

Network Architectures in Synergy with Ultra-wideband WDM Multiplexing Solutions towards a 1,000 Wavelength Channel Network

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Abstract: The paper presents the design issues for the development of networks exploiting recent advances and trends in optical technology allowing large numbers of WDM channels. The targeted topology consists of non-hierarchical all-optical rings made up by WDM PON networks and suitable optical cross-connects. The resulting benefits in terms of node consolidation, and increased capacity are analysed for a MAN/WAN network employing transmission and routing in the spectral window 1450-1650 nm and covering both residential and business customers. A single multiplexer/demultiplexer for the entire spectral range is presented and its system performance is calculated.

1. INTRODUCTION

The current deployment of WDM systems mainly targets capacity upgrades of point-to-point links using optoelectronic regeneration on both ends. As part of a gradual network evolution, the concept of all-optical networking proliferates by force of its ability to reduce the processing associated with transit traffic and the possibility to perform network functions like protection at the optical layer. At the same time novel requirements for a less hierarchical network composed by fewer network elements are emerging in response to the never ceasing quest for reduced

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deployment cost and increased network reliability. In particular, the ongoing explosion of Internet related services have stimulated the generation of network concepts where packets are directly interfaced to the optical layer. In this context, the most critical factor is the number of available wavelength channels that allows to simultaneously meet the demand for both capacity enhancements and flatter network structures. Non-hierarchical networks based on a large number of wavelength channels are a subject of intense research effort [1-2]

Regarding the issue of capacity upgrade, currently there are two main approaches. In the first approach the systems are forced to operate at an increasingly finer channel spacing within the gain bandwidth of the EDFA. In the second approach, the number of wavelength channels is traded for a higher bit-rate per channel. In both cases the product (*number of channels*) \times (*bit-rate/channel*) remains constant limited by the current amplifier gain bandwidth. Particularly in the former case the associated requirements in terms of wavelength stability, crosstalk, physical dimensions of the multiplexers/demultiplexers, non-linear effects in the fibre etc. are quite stringent. The inefficacy is due to the striking mismatch between the low attenuation spectral range centered around the 1550nm wavelength which is approximately 200nm, and the gain spectrum of the EDFA which is limited to a maximum of 35nm. Recently efforts had been made to utilise both the C and L bands of the Er^{+} doped amplifiers [3]. Simultaneously, the renewed interest for Raman amplifiers as well as the prospect of using SOAs as in-line amplifiers [4] has opened-up the possibility to envisage transmission (and routing) beyond the C and L bands of the Erbium optical amplifiers. Under any circumstances, one of the next major developments of optical networks will encompass all-optical transmission and routing in the spectral range 1450-1650 nm towards the ultimate goal of 1280-1680 nm.

So far, studies have been presented which tackle parts of such technology considerations [5-8]. The aim of this paper is to present the calculated performance of a wavelength multiplexer/demultiplexer (mux/demux) in the range 1450-1650 nm and to highlight the essentials of a network architecture that is based on such a large number of WDM channels.

In section II, a generic partitioned network structure based on non-hierarchical rings that could radically modify the way trunk and access networks are perceived is illustrated. Also, a possible OXC architecture that provides an interface between the two network classes i.e. access and trunk is presented. In section III, the derivation of the performance of the mux/demux is presented and its system implications are identified.

At this point estimation on the total number of wavelength channels has to be given. Wavelength multiplexers/demultiplexers with channel spacing 0.2-0.5 nm have been reported [5, 9]. Assuming that this constant channel

spacing is feasible across the entire spectrum (section III), the number of wavelength channels could range between 400 and 1,000.

2. NETWORK ISSUES

2.1 Network structure

Network designers can capitalise on a vast increase in the number of available wavelength channels to generate a less-hierarchical network layout with significant node consolidation and reduced processing of transit traffic. The cost of transmission compared to the cost of extensive tandem switching is continuously dropping indicating that node consolidation could be the means of scaling down the cost of providing broadband services to the customer. At the same time levels of the traffic aggregation hierarchy, particularly in MAN networks can be eliminated. In figure 1 such a partitioned network is illustrated that has as a basic building block a ring network. A ring network is a well-known network topology with excellent protection/restoration properties and is the predominant choice in most deployed networks. The physical extension of each ring incorporates a cluster of nodes. Clustering helps to localize any network fault, and it scales down wavelength channel requirements (via wavelength re-use in physically different rings).

Of particular interest is the bidirectional dual ring (i.e. with a clockwise and counter-clockwise traffic flow). The ring networks shown in figure 1, could be either single or multiple dual fibre. The interconnection between the rings is achieved via suitably designed optical crossconnects (OXC) located on a shared node between two (or more) rings. Apart from this common node, additional physical connectivity is provided via direct links resulting in a partially meshed network that reduces the number of hops that needed to reach the final destination. Providing interconnection between MAN/WAN rings allows constructing larger networks. In the following section the rationale in integrating a MAN with a PON-based access networks is presented.

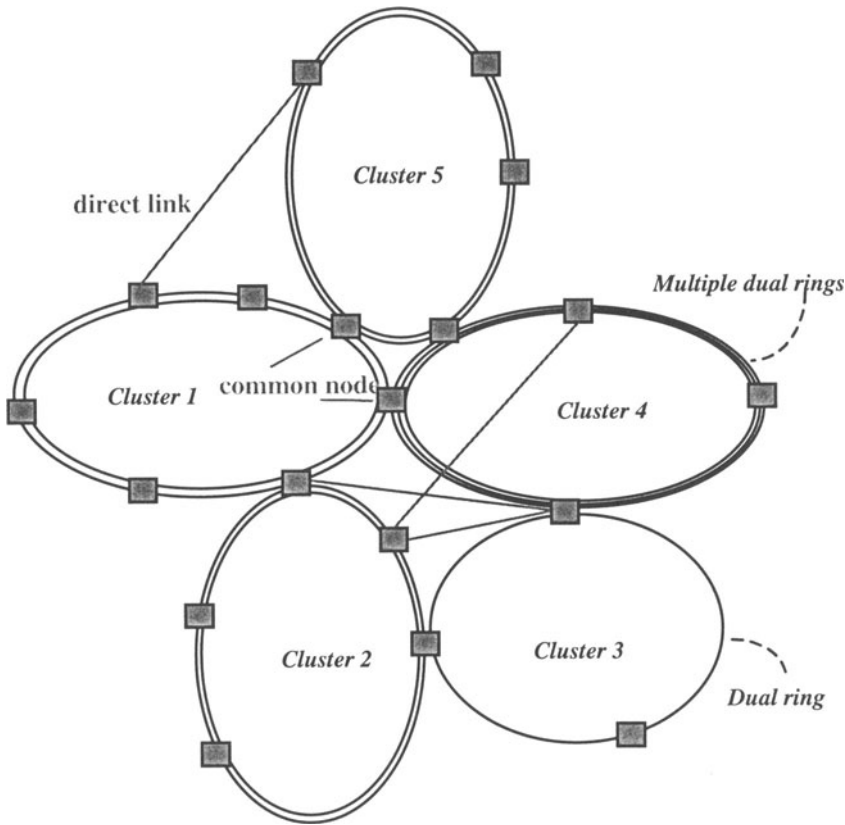


Figure 1. [A partitioned network based on rings]

2.2 Dimensioning of an ultra-wideband WDM PON

The overall architecture of a single ring is presented in more detail in figure 2. There are 4 nodes interconnected via multiple dual rings. Each node is attached to a WDM PON like the one described below that form the access network. The traffic generated within each PON can be connected to the other nodes either transparently via direct access to the OXC or via an IP router, ATM switch or SDH crossconnect.

The ultra-wideband WDM PON is formed by means of a WDM demultiplexer (downstream traffic) or multiplexer (upstream traffic) that

covers the spectral range 1450-1650 nm. The proposed architecture exhibits fundamental differences compared to the established PON structure.

In a traditional PON which is based on power splitting, a single wavelength is divided in successive splitting stages in such a way that all ONUs receive copies of the same signal. The power splitting PON will be the first to be installed avoiding the cost of installing a transceiver pair for each customer, since the OLT is shared by all. The sharing of the bandwidth among hundreds of customers in a power splitting PON takes place by means of TDMA multi-access protocol techniques. This at the same time carries out traffic concentration, which is a further source of cost savings. The power splitters create a broadcast medium in the downstream requiring encryption for the support of point-to-point services.

Very different is the traffic situation in the upstream direction. The transmissions from all ONUs now converge to the shared feeder fiber creating the need for access arbitration. Each slot contains apart from the payload a physical layer preamble for the burst mode operation. Since each transmission comes from a different transmitter and a different distance, several physical layer problems must be overcome. To make slots unambiguous to all units, the ONUs are directed to add an electronic delay that would bring them all at the same virtual distance. The amount of delay, which is inversely proportional to the ONU distance, is identified by means of a ranging process and then communicated to the ONU. Once a slotted transport medium has been created, it is the role of the Medium Access Control (MAC) to arbitrate the access to the slots. The slot allocation is based on access permits sent downstream, which identify the ONU taking the next slot. The MAC protocol is typically of a dynamic reservation type and not semi-static [10] to respond to the temporal fluctuations of traffic that can be quite dramatic in the broadband services.

In contrast to power splitting, the wavelength splitting can offer much larger bandwidth to the final customer. In this system, a particular wavelength channel is always directed towards a prespecified PON branch passively but without power splitting. This can be achieved using an $1:M$ wavelength demultiplexer, M being the total number of wavelength channels. The demultiplexer connects an input wavelength to a particular output fibre. Assuming a minimum of 400 wavelength channels, power budget degradation can be avoided since whilst a 400-fold passive splitting would have resulted in 26 dB losses the demultiplexer losses can be stay below 5-7 dB maximum (section III). Therefore, a larger number of customers could be serviced assuming the same power budget. For the necessary power equalisation, band-optimised optical amplifiers can be used like in [3]

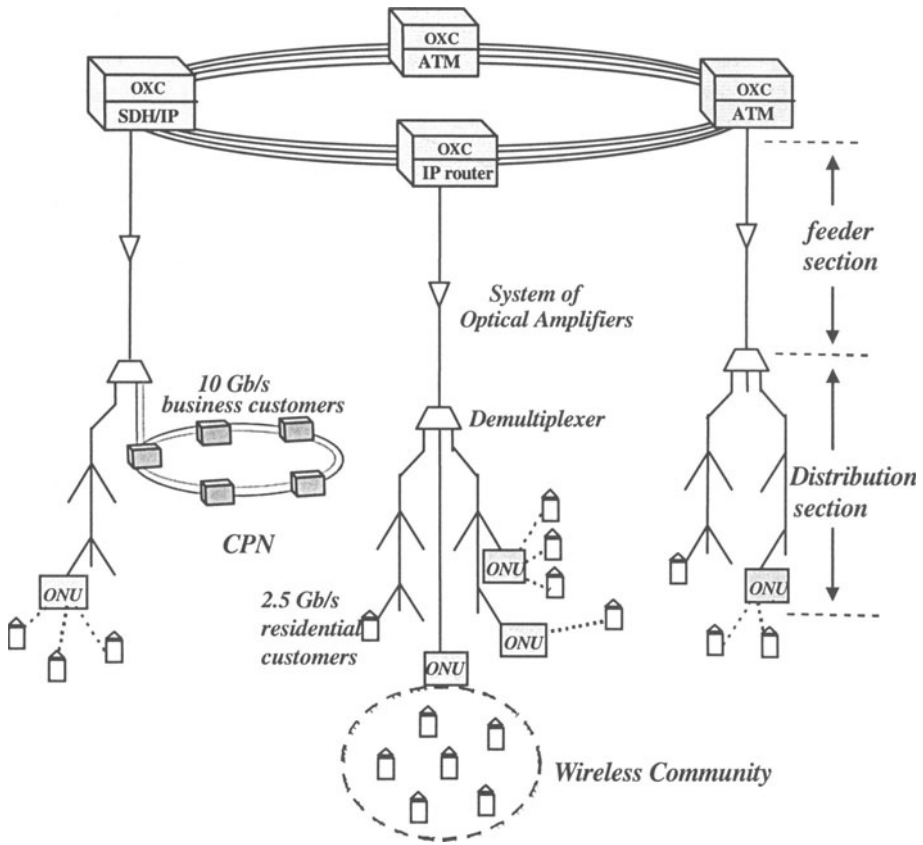


Figure 2. [A generic architecture for the proposed ring]

In the downstream direction each wavelength, after the demultiplexer, is related to one single-wavelength PON. However, the power splitting part is limited and the same wavelength is terminated in a small number of optical network units (ONUs). A number of customers could be connected to a single ONU using various techniques, like xDSL, which leaves in a first stage the copper based home equipment intact delaying the added costs of optics in the home. Customers with higher bandwidth needs e.g. teleworkers or professionals or even small offices can be placed in a channel shared by fewer TDMA users and can be upgraded to fibre-to-the-home (FTTH). Even medium businesses can eventually be upgraded to a separate WDM channel instead of TDMA sharing. The additional advantage of the separate wavelength apart from the abundant bandwidth is also enhanced security and connectivity since a particular wavelength would be passively routed to a specific destination and the contained information would not be broadcast to all customers. These wavelength channels could operate at 2.5

Gb/s. In the upstream direction further modifications to MAC related hardware has to be introduced to achieve these high speeds. However, the necessary technology is already developed e.g. Gigabit Ethernet.

The solution shown in figure 2 illustrates an advanced infrastructure that addresses simultaneously both market segments i.e. business and residential customers. The total number of wavelength channels (>400) is divided into two groups. The first subgroup of channels is destined to the *residential* customers. The other subgroup serves the high capacity *business* users (CPNs, ISPs, wireless LANs etc). The *residential* users are connected in the network in a non-transparent mode whilst transparent connections serve *business* customers. Different scenarios could be envisaged for channel splitting between residential and business customers depending on traffic patterns, population density, demand for new services etc. Here it is presumed that from the 400 wavelength channels per PON, 300 channels are allocated to residential customers and 100 channels are allocated to the high capacity users.

Assuming that on average 2 Mb/s fully symmetrical bandwidth is offered for interactive services to each residential customer, then 1,250 customers can be served by this single-wavelength power-splitting PON. The overall access system could be seen as formed by 300 single-channel power-splitting PONs, one per wavelength. Consequently, it can be concluded that 375,000 residential customers can be served from the overall access system. In this case, a total capacity of 750 Gb/s is allocated to residential customers imposing the need for node consolidation and implying that Terabit routers or crossconnects with a large number of ports (>300) should be accommodated to the central office as it is shown in fig.2.

The business customer channels are not crossconnected via the SDH/ATM switch. These channels are connected in a transparent mode to the trunk network via the OXC. This means they have direct access to the OXC and, therefore, a “clear channel” is provided. The bit rate per channel for the business customers can be at 10Gb/s or even higher.

2.3 Dimensioning of the MAN network

The nominal transmission rate of each channel in the trunk network depends on many parameters. Namely, service demand and number of wavelength channels available as well as on the trade-off in cost between adding a new wavelength channel or increasing the bit rate in order to achieve a given throughput. In any case, transmission at 10-40 Gb/s, or even at higher rates could be assumed. For the residential customers, it is expected that grooming and bandwidth aggregation can be provided by the Terabit IP

router/SDH DCC. Hence for residential customers, 75 wavelength at 10 Gb/s should be allocated in each node.

These wavelengths are destined either to nodes within the ring or to nodes located in other rings. The multiple fibre ring gives the option to direct the particular traffic to the final destination either using transparent connections or via the adjacent “digital electronic switch” through o/e conversion in a multi-hop scheme. All these wavelength channels are routed within the network via the OXC. These channels must have a different nominal wavelength from the one used by *business* customers. Obviously, any wavelength channel can be present only once in a given link. Therefore the traffic emanating from a particular node should be transported using either a different subset of channels or via another fibre. In the former case, the total number of nodes in a dual fibre ring depends on the total number of wavelength channels available. Assuming, 400-1000 channels it follows that 4-10 nodes can be placed per dual fibre.

Now, one can estimate the total number of dual fibres needed per ring. A reasonable minimum is one dual fibre for residential and one for business customers for connections within the ring, one dual fibre for residential and one for business customers for connections outside the ring. Thus, a total of 4 dual fibres would be needed. In any case, these are indicative values. In addition one may envisage additional fibres for heavy transit traffic; the number of dual fibres would range from 4 to 20 per ring.

2.4 The proposed OXC architecture

From the aforementioned analysis, it is emerging that an OXC architecture capable to crossconnect a large number of wavelength channels between a relatively small number of fibres is sought. In the proposed ring structure, the OXC is co-located with the DXC (SDH/ATM/IP router). Here we briefly present an architecture that is particularly suitable when there is a large number of wavelength channels per link [11].

It is named “wavelength crossconnect” (WXC) and it is illustrated in fig.3. N input/output fibres are assumed with M wavelength channels per fibre. The multiwavelength signal from each incoming fibre is amplified before power split N times at the input stage and directed towards a wavelength selector. The wavelength selector can select an arbitrary number of wavelengths ranging from 0 to M and it is the main building block of the crossconnect. Entering the selector, the wavelength channels are demultiplexed and each wavelength is either forwarded (on-state) or blocked (off-state) towards the multiplexer from a dedicated device. This device can be a SOA gate, a modulator or any other device that is capable of generating a large extinction ratio. The most promising candidate is a SOA gate since it

has a significant on/off ratio, it can provide gain, and it also provides fast reconfiguration [12]. The selected channels after multiplexing are directed towards a $N:1$ power combiner attached to an output fibre. A wavelength channel can be switched from any input fibre to any output fibre when the appropriate gate in the dedicated selector is activated. An important characteristic of the architecture is that only one out of N gates per wavelength channel destined to the same output fibre is activated at any time.

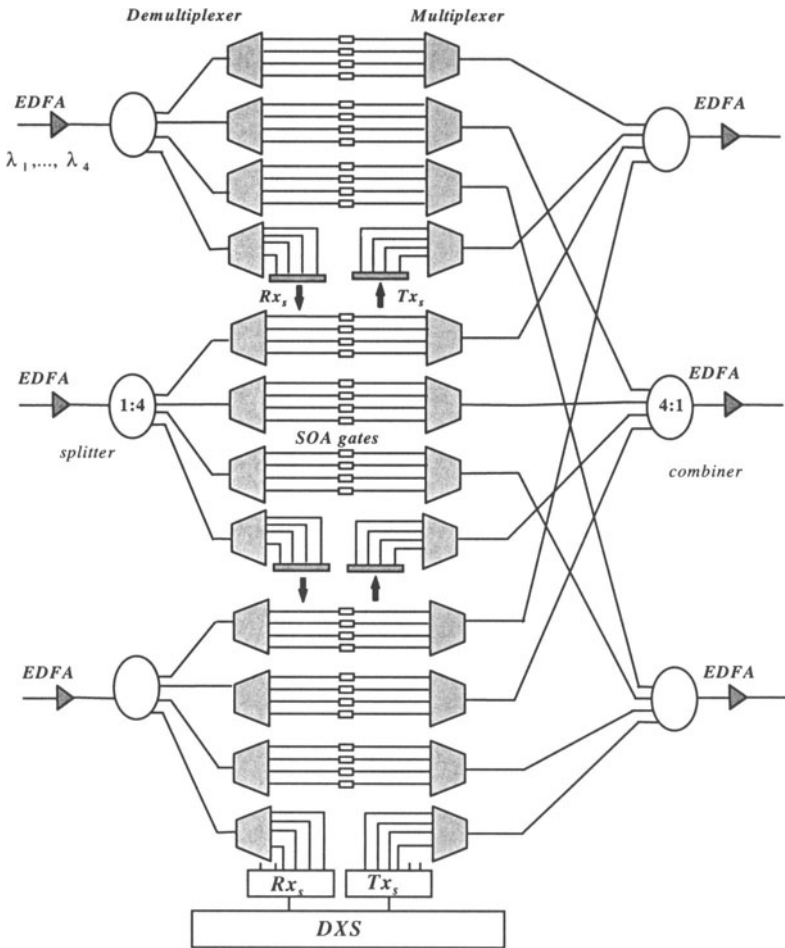


Figure 3. [The OXC architecture.]

The proposed architecture integrates space and wavelength switching. There are no crosspoints or crossovers between any two wavelength channels since wavelength switching from a given input fibre to the

requested output fibre is achieved with the activation of a single gating element (e.g. a SOA gate). The performance of the proposed architecture is independent on the number of the wavelength channels and the architecture is modular with respect to wavelength and link. The total number of gates in MN^2 , the components scale linearly with the number of wavelengths.

There are two sources of crosstalk in the WXC architecture. The hetero-wavelength crosstalk due to imperfect demultiplexing between adjacent channels, and the homo-wavelength crosstalk due to imperfect extinction of the SOA gates that operate at the same nominal wavelength from the other $N-1$ input fibres. Also, the hetero-wavelength crosstalk due to imperfect demultiplexing can be a source of homo-wavelength crosstalk at the output fibre. Fortunately, since the diffraction gratings in the wavelength selector operate in tandem, the overall adjacent channel rejection is twice the rejection of a single multiplexer/demultiplexer. Thus, this crosstalk either seen as hetero-wavelength or homo-wavelength is significantly suppressed. Homo-wavelength crosstalk is well mastered due to the high on/off ratio of a SOA.

Here the node cascadeability is assessed against the power penalty due to homowavelength crosstalk. In the current case, a small number of links (4-20) is envisaged. Two extreme cases are examined. A node with 4 input fibres (i.e. 3 sources of homo-wavelength crosstalk at the output) and a node with 20 fibres (19 homowavelength interferes). In both cases the power penalty is calculated by the statistical method used in [13]. The power penalty for an AC coupled receiver is defined as

$$\mathfrak{R} = -10 \log_{10} \left(1 - 6 \cdot \sqrt{\sum_i^N \varepsilon_i} \right) \quad (1)$$

where ε is the ratio $P_{sig}/P_{crosstalk}$ for a single interfere. It is assumed that all crosstalk sources from all nodes have the same coefficient (ε) which is -50 dB [12]. In figure 4 the power penalty is calculated as a function of nodes to be cascaded assuming 4 input/output fibres per node (solid line) and 20 fibres per node (dashed line).

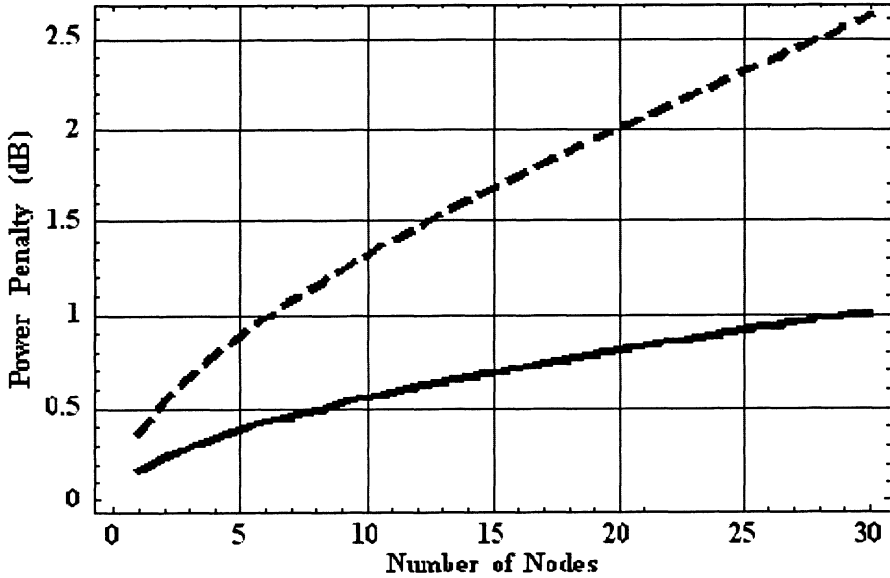


Figure 4. [Power penalty v. number of nodes for 4x4 I/O fibres (solid line) and for 20x20 I/O fibres (dashed line)]

One is tempted to calculate the throughput of the WXC. For a 4 I/O fibre WXC, 400 channels at 10 Gb/s per channel, the capacity is 16 Tb/s whilst for 20 I/O fibres this capacity is 80 Tb/s. In the proposed architecture the total number of ports is analogous to the number of wavelengths. For a large number of wavelength channels ($M > 400$), the number of ports escalates to prohibitive numbers. One way of dealing with this problem is to consider the concept of wavelength bundle routing [8]. At the same time upgrading the bit rate of a wavelength channel for example from 2.5 Gb/s to 40 Gb/s can more easily be accommodated when a hierarchical switching concept is adopted.

In the proposed architecture if the wavelength bundle consists of wavelengths that are spectrally displayed by one grating order (e.g. $m \lambda_i$, $(m+1) \lambda_i$, ..., m is the grating order), then the entire bundle can be switched by the same gating device. In this way, the total number of ports will be reduced by a factor proportional to the number of wavelengths in the bundle. Partitioning the I/O fibres of the OXC for servicing exclusively transit and local traffic allows for a significant reduction in the total port count.

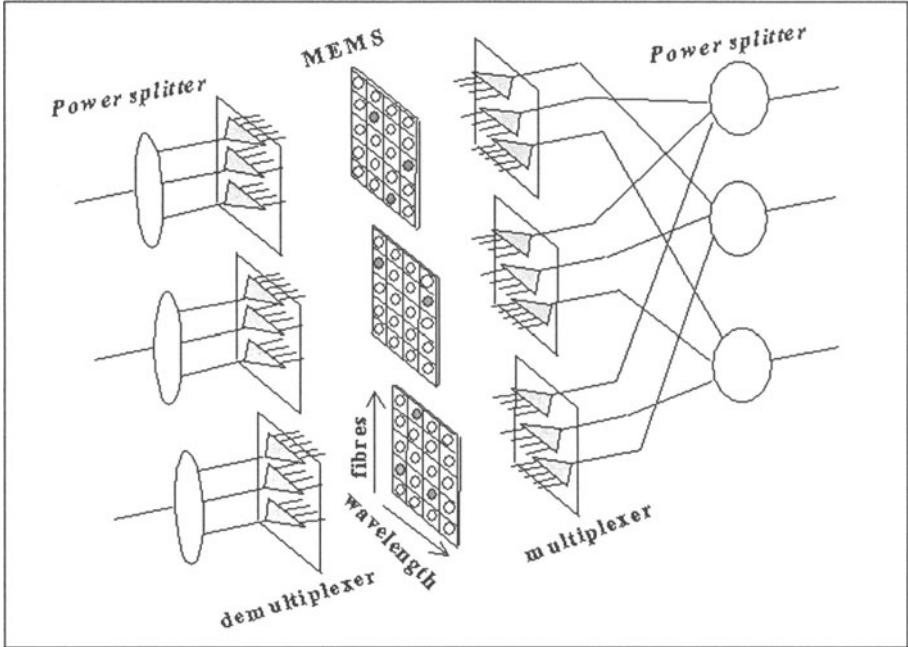


Figure 5. [The WXC architecture implemented with free-space concave holographic grating and a 2-D array of MEMS

Further modifications to the WXC architecture, to tailor advancements of optical technology, are feasible in order to reduce cost and simplify the overall operation. One advantage of free space concave gratings is that allows taking advantage of the massive parallelism offered by free-space optics. It has been shown experimentally [14] that more than 20 fibres can be placed on a plane vertical to the plane of dispersion using free-space concave gratings to acquire up to 20 demultiplexers in parallel. Hence, for relatively low number of I/O fibres, a single device can replace the $N+1$ demultiplexers illustrated in figure 3. Using the MEMS technology [15], a 2-D array of 20×400 (or more) of “shutters” can be, eventually, implemented. The modified WXC architecture is illustrated in figure 5.

3. OPTICAL TECHNOLOGY ISSUES

A free-space concave grating has been identified as a key device in spectrally extended wavelength routed networks [5, 14]. As it is pointed out in [5, 16], the aberration corrected spectrum of these devices exceeds 100

nm and this additional bandwidth can be used for wavelength routed purposes.

In contrast, integrated optic devices like AWGs or two dimensional concave gratings, have inherent limitations to cover this extended wavelength range since they operate at high diffraction orders which in turn limits the Free-Spectral-Range [9]. Despite that, WDM transmission of 200nm based on AWGs can be achieved using a cascade of band selective filters. Effectively, this approach will lead to a sort of hierarchical multiplexing/demultiplexing something that will complicate wavelength routing concepts, especially the construction of a viable OXC, it will increase the overall cost, and it will degrade the power budget of the link.

Here the coupling efficiency and crosstalk performance of a single free-space holographic concave grating listed in [5], Table I is presented. This concave grating has 10 nm/mm linear dispersion. It is pointed out that this demultiplexer has been optimised for best performance at 1550 nm.

Table 1. [Parameters of the holographic concave grating.]

Radius of Curvature R	347.14368 (mm)
Distance of source r_A	344.30981 (mm)
Distance of main image r_B	350.00977 (mm)
Angle of incidence α	18.011561 (degrees)
Angle of diffraction β	7.4629230 (degrees)
Recording angle γ	44.195223 (degrees)
Recording angle δ	33.977113 (degrees)
Recording wavelength λ_o	488 (nm)
Distance of recording source C	926.5228 (mm)
Distance of recording source D	740.3296 (mm)

In Table I, accuracy up to seventh digit has been maintained to highlight the sensitivity of the computational method. Using these values, system related parameters like coupling efficiency and heterowavelength crosstalk can be calculated. Both coupling efficiency and crosstalk are calculated using the overlapping integral between the input and output single mode fibres [17, 18] based on the analytic expression of the wave aberration function as described in [5].

The coupling losses due to diffraction effects are calculated to be 0.8 dB. One should add another 1.5 dB of losses due to the diffraction efficiency of the grating (for a holographic grating, efficiency curves are typically 70%-75% for both polarisations in the spectral range of interest). In figure 6 the coupling losses are calculated across the wavelength range 1530-1570 nm. It can be observed that the losses are practically constant across the whole spectrum. The overall losses include losses due to residual aberrations,

estimated grating efficiency and diffraction effects due to the grating aperture.

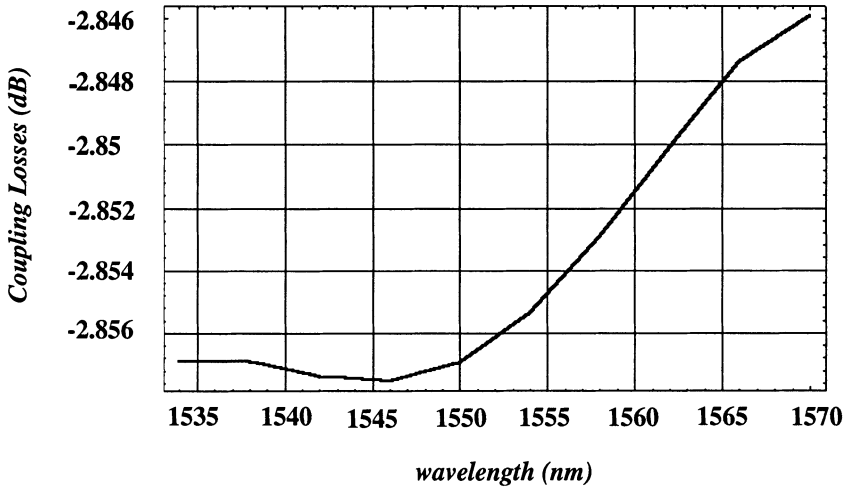


Figure 6. [The coupling losses of the holographic grating in the band 1530-1540 nm.]

The coupling losses across the wavelength range 1450-1650 nm are shown in figure 7.

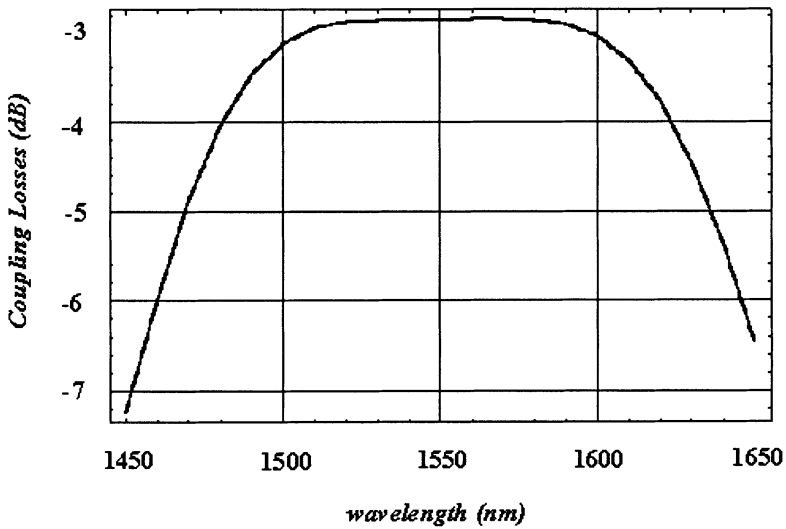


Figure 7. [The coupling losses of the holographic grating in the band 1450-1650 nm.]

Apparently immediate improvement of the coupling loss figure of 3 dB is achievable with a minor modification of the holographic recording scheme. Further design improvements are possible. The crosstalk at the immediate neighbors of $\lambda=1550\text{nm}$ is illustrated in the figure 8. The crosstalk at the first neighbor is -53.1 dB.

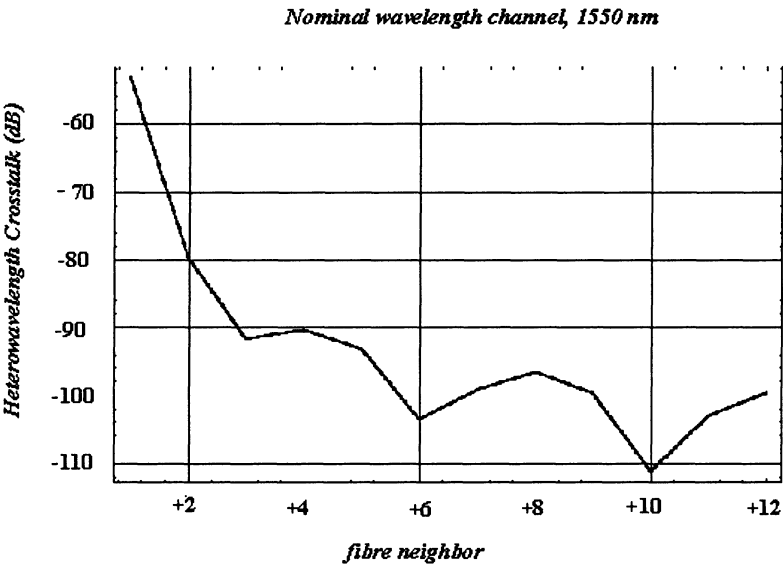


Figure 8. [The crosstalk at the neighbour channels due to the channel at 1550 nm.]

The crosstalk at first immediate neighbours due to $\lambda=1570\text{nm}$ is illustrated in the figure 9. The exact value for the first neighbour is -52.1 dB.

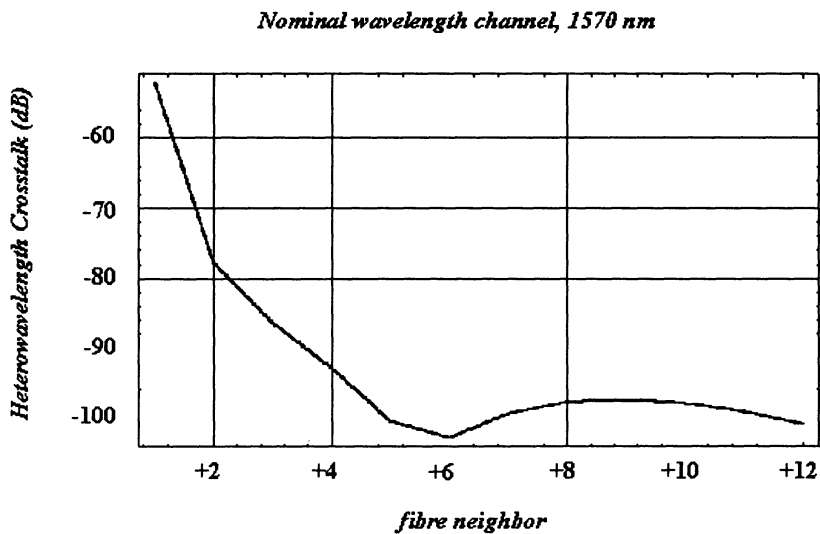


Figure 9. [The crosstalk at the neighbor channels due to the channel at 1570 nm.]

Remarkably, the crosstalk at the first neighbor due to $\lambda=1450\text{nm}$ is -47.9 dB. The crosstalk at the first neighbors is illustrated in figure 10. A similar curve is obtained for $\lambda = 1650$ nm.

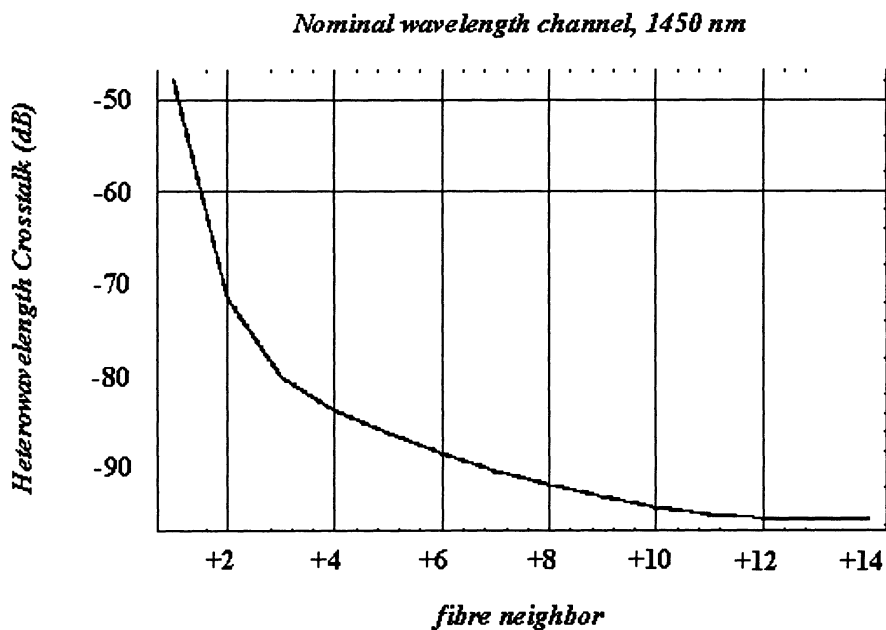


Figure 10. [The crosstalk at the neighbor channels due to the channel at 1450 nm.]

It is mentioned again that this grating was optimised having in mind the EDFA's gain spectrum. From the above analysis, it is concluded that the same concave grating is capable of multiplexing/demultiplexing wavelength channels that spectrally cover 200nm of bandwidth. The total capacity of this grating is of 400 wavelength channels.

4. CONCLUSIONS

The implications in network structures when considering WDM transmission in the band 1450-1650 nm are enormous. Extraordinary capacity enhancements, node consolidation, elimination of many multiplexing layers and broadband accessing for large sections of the population are simultaneously feasible. We have presented some considerations regarding network architectures and we have studied the feasibility of these concepts in terms multiplexing technology and connectivity offered by wavelength crossconnects (WXC).

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