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The Super-PON concept and its technical challenges

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Abstract

This paper describes the architecture and the technical challenges for the design of a large-split and long-range Passive Optical Network (PON) intended for Fiber-To-The-Home (FTTH) deployment. The system, called Super-PON, can support a splitting factor of 1024 (or more but with a more complex and hence costly implementation) and a range of 100 km. The overall network capacity is 2.5 Gbps TDM downstream and 300 Mbps ATM-based TDMA upstream. As compared with already designed PON systems, the proposed Super-PON requires the introduction of optical amplifiers along the fiber paths. The presence of these optical amplifiers brings new technical challenges especially for burst mode amplification in the upstream direction of transmission. Analysis and potential solutions to solve these problems while allowing further capacity upgrades using WDM/WDMA techniques are described in this paper along with a discussion of network survivability issues.

Keywords

PON, TDMA, ATM, optical amplification.

1 INTRODUCTION

Passive Optical Networks (PONs) using optical splitters to share the overall system cost among subscribers were recognized about 7 years ago as an economical way forward for Fiber-In-The-Loop (FITL) (Stern, 1989). At that time, the need to modernise the copper-based access network for narrowband services triggered the development of the so-called TPON systems (Telephony over PON) which were specifically aimed at minimizing the cost of fiber technology for telephony and narrowband services (Stern 1989, McGregor 1989). The

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encouraging results demonstrated by several field trials using these TPON systems in the early 1990's have stimulated the development of PON systems capable of supporting ATM-based broadband services. The development of these ATM-PON systems was both technology and market driven due to the fact that much of the present growth in telecommunication networks is for the business sector where the demand is for high-speed data transfer in addition to telephony and narrowband-ISDN.

Typically, the capacity of ATM-PON ranges between 50 Mbps and 622 Mbps with a splitting factor of 16 or 32 over lengths not longer than 20 km (Ballance 1990, Mestdagh 1991, Ishikura 1991, du Chaffaut 1993). The recent results of an ATM-PON field trial that has been carried out in the Bermuda's islands can be found in (Van der Plas, 1995). The economical viability of these current ATM-PON systems has been demonstrated for business users as well as for a cluster of residential users located in buildings (Fiber-To-The-Building, FTTB). However, with the current cost of optoelectronic devices ATM-PONs for residential users living in separate houses can only be justified economically when deployment is done in a Fiber-To-The-Curb (FTTC) configuration where fiber terminates on a street cabinet from which Asymmetric/Very-high speed Digital Subscriber Line (ADSL/VDSL) technology can be used to provide broadband services, like video on demand, over the embedded twisted-wire pair network primiraly used for the Plain Old Telephone Service (POTS) service. Upgrades of these hybrid fiber/copper networks towards FTTH for residential users can be accomplished in several ways, one of which being the replacement of active remote electronics in the curb site by optical splitters. The resulting large-split PON-based FTTH system, later referred to as Super-PON, shares costs among a much larger number of subscribers than conventional ATM-PON systems do and may thus become an attractive techno-economic solution in the medium terms for the provisionning of existing and future anticipated services for residential users. Besides this upgrade strategy for local access network, Super-PONs may also be an attractive solution for FTTH deployment in so-called green fields where the wired telecommunication infrastructure is not yet in place. In this case, preliminary studies have shown that due to the required/expected switching node consolidation, the access network will have to cover a much longer range (say, 100 km) than the 20 km of conventional ATM-PON systems.

Taking into account the evolution of FTTC systems towards FTTH systems as well as the deployment of FTTH in green fields, Super-PONs will have to support a high capacity over a large-split (say, of the order of 1000 or more) and a large-range (say, up to 100 km) fiber-based access network. These requirements bring new technical challenges that are mainly associated with multiple access techniques for upstream transmission over the shared PON medium, the use of optical amplifiers along the optical paths to overcome the large network losses, and the need to provide some sort of network survivability mechanisms in order to fulfil the requirements of service availability. These challenges and their potential solutions are discussed in this paper which is organized as follows. The next Section presents the general architecture of Super-PONs and will briefly discuss the trade-offs that exist between the required user capacity and the maximum splitting factor. This section also details the network power budget and will serve to introduce the many parameters that will be used in the subsequent section. Section 3 discusses the technical challenges and presents alternative solutions to overcome them. Emphasis will be given to the analysis of amplified burst-mode upstream transmission. Finally, Section 4 provides a summary and final remarks.

2 THE SUPER-PON ARCHITECTURE

Figure 1 depicts the general architecture of a Super-PON access network system. A single-fiber cable plant is proposed with wavelength multiplexing in the 1.3 μm and 1.5 μm windows for, respectively, up- and downstream transmissions. As an alternative, a two-fiber system could be designed as well, depending on the level of allowable crosstalk introduced by WDM devices in the single-fiber solution.

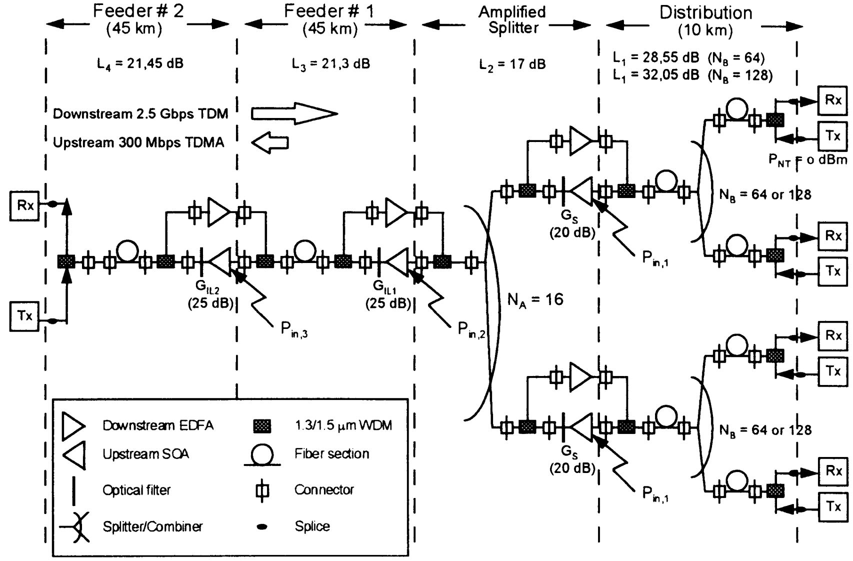

Figure 1 The general architecture of a Super-PON showing the placement of optical amplifiers, connectors/splices, WDM devices for the separation of downstream (at 1.5 μm) and upstream (at 1.3 μm) transmissions and optical amplifiers. The power losses of the different network sections are also indicated along with the gain of optical amplifiers.

Due to the targetted high splitting factor, $N = N_A.N_B$ (see Figure 1 for the definition of N_A, and N_B), high bit rates have to be supported over Super-PONs.

In addition, the choice of multiplexing/multiple-access schemes over Super-PON is of prime concern for an optimum design keeping in mind current technological maturity and eventual upgrading scenarios according to forecast advances in opto-electronic devices. A comparison of multiple access schemes and their potential domains of applications can be found in (Mestdagh, 1995). A 2.5 Gbps downstream Time Division Multiplexing (TDM) and a 300 Mbps upstream packet-based Time Division Multiple Access (TDMA) scheme is proposed for the first generation of Super-PONs. This will allow to later introduce Wavelength Division Multiplexing (WDM) and Wavelength Division Multiple Access (WDMA) schemes as an overlay to TDM/TDMA when the demand for higher network capacity will arise.

The high network losses experienced by the optical signals in the Super-PON requires the introduction of optical amplifiers for both downstream and upstream directions of transmission. The architecture of the Super-PON system that will be analyzed in this paper is depicted in Figure 2. The access network system has been divided into four sections, namely the distribution section, the amplified splitter/combiner section, the first feeder section, and the second feeder section. This will facilitate the calculation of the optical signal power at the input of each amplifier as a function of the losses and gains experienced by the signal in the previous network sections.

The network contains two in-line optical amplifiers, one in each feeder section and 16 optical amplifiers in the input/output branches of the amplified splitter/combiner section. Two different values for the splitting factor of the splitter/combiner located in the distribution section will be considered, N_B=64 and N_B=128, while N_A will be fixed at 16. As such, we will focus our analysis on Super-PONs having either an overall splitting factor N of 1024 or 2048.

Each section is characterised by a total loss $L_{T,i}$ (i=1,2,3,4) equal to the sum of the link losses L_i, the splice losses L_{si}, the connector losses L_{ci}, the WDM losses $L_{WDM,i}$ and the splitter losses $L_{Spl,i}$. The gain of the optical amplifiers will be denoted G_s for the amplified splitter/combiner and $G_{IL,i}$ for the feeder sections.

The five different losses (expressed in dB units) can be calculated as follows:

. $L_i = l_i.\alpha(\lambda)$, where l_i [in km] and $\alpha(\lambda)$ [in dB/km] are respectively the fiber length of section i and the fiber attenuation at the wavelength λ;

. $L_{si} = N_{si}.L_s^{'}$, where N_{si} is the number of splices in section i and $L_s^{'}$ [in dB] is the loss per splice;

. $L_{ci} = N_{ci}.L_c^{'}$, where N_{ci} is the number of connectors in section i and $L_c^{'}$ [in dB] is the loss per connector;

. $L_{WDM,i}$ = 0.5 dB is the loss per WDM device;

. $L_{Spl,i} = 3{,}5.Log_2 N_{A,B}$, where $N_{A,B}$ is the splitting factor of the splitter/combiner in section i [in dB], with $N_A = 16$ in the amplified splitter section and $N_B = 64$ or 128 in the distribution section (the factor 3.5 is taken as a conservative rule).

Table 1 summarises the numerical values of the losses and amplifier gains of the four sections for the upstream direction of transmission operating at a wavelength of 1.31µm. It is seen that the end-to-end upstream network losses are 88.3dB for N =1024 and 91.8dB for N =2048. In order to compensate for these high losses, we will assume $G_s = 20dB$ and $G_{IL,1} = G_{IL,2} = G_{IL} = 25dB$. Such gains are readily achievable with standard commercially available optical amplifiers.

Essentially, it is the presence of optical amplifiers along the fiber path that imposes new technical challenges in the design of TDM/TDMA Super-PONs. These challenges are described in the next section to which we turn now.

Table 1 Network power budget for upstream transmission at 1.31 μm.

		Feeder # 2	Feeder # 1	Amplified splitter	Distribution
	l_l	45 km	45 km		10 km
	α	0,36 dB/km	0,36 dB/km		0,36 dB/km
L_l		16,2 dB	16,2 dB		3,6 dB
	N_{sl}	15	14		3
	L_s	0,15 dB	0,15 dB		0,15 dB
L_{sl}		2,25 dB	2,1 dB		0,45 dB
	N_{cl}	4	4	4	5
	L_c	0,5 dB	0,5 dB	0,5 dB	0,5 dB
L_{cl}		2 dB	2 dB	2 dB	2,5 dB
	$N_{WDM,l}$	2	2	2	2
	L_{WDM}	0,5 dB	0,5 dB	0,5 dB	0,5 dB
$L_{WDM,l}$		1 dB	1 dB	1 dB	1 dB
	$N_{A,B}$			16	64 or 128
$L_{spl,l}$				14 dB	21 or 24,5 dB
$L_{T,l}$		21,45 dB	21,3 dB	17 dB	28,55 or 32,05 dB
G_l		25 dB	25 dB	20 dB	

3 TECHNICAL CHALLENGES

As indicated, one of the major problems for bidirectional transmission over Super-PONs is associated with the use of optical amplifiers along the fiber path. For downstream transmission, Erbium-doped Fiber Amplifiers (EDFAs) operating in the 1.5 μm window can be used to broadcast the TDM data stream to all network terminations. In fact, a PON network comprising a cascade of 4 x 3 x 7^6 x 4 x 7 splittings, corresponding to 39 530 064 potential users, has already been experimentally demonstrated for the broadcast of 384 digital video channels over 12 optical carriers each supporting 2.2 Gbps (Hill, 1990).

Upstream TDMA transmission presents much more challenging problems. Two main issues can be identified: the accumulation of amplified spontaneous emission noise (ASE) of the optical amplifiers, and the time response of optical amplifiers with μsec bursts of data. The former issue becomes particularly detrimental when several optical amplifiers (OAs) are placed in parallel since each amplifier generates its own ASE noise that accumulates at the output of the amplified power combiner (i.e., noise funneling effect). In order to quantify this effect, let us first consider Figure 2 which represents a 1:16 amplified power combiner comprising 16 optical amplifiers (for upstream amplification) of which only n ($n \leq 16$) are biased to their operating point while the other (16-n) OAs are set in the OFF state. With the TDMA MAC protocol, only one of the n biased OAs actually amplifies the input burst data signal while the other (n-1) biased OAs only generate ASE noise.

The Signal-to-Noise Ratio (*SNR*) degradation due to the ASE noise funneling effect can be evaluated as follows. Suppose the amplifier gain is G_s and that each biased amplifier generates identical (but independent) ASE power. Then, the output of the useful amplifier that effectively amplifies the burst of data is given by $G_s.P_{in}$, where P_{in} is the signal power at the input of the amplifier (P_{in} is assumed to be low enough so that OAs don't saturate). Therefore, assuming an ideal photodetector with unity quantum efficiency, the photocurrent generated by the amplified optical signal is given by :

$$i_{sig} = \frac{e}{h\nu}.G_s.P_{in} \tag{1}$$

where e is the electronic charge, h is the Planck's constant and ν is the optical carrier frequency.

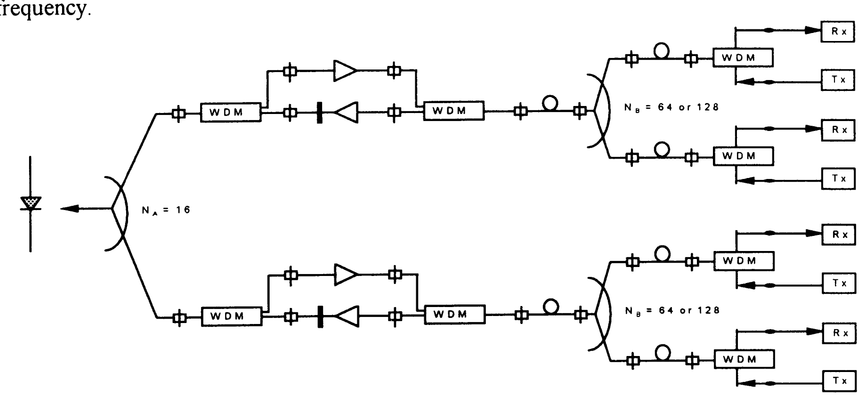

Figure 2 The Super-PON configuration without in-line amplifiers (i.e., short feeder length).

Among the distinct noise contributions due to ASE components, the two most dominant will be considered; that is the signal-ASE and the ASE-ASE beat noises. This assumption is justified provided the gains of OAs are sufficiently high (say, higher than 15 dB) so that shot noises as well as thermal receiver noise become negligible as compared with the beat noises. With a single OA, the electrical power of the beat noises can readily be expressed as follows (Mestdagh, 1995):

$$P_{sig-ASE} = \frac{4e^2}{h\nu}.n_{sp}.(G_s - 1).G_s.P_{in}.B_e \tag{2}$$

$$P_{ASE-ASE} = 2.e^2.n_{sp}^2.(G_s - 1)^2.\Delta\nu_{opt}.B_e \tag{3}$$

where $P_{sig-ASE}$ and $P_{ASE-ASE}$ are respectively the power of the beat between the signal and the ASE and the power of the beat between the ASE components themselves, n_{sp} is the spontaneous emission factor of the OA ($n_{sp} = 2$, which is equivalent to a noise figure of 6 dB, will be assumed throughout the present analysis), $\Delta\nu_{opt}$ is the OA's optical bandwidth ($\Delta\nu_{opt} = \frac{c.\Delta\lambda_{opt}}{\lambda^2}$ where c is the speed of light), and B_e is the electrical bandwidth of the receiver.

With the Super-PON configuration depicted in Figure 2, expressions (2) and (3) must be modified to take into acount the additional beatings between the signal and the ASE noises generated by the other (n-1) biased OAs as well as the beatings between ASEs from all possible combinations in pair of the n biased amplifiers. This gives:

$$P'_{sig-ASE} = n.P_{sig-ASE} \tag{4}$$

$$P'_{ASE-ASE} = \frac{n(n+1)}{2}.P_{ASE-ASE} \tag{5}$$

where $P_{sig-ASE}$ and $P_{ASE-ASE}$ are given by Eqs.(2) and (3), respectively.
Using Eqs.(1), (4) and (5), the SNR at the receiver is given by :

$$SNR = \frac{(G_s.P_{in})^2}{2h\nu.n_{sp}.(G_s-1).B_e.\left[2.n.G_s.P_{in} + \frac{n(n+1)}{2}.n_{sp}.(G_s-1).h\nu.\Delta\nu_{opt}\right]} \tag{6}$$

where $P_{in} = L_1.P_{NT}$ (in what follows we will assume $P_{NT} = 0dBm$).
Assuming large gains (e.g., $G_s \geq 15$ dB) and $n_{sp} = 2$, Eq.(6) reduces to:

$$SNR = \frac{P_{in}^2}{4.h\nu.B_e.\left[2.n.P_{in} + n(n+1).h\nu.\Delta\nu_{opt}\right]} \tag{7}$$

and is therefore independent of the gain G_s.

Eq.(7) shows that the SNR increases with P_{in} (i.e., when N_B decreases) while it decreases as n increases. In order to achieve a bit error rate $BER \leq 10^{-9}$ with binary On-Off Keying (OOK), the required SNR must satisfy $SNR \geq 15.6\ dB$. Figure 3 plots the maximum value of n as a function of N_B assuming a 3dB margin above the minimum required SNR (i.e., we imposed the condition $SNR \geq 18.6\ dB$ in Eq.(7)) and $\Delta\lambda_{opt} = 10\ nm$. The maximum number of connected users, $N=N_A.N_B$, is also shown on the same plot. It is seen that as long as $N_B \leq 64$ each of the 16 OAs can be continously biased (i.e., even if there is no upstream packet at their input) without degrading the SNR below 18.6dB. For N_B>64, the maximum allowed number of biased OAs monotonically decreases with N_B. In other words, this means that if N_B>64, then the OAs in the 1:16 amplified power combiner must be able to be switched on and off to minimize the SNR degradation due to the accumulation and beatings generated by ASE noises. Since the duration of upstream ATM bursts is of the order of a μsec (53 bytes (ATM+overhead) at 300 Mbps), fiber-doped optical amplifiers with long time response of the order of 10 msec are excluded from consideration so that only semiconductor-based optical amplifiers (SOAs) with time response of the order of a few nsec can be used. Each SOA in the amplified power combiner must be controlled so that it can be quickly set in the ON state (i.e., biased at their operating point) when a TDMA upstream packet arrives at its input. At the same time, all other SOAs are set in the OFF state. Although this solution would increase N up to about 2000 as it can be seen from Figure 3, it would be much more attractive to restrict N_B

to a maximum of 64 (providing N=1024) since then the SOAs must not be switched ON and OFF according to the MAC protocol. Therefore, in order to simplify the design and control of the amplified power combiner, it is proposed to dimension the Super-PON system with a maximum splitting factor of 1024 with N_A=16 and N_B=64. Notice that even in this case, SOAs are the only useful candidates for use in upstream direction of transmission thanks to their very short response time.

Eq.(7) shows also that the *SNR* can be improved by incorporating an optical filter with bandwidth $\Delta\nu_{opt}$ behind each SOA. Figure 4 plots the *SNR* calculated from Eq.(7) as a function of n for various values of $\Delta\lambda_{opt}$ ($\Delta\nu_{opt} = c.\Delta\lambda_{opt} / \lambda^2$). It is clear that *SNR* increases as $\Delta\lambda_{opt}$ decreases. However, care must be taken in order to not restrict by too much the usable signal wavelength window. Indeed, this may have serious consequences not only on the cost of the subscriber equipment that would need very precise emitting wavelength control, but also on the possibility to later upgrade the network capacity by using WDMA techniques. $\Delta\lambda_{opt} = 10\ nm$ seems to provide the best compromise between first installation equipment cost and capability of capacity upgrade by WDMA.

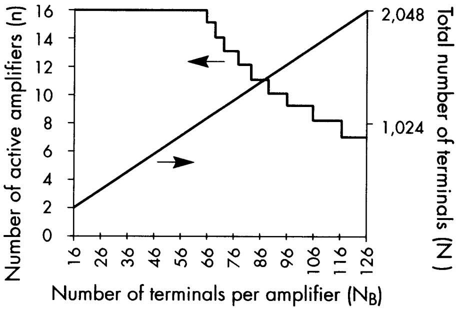

Figure 3 The maximum value of biased amplifiers in the amplified power combiner as a function of N_B assuming $SNR \geq 18.6dB$ and $\Delta\lambda_{opt} = 10nm$.

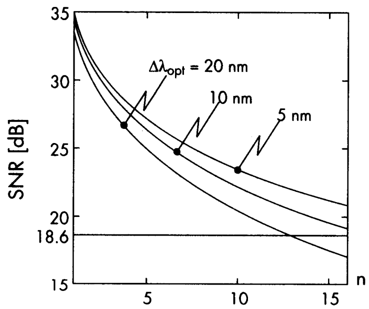

Figure 4 *SNRs* in front of the optical detector shown in Figure 3 as a function of n for various values of $\Delta\lambda_{opt} = 5$nm, 10nm, and 20nm. N_B=64 so that $N = N_A . N_B = 1024$.

Let us now turn our attention to the case of a long feeder Super-PON as depicted in Figure 1. As compared with Figure 2, this long feeder Super-PON contains two additional OAs for in-line amplification. These two OAs will introduce their own ASE noise that will mix with the amplified signal and ASEs from the splitter/combiner amplifiers to create many beat noises.
The generated beat noises can be grouped into two main categories: (a) signal-*ASE* beat noises; between the signal and the *ASE* from the *n* OAs in the power combiner (ASE_s) and between the signal and the *ASE* from the first (ASE_{IL1}) and second (ASE_{IL2}) in-line OAs, and (b) the *ASE-ASE* beat noises from all combinations in pair. Following the same analysis as that outlined in (Mestdagh, 1995), and using the parameters defined in Figure 1, the signal-ASEs and ASEs-ASEs beat noise electrical powers are readily obtained as :

$$P_{sig-ASE_s} = n.\frac{4e^2}{h\nu}.n_{sp}.G_{IL}^3.(G_s-1).L_2L_3L_4^2.P_{in,3}.B_e \tag{8}$$

$$P_{sig-ASE_{IL1}} = \frac{4e^2}{h\nu}.n_{sp}.G_{IL}^2.(G_{IL}-1).L_3L_4^2.P_{in,3}.B_e \tag{9}$$

$$P_{sig-ASE_{IL2}} = \frac{4e^2}{h\nu}.n_{sp}.G_{IL}.(G_{IL}-1).L_4^2.P_{in,3}.B_e \tag{10}$$

$$P_{ASE_s-ASE_s} = \frac{n(n+1)}{2}.2e^2.n_{sp}^2.G_{IL}^4.(G_s-1)^2.L_2^2L_3^2L_4^2.\Delta\nu_{opt}.B_e \tag{11}$$

$$P_{ASE_{IL1}-ASE_{IL1}} = 2e^2.n_{sp}^2.G_{IL}^2.(G_{IL}-1)^2.L_3^2L_4^2.\Delta\nu_{opt}.B_e \tag{12}$$

$$P_{ASE_{IL2}-ASE_{IL2}} = 2e^2.n_{sp}^2.(G_{IL}-1)^2.L_4^2.\Delta\nu_{opt}.B_e \tag{13}$$

$$P_{ASE_s-ASE_{IL1}} = n.2e^2.n_{sp}^2.G_{IL}^3.(G_{IL}-1).(G_s-1).L_2L_3^2L_4^2.\Delta\nu_{opt}.B_e \tag{14}$$

$$P_{ASE_s-ASE_{IL2}} = n.2e^2.n_{sp}^2.G_{IL}^2.(G_{IL}-1).(G_s-1).L_2L_3L_4^2.\Delta\nu_{opt}.B_e \tag{15}$$

$$P_{ASE_{IL1}-ASE_{IL2}} = 2e^2.n_{sp}^2.G_{IL}.(G_{IL}-1)^2.L_3L_4^2.\Delta\nu_{opt}.B_e \tag{16}$$

where $P_{in,3} = P_{NT}.L_1.L_2.L_3.G_s.G_{IL}$ is the optical signal power at the input of the second in-line optical amplifier.

After straightforward algebraic manipulations, we obtain :

$$SNR = \frac{P_{in,3}^2}{2.h\nu.n_{sp}.B\left[F_1(n,P_{in,3},G_s,G_L,L_2,L_3)+F_2(n,\Delta\nu_{opt},G_s,G_{IL},L_2,L_3)\right]} \tag{17}$$

where $F_1(n,P_{in,3},G_s,G_{IL},L_2,L_3) = 2.(n.G_sG_{IL}.L_2L_3+G_{IL}.L_3+1).P_{in,3}$ (18)

and $F_2(n,\Delta\nu_{opt},G_s,G_{IL},L_2,L_3) = n_{sp}.h\nu.\Delta\nu_{opt}.[\frac{n(n+1)}{2}.G_s^2G_{IL}^2.L_2^2L_3^2$

$+n.G_sG_{IL}.L_2L_3.(G_{IL}.L_3+1)+G_{IL}^2.L_3^2+G_{IL}.L_3+1]$ (19)

Figure 5 plots the *SNR* as a function of *n* for three distinct values of the optical filter bandwidth placed just behind each OA.

When n=1, $SNR \cong 32\,\text{dB}$ and is almost independent of the filter bandwidth (for the range of $\Delta\lambda_{opt}$ considered here). The introduction of the two in-line OAs therefore degrades the *SNR* by about 3dB as can be seen by comparison with Figure 4 which provides $SNR \cong 35\,\text{dB}$ when n=1. As *n* increases, the degradation in *SNR* due to the two additional in-line OAs becomes relatively less significant. Even for n=16 (i.e., all OAs in the amplified power combiner are biased and generate independent ASE noises) the *SNR* can still be maintained above 18.6dB (actually $SNR = 18.7$ dB). Notice that when the two in-line OAs are abscent, $SNR = 19\,\text{dB}$ for n=16 and $\Delta\lambda_{opt} = 10nm$ (Figure 4) so that the degradation due to the in-line OAs is only 0.3dB for n=16. In essence, this is because the dominant beat noises are those stemming from beatings of the n ASEs from the OAs in the power combiner with the signal and among themselves. Beatings with ASEs from the two in-line OAs are comparatively negligible. In conclusion, upstream burst-mode transmission over a 1024-split Super-PON covering a range of 100 km can be achieved by the use of SOAs without requiring on-off switching capability of the SOAs.

The situation becomes much more complex if N_B has to be increased up to 128 in order to obtain an overall splitting factor of 2048. Indeed, as shown in Figure 6, n must satisfy $n \le 6$ in order to have $SNR \ge 18.6\,\text{dB}$ with $\Delta\lambda_{opt} = 10nm$. This means that the SOAs in the power combiner must be switched on and off according to packet arrivals. This requires a complex control system related to the MAC protocol that manages the packet flow through the network. Notice finally that this complex control may be avoided by reducing $\Delta\lambda_{opt}$. However, as shown in Figure 6, $\Delta\lambda_{opt}$ must be reduced down to $\Delta\lambda_{opt} \le 0.5nm$ in order to achieve $SNR \ge 18.6\,\text{dB}$ when n=16. Clearly, this is unacceptable since there will be no space left for network capacity upgrade by WDMA.

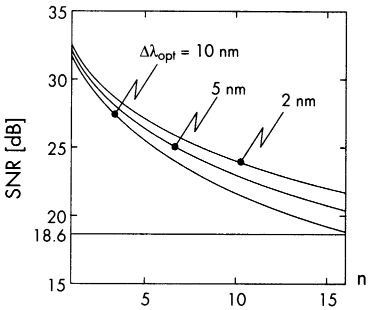

Figure 5 : *SNRs* for the long feeder Super-PON as a function of n for various values of $\Delta\lambda_{opt}$ =2nm, 5nm, and 10nm. N_B=64 so that $N = N_A . N_B = 1024$.

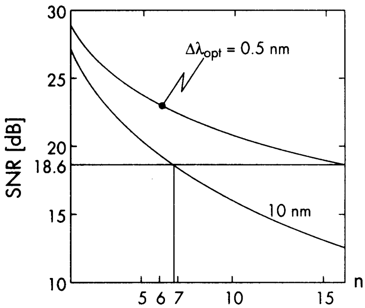

Figure 6 : *SNRs* for the long feeder Super-PON as a function of n with $\Delta\lambda_{opt}$ =0.5nm and 10nm. N_B=128 so that $N = N_A . N_B = 2048$.

Network survivability - A key issue for the viability of Super-PONs is to assure sufficient robustness against failures of network elements that are shared by a large number of subscribers. This is especially the case for the line card at the central office, the feeder, and the amplified splitter/combiner. Therefore, redundancy of these network elements appears to be mandatory. A possible configuration of a survivable Super-PON network is shown in Figure 7. It is seen that, in addition to duplication of these network elements, the duplicated feeder should be installed along a diverse route in order to avoid network breakdown due to cable cuts. Moreover, it might also be required to provide diverse routing of the sub-feeder of the drop section that serves up to 64 or 128 subscribers (not shown in the figure).

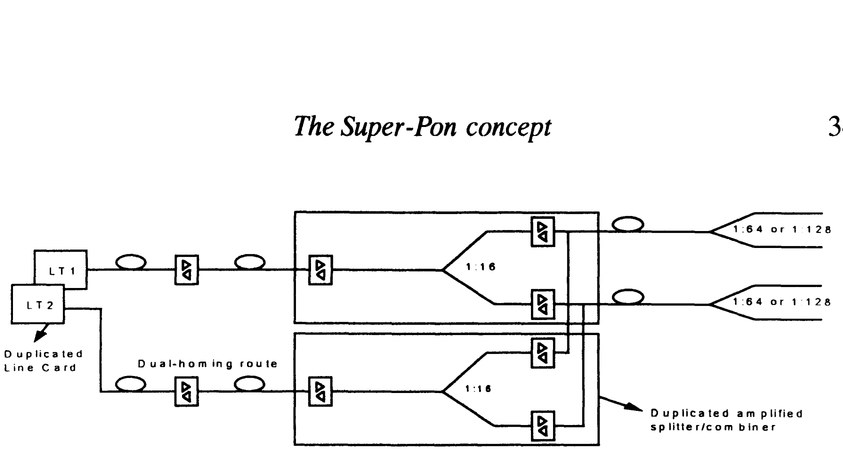

Figure 7 One possible configuration to improve the access network reliability by duplication and diverse routing of high group failure network elements.

Capacity upgrades - To upgrade the capacity of the initial TDM/TDMA Super-PON, additional channels could be added by the introduction of WDM/WDMA techniques. The challenge is to define an upgrading strategy that has no impact on the subscriber equipment in order to minimize the installation costs of the upgrade. One possible downstream upgrade scenario that does not require any change or replacement of already installed subscriber equipment is depicted in Figure 8.

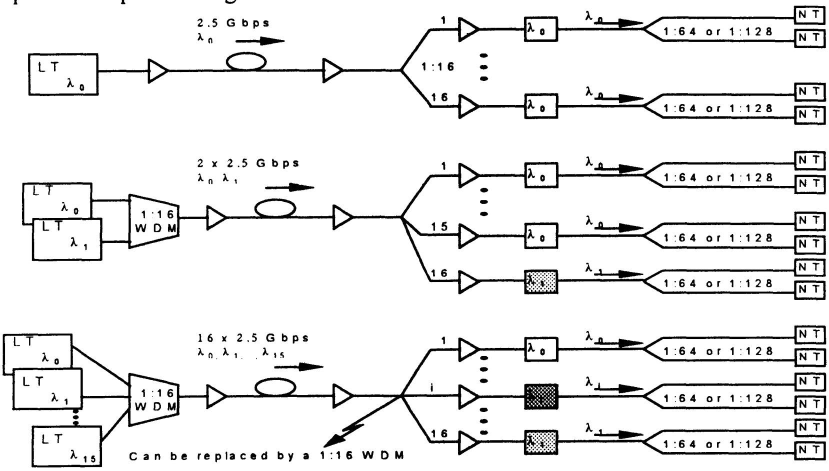

Figure 8 An upgrade scenario for downstream Super-PON capacity by using WDM technology without modification of the subscriber equipment.

The 1:16 amplified splitter initially contains passband optical filters centered around the transmitter wavelength λ_0. Downstream capacity upgrade is achieved by transmitting separate 2.5 Gbps TDM channels on distinct wavelengths within the 1.5 μm window. Up to 16 wavelength channels can be added gradually by replacing the λ_0-centered passband filter by another passband filter centered around one of the wavelengths not yet in use for the upgrade. Eventually, when all 16 WDM downstream channels are in operation, then the 1:16 splitter can be replaced by an almost lossless WDM device resulting in an improved overall network power budget. Upgrading of the upstream capacity can be accomplished by wavelength conversion at the amplified splitter as shown in Figure 9.

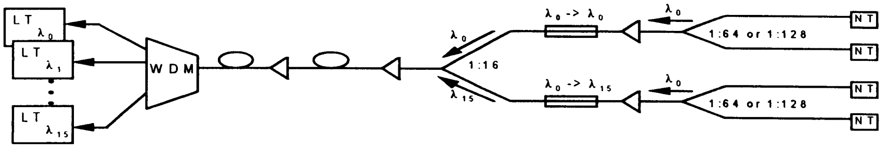

Figure 9 An upgrade scenario for upstream Super-PON capacity by using wavelength convertors within the amplified power splitter/combiner.

Although wavelength convertors are still at the preliminary laboratory stage, encouraging results have recently been achieved. A review of the state-of-the-art alternatives for wavelength conversion can be found in (Masetti, 1995). A very promising device is the so-called "clamped-gain SOA" which can be monolithically integrated to provide both wavelength-conversion and optical amplification (Soulage, 1995). In addition, these devices have a much improved performance regarding crosstalk than conventional SOAs.

4 CONCLUSIONS

The new concept of Super-PON for application in the local access network has been introduced and its technical challenges discussed. One of the major challenging problems with Super-PONs is associated with the use of optical amplifiers and packet-based TDMA for upstream transmission. It has been shown by an analytical analysis that an overall splitting factor of up to 1024 can be sustained without the need to provide switching capability for the necessary semiconductor optical amplifiers (SOAs) placed in parallel within the power splitter/combiner. However, if the target splitting factor must be increased up to 2048 or more, then the SOAs in the power splitter/combiner must be switched on and off according to the TDMA MAC protocol unless optical filters with a passband less than 0.5nm are inserted behind each amplifier (forbidding capacity upgrade by WDMA). Therefore, in order to simplify the design and control of Super-PONs, and hence improving its reliability, it is advised to limit the maximum splitting factor to 1024 at the most.

The Super-PON concept is currently investigated within the PLANET Consortium that is partly funded by the Commission of the European Communities in the framework of the ACTS programme. Results of the studies and developments will be presented during the conference.

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