical add

The optical add inserts packets into the MAN ring coming from the LAN connected to one particular AP. Packets that cannot be transmitted are queued to wait for a vacancy signaled by the information coming from the packet manager. As these packets can be transmitted in any of the ring wavelengths, it is necessary either a tunable transmitter or a transmitter array. We chose this later alternative and propose an array of lasers of fixed wavelengths, which allows an independent management of each wavelength channel. The output from this array is multiplexed and joined to the ring flow using a 2x1 coupler. A cheaper alternative for schemes with less than 8 wavelengths is to exchange the multiplexer by an 8x1 coupler although losses are higher in the later. To avoid collisions with the in-transit traffic when a packet is inserted, it is necessary to add a delay line between the packet manager and the optical drop stages.

2.2 The Point of Presence (POP)

POP nodes are identical to access points, except in the optical drop. They need two different FBG to drop packets in both external wavelengths. There is no need, however, of an optical switch, since all the packets that reach any POP at any of the external wavelengths must automatically be dropped to the wide area network. Thus, power losses at the POP nodes are lower for all channels than the losses they suffer at the AP nodes.

3. **Simulations and Results**

First, we calculated the power budget for a node. We used a typical 10Gbps Ethernet transceiver, designed to support up to 80Km of standard single mode fiber (SMF), and introduced values for the losses of the optical components found in the characteristics sheets of commercial products. The presence of several couplers and multiplexers make these losses quite heavy and higher than the total margin between the transmitter and the receiver (16dB). Thus, it is necessary the use of optical amplifiers in the network design, and in particular, an EDFA was included at the input of every node, as shown in Figure 2. Alternatively, it could be possible to introduce one EDFA every group of nodes, but this design, although cheaper, will need higher power outputs that could excite non-linear effects in the fiber, and in addition, with an EDFA at every node, all the nodes in the network have the same design, which makes the network more easily scalable.

However, EDFAs have also some disadvantages. First, they introduce amplified spontaneous (ASE) noise. Second, their gain depends strongly on the wavelength, especially when there is a chain of amplifiers, as it is our case. This second effect has a very strong impact over the network performance as small differences will be considerable enlarged through several hops. This effect can be overcome either using a flat gain EDFA or with gain-flattening filters that are specifically devised for a particular amplifier. But, even provided that the EDFA has a flat or flattened gain, in our design, different packets follow different paths inside the node depending on their wavelength and address and thus, they suffer different losses. The worst case is that of a packet transmitted at the node's own wavelength but whose destination is not the LAN connected to this node. This packet enters the drop stage through the circulator and, after reflection in the FBG, goes through the circulator a second time, is switched and then, is re-inserted in the ring by the coupler. To compensate the higher power in the other channels, an attenuator has to be inserted after the FBG. The power output of the transmitter array has also to be controlled in order to equal it to the in-transit traffic power for all the channels.

The presence of ASE noise is unavoidable when we have EDFAs in the network and the noise figure (NF) in commercial EDFAs is usually higher than 4.5dB. The fact that the network consists of an amplifier chain makes matters worse because, theoretically, ASE noise will be amplified at every node. To minimize the ASE effects, it is convenient to use an optical filter to limit the actual bandwidth at the minimum that the used number of wavelengths permits. In addition, we have the advantage that the FBG in the drop stage can be also used as a noise filter for the node wavelength if it is properly designed.

There still remains to account for the dispersive effects of the fiber, which are important since we are working at 10Gbps and the distance between nodes is 2Km. We should add to this value the delay line at each node that has been calculated to have a length of 0.262Km. To compensate partially the group velocity dispersion introduced at the ring we have changed the SMF of the delay line by dispersion compensating fiber (DCF). The DCF, due to its small size, is more prone to non-linear effects and has higher attenuation and larger insertion losses (about 1.5dB) than SMF. In addition, the compensation will be different for different channels due to the slope effect.

We chose the wavelength set in the C-band, in the flat gain region of a commercial EDFA. Although to minimize gain differences, it will be best to keep the wavelength separation small, this will increase the probability of non-linear effects (such as four wave mixing) that can be otherwise reduced by dispersion. Thus, we took wavelengths from 1549.31nm (193.5THz) to 1560.61nm (191.1THz), separated 1.6nm (200GHz). The channels devoted to external traffic were the wavelengths at the two extremes of this set.

We have used OptSim 4.0 from RSoft, Inc. to simulate the proposed network, evaluate its performance and assess its limits. The OptSim environment is a powerful tool that permits the inclusion of all types of optical impairments due to passive and active optical devices (including optical and electrical noise) and has built-in models for most components. In particular, it has three different models for the fiber: First, a model where only attenuation is considered; second, a linear fiber model that includes also dispersive effects, and finally, a full fiber model, that incorporated non-linear effects.

We have created a model of the node including all the described components. The transmitter introduces the 8 channels with a binary signal at 10Gbps by a CW-laser externally modulated. The signal has a total duration of 12.8ns, which implies that for BER calculation, 128 bits at 200samples/bit are taken into account. All wavelengths are transmitted through N node groups. A node group consists of an AP node for each internal channel i.e. 6 nodes. At the end of the N node groups, the Q value (i.e. the BER) was obtained at the packet manager and at the IP-router receptor for the 6 internal channels. We have not analyzed the external wavelengths because they do not set the limit as, in average, the external traffic has to suffer half the hops that the internal packets. Although it is usual to extract only a small percentage of optical power to the packet manager our choice is to use a 50/50 tap for which the losses at the router receptor and the packet manager are more balanced. In our case it is critical to read correctly the address of the packet in order to route it adequately to its destination, so the packet manager needs a significant amount of optical power. The criteria followed to set a limit impose a maximum BER for the packet manager of 10^{-12} ($Q \sim 7$) and of 10^{-9} ($Q \sim 6$) for the router receptor.

The critical point in our study is to choose the right EDFA. We have used a flat-gain amplifier whose small signal gain is 25dB, higher than the maximum losses in the node for all configurations. This EDFA works at saturation with fixed output power and has a noise figure of 4.5dB. To choose the EDFA output power that does not excite non-linear effects, a control experiment was performed with a simplified model using the DCF as the delay line. In order to assess the influence of non-linear effects, we compared results obtained using the linear fiber model (attenuation and dispersion only) and the full fiber model, including non-linearities. Results are shown in Figure 3.

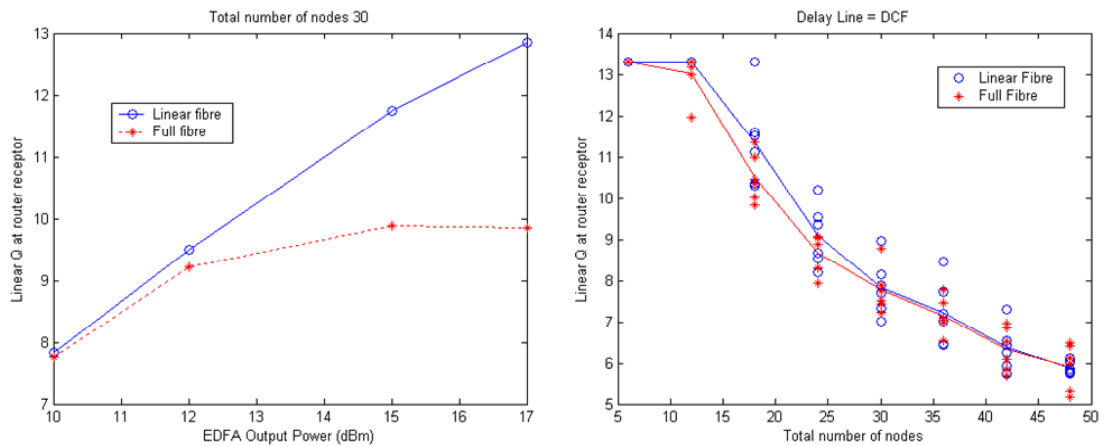


Figure 3: a) Impact of non-linear effects on Q as a function of EDFA output power for 30 APs.
b) Q versus number of nodes for 10dBm EDFA power output and 8 wavelengths.

Figure 3(a) shows the value of Q averaged over the 6 external wavelengths when the EDFA output power is varied using the linear fiber model (circles) and the full fiber model (stars) when the total number of nodes is 30. We found that non linear effects begin to affect our system over 12dBm, and thus, we fixed our EDFA output power to 10dBm. Figure 3(b) shows no significant differences between the two models with 10dBm EDFA output power, as the total number of nodes is increased.

Another important feature of our design is that channels are filtered by means of the FBGs. These filters have been modeled by a flat-top band-pass filter centered on the reflected frequency with a flat pass-band of 40GHz, combined with a notch filter of the same characteristics. The choice of this value was made by varying the filter bandwidth to maximize Q and minimize power variability among wavelengths.

Using the devices stated above, we have made several simulations where the power budget was fulfilled for the packet manager and the router receptors, and different configurations were studied to account for dispersive effects. Figure 4 shows the average Q versus the total number of nodes at the router receptor (a) and at the packet manager receptor (b) as solid lines, and the particular values for each wavelength as symbols. Notice that the total number of nodes is always a multiple of 6, as there is the same number of APs for all the 6 external wavelengths.

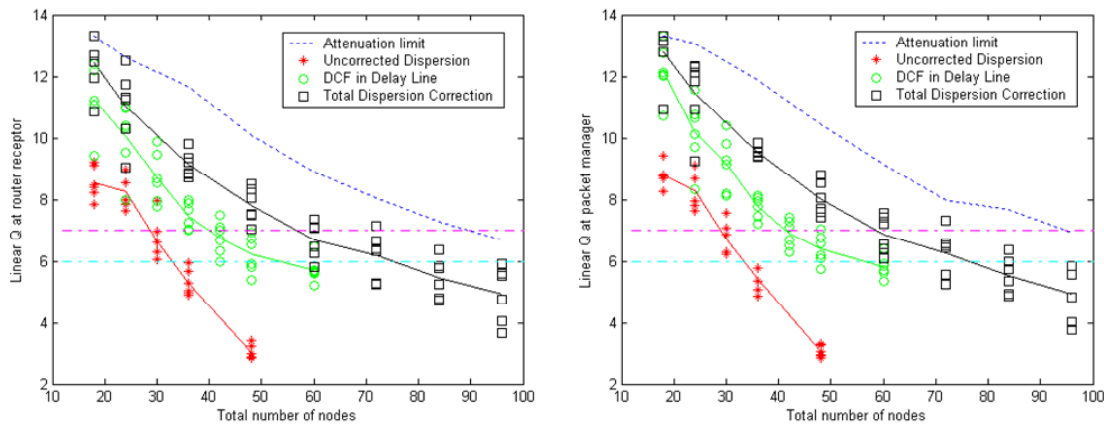


Figure 4: a) Q at the router receptor and b) Q at the packet manager versus number of nodes.

Dashed lines show the limit set by fiber attenuation and noise obtained in the configuration using a SMF at the delay line without taking into account any dispersive effects. Stars show the Q values obtained in the same condition, but including fiber dispersion. In this case the maximum number of nodes with an acceptable Q is only 24 nodes (4 nodes per wavelength). Using DCF as the delay line (shown in the same figure as circles) the limit increases up to 36 nodes. We have to point out that in this case the dispersion is not completely compensated as the DCF has a given length because it is used as the delay line. Finally, we decided to include a DCF module at the exit of the node, whose length was calculated to minimize the dispersion for the set central wavelength. The delay line in this configuration is again SMF. With this configuration, represented by square symbols, 48 nodes (8 nodes per wavelength) could be maintained, although it is still far from the limit set by attenuation and noise. One of the reasons is that DCF corrects dispersion only at one given wavelength, and dispersion slope and residual dispersion accumulate through several hops and cause the wavelength variability shown in the Figure. This last configuration has the advantage that the DCF is far from the EDFA output, thus minimizing fiber non-linearities and theoretically allowing higher powers. To facilitate the visualization of the limits, dash-point lines show Q values of 6 and 7 (corresponding to BERs of 10^{-9} and 10^{-12} , respectively).

4. Conclusions and Summary

A practical design of a metropolitan ring network based on packet-switching over WDM has been presented and analyzed regarding constraints imposed by physical impairments. We determined that an EDFA is necessary at the input of every node to keep the power balance within a tolerable margin. On the other hand, EDFAs introduce ASE noise and in consequence packets lose power after passing through several nodes. Thus, they impose a limit to the network size in terms of the maximum number of nodes through which a packet can hop. Dispersion, however, is even more constraining for the network size due to the inter-node links of standard single mode fiber. Other fibers with less dispersion, such as DSF and NZDSF, have not been considered for our design because our intention is to reduce its costs by reusing the already deployed SMF when possible, and also, they are likely to induce more non-linear effects. In our design, dispersion can be partially compensated using DCF, but this compensation is not very exact as there are 8 wavelengths in a range of more than 11nm. A better compensation will be achieved by reducing channel inter-space, but this could increase the efficiency of non-linear interactions. On the other hand, the FBG could be tailored to compensate for the slope effect and the residual dispersion caused by the DCF modules. Increasing EDFA output power would theoretically increase the network performance if non-linear effects could be ignored, but we have shown that for powers higher than 12dBm, non-linearities can be more degrading and more difficult to control even than dispersion.

In all our simulations, we have introduced the characteristics of commercial products, and OptSim fiber models are based on parameters obtained from real fibers. Even so, for the simulations we have chosen the devices that were better adapted to the network, and we have assumed that they responded following the model exactly. However, real components may have a behavior that differs from the theory, which makes our predictions somewhat optimistic.

Acknowledgements

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