Study and demonstration of extensions to the standard FSAN BPON

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Abstract

Different extensions to a standard BPON (Broadband Passive Optical Network) are reported. The optical splitting factor was increased from 1:32 to 1:256. A dynamic MAC (Medium Access Control) protocol was demonstrated, which is QoS (Quality of Service) aware and improves the bandwidth efficiency of packet based services on a BPON. Another enhancement is to offer Gigabit Ethernet point to point services as WDM (Wavelength Division Multiplexing) overlay on a BPON.

1. Introduction

For many network operators, an optical access network is the ultimate target for the delivery of fixed broadband services. The BPON is generally accepted as a cost-effective FTTH (Fibre To The Home) solution well-suited to the future needs of broadband services. A major feature of the BPON is that 32 customers can be concentrated on a single fibre to the central office using a simple passive optical splitter. Since this optical splitter requires no electrical power, it eliminates a major cost and maintenance element in today's digital loop carrier systems. The BPON supports a bit rate of 622 or 155 Mbit/s in the downstream and upstream direction, which is shared by the users through time division multiplexing. ATM (Asynchronous Transfer Mode) is used at the link layer. The multi-service capability and support of different QoS (Quality of Service) classes of ATM are well suited to efficiently deploy IP (Internet Protocol)/Ethernet data packets, video streams, as well as the legacy narrowband and leased line services over a single full service access network infrastructure. A standard APON (ATM Passive Optical Network) was specified by the FSAN group (Full Service Access Network) [1], resulting in recommendation G.983.1 endorsed by ITU-T in 1998. More recently, some extensions were standardised and the name changed into BPON. The most relevant extensions in the context of the present paper were the specification of WDM (Wavelength Division Multiplexing) enhancement bands in G.983.3 and DBA (Dynamic Bandwidth Allocation) in G.983.4, both approved in 2001 [1]. Concurrent with the mentioned standardisation efforts, enhancements to the G.983.1 BPON have been investigated in research.

This paper addresses the technical feasibility of several extensions to BPON. A first enhancement is an increased splitting factor. Previous papers already reported on a spectacular increase of the splitting factor of up to 1:2048 by the use of optical amplifiers in a SuperPON. This system however requires a new standard and is only economically feasible on a long term [2],[3]. In the present paper, approaches compliant with the existing standards and economically feasible on a medium term are demonstrated . A next section describes the experimental evaluation of a dynamic MAC (Medium Access Control) protocol. The mechanism allows for an efficient multiplexing of the upstream traffic on the shared PON medium, thereby respecting the service levels of the different supported QoS classes. A last section explores the possibilities of the WDM enhancement band. In current FTTH products, the enhancement band is already used to carry video broadcast services. The present paper reports on overlaying point-to-point WDM links. These could be used to offer Gigabit Ethernet services for high-end business users, while other subscribers are still connected to the basic services offered on the BPON.

2. Extension of the splitting factor

An increased optical splitting factor could be useful in areas where the initial service penetration is low, such as for "overbuild" deployment (i.e. where narrowband facilities already exist to the customer). When introducing FTTH by means of PON networks, the operator needs to consider every home passed as a potential subscriber, and hence to foresee a fibre passing his/her premise for possible connection to a PON LT (Line Termination) at the central office. Given that current low cost optical components limit the "optical" splitting factor of a BPON to typically 32 users, the necessary amount of LT can become quite large to serve every possible newly-connected user. This represents a substantial initial investment, which is not efficiently used during early deployment or overbuild scenarios when penetrations are below a few ten percent.

By improving the optical budget on the BPON fibre, up to 128 or 256 homes could be "passed" by a single HS (High Split) LT. Up to 64 of these homes could be connected, which is the maximum number of ONUs (Optical Network Unit) that can be identified by a G.983.1 compliant system. In preparation for higher service penetrations, the optical splitter in the outside network would be limited to a 8, 16 or 32-way split; further splitting would be done in the OMDF (Optical Main Distribution Frame) in the central office (cf. Figure 1). Once more than 64 customers had subscribed to the service or the total bandwidth utilisation had become larger than 622/155 Mbit/s, customer clusters would be gradually switched over to individual LTs in the central office.

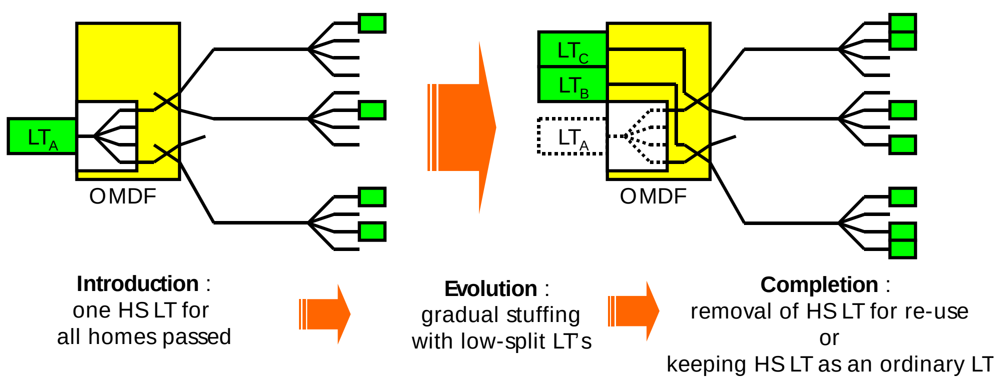


Figure 1: Extension of the splitting factor as an introduction scenario for FTTH.

Extending the splitting ratio from a typical value of 32 to 128 or 256 requires increasing the optical power budget in both transmission directions. A cost-effective and reliable solution implies keeping the users' hardware unchanged and the fibre plant purely passive. Consequently, the optical power budget will have to be won at the CO (Central Office) side. Two approaches were demonstrated and evaluated (Figure 2):

- A transparent solution is based on an Erbium Doped Fibre Amplifier (EDFA) to boost the downstream signal and a passive 8 to 1 single-mode-to-multimode coupler, also called LLC (Low Loss Combiner), to reduce the optical loss in the upstream direction. A pump laser is shared by four EDFAs to reduce the cost. These optical components are inserted in front of the LT, making it unnecessary to modify the hardware of the BPON system.
- A hardware upgrade solution is based on a HPLD (High Power Laser Diode) for the downstream transmission and an APD (Avalanche Photo Detector) to improve the receiver sensitivity in the upstream direction.

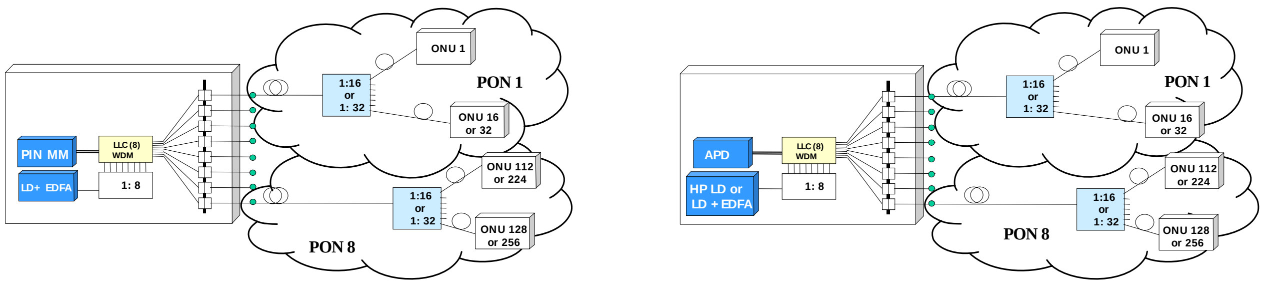


Figure 2: Extension of the splitting factor in a transparent implementation (left) and a hardware upgrade implementation (right).

Cost evaluation

An economic analysis was carried out for several cases. The investment of the central office equipment was systematically estimated at the beginning (no users) and the end (all users connected) of the subscription to FTTH. The investment estimation takes into account how many LTs are used (and hence the necessary amount of slots at the access nodes), the extra components needed to achieve a high split, the OMDF and optical switches for switchover, and the contribution of the necessary amount of access nodes. As shown in Table 1, the cost results depend on the amount of conventional LTs that can be replaced by the High Split LT at the start of the introduction and the impact on the necessary amount of access node slots at that time, and by the cost of the High Split LT itself. Class B and Class C refer to a standard APON with an optical power budget varying respectively between 10 - 25 dB and 15 - 30 dB, as defined in G.983.1.

Table 1: Cost comparison for a high split ratio of 128 (up) and 256 (below) – Reference is the cost of an equivalent Conventional Split configuration.

Regrouping factor	Class B			Class C		
	Initial Cost	Reference	Final cost	Initial Cost	Reference	Final cost
High Split Ratio of 128						
4 x (32 split)	0.65	1	1.53	0.60	1	1.49
8 x (16 split)	0.44	1	1.38	0.46	1	1.41
16 x (8 split)	0.35	1	1.32	0.31	1	1.29
High Split Ratio of 256						
8 x (32 split)	0.44	1	1.37	0.40	1	1.34
16 x (16 split)	0.38	1	1.34	0.32	1	1.29
32 x (8 split)	0.26	1	1.25	0.22	1	1.21

For small regrouping factors there is already a significant economy. When comparing equal regrouping factors for a split of 128 versus 256, the cost values are very similar. The advantage of the 256 version is the capacity of having higher regrouping factors. The difference between Class B and Class C is also limited, with a small benefit for Class C due to the higher cost of the Class C - LT. The investment in extra components like the EDFA and LLC can even be recuperated by reusing these components in other parts of the network after a complete switchover.

Requirements for optical budgets with extended split

Table 2 presents the required optical budgets (calculated OPL (Optical Path Losses) and optical levels at the LT side) necessary to get the different extended split PON topologies. The upstream part was assumed to use the LLC, as it relieves the sensitivity requirements on the LT receiver. Note that the first configuration, regrouping 4 PONs of 32 ONUs each, is only using half of the ports of the 1:8 LLC.

Table 2: Requirements for an extended split PON Class B 155 / 155 Mbps (with LLC in Upstream).

Split stage at C.O.	Split stage in PONs	Minimal OPL (dB)	Maximal OPL (dB)	Minimal transmitted power (dBm)	Maximal transmitted power (dBm)	Minimal OPL (dB)	Maximal OPL (dB)	Needed Sensitivity (dBm)	Needed Overload (dBm)
128 ONUs		Downstream				Upstream			
4	32	25.1	34.9	5.9	17.1	19.0	30.1	-34.1	-17.0
8	16	24.7	38.3	9.3	16.7	15.7	30.2	-34.2	-13.7
16	8	26.3	39.1	10.1	18.3	17.8	31.4	-35.4	-15.8
256 ONUs		Downstream				Upstream			
8	32	28.0	38.1	9.1	20.0	19.0	30.1	-34.1	-17.0
16	16	27.8	41.8	12.8	19.8	19.3	34.0	-38.0	-17.3
32	8	29.6	43.6	14.6	21.6	20.8	34.8	-38.8	-18.8

Demonstrator

A demonstrator was realised based on a standard APON transport system with Class B ONUs. The set-up was used for BER (Bit Error Rate) measurements in both directions, in order to evaluate whether the requirements of the topologies considered in Table 2 could be fulfilled. In accordance to ITU-T G.983.1, the BER validation threshold was taken at 10^{-10}. More details on the measurement set-up can be found in [4].

The most important experimental results are summarised in Figure 3. The left diagram of Figure 3 shows the maximum attenuation in the downstream direction as a function of the average emitted LT transmitter power (HPLD or LD+EDFA). The requirement to regroup 8 PONs of 32 users is also shown as an illustration, indicating the margins offered by the ONU receiver. The right diagram of Figure 3 shows the BER of a burst mode receiver with an APD, which is used in combination with a LLC. In this experiment, the upstream bandwidth is shared by two ONUs (60 Mbps traffic each), resulting in a succession of cells with a strong signal power from ONU2, cells with a weak signal power from ONU1, and empty cells. The second user introduces a small penalty of 0.6 dB. This represents a worst-case version of a real-life operation.

In the downstream direction, all configurations of Table 2 are feasible with the transparent version consisting of an EDFA and a conventional LT transmitter. In the hardware upgrade version, the average power of the HPLD is limited to 10 dBm. It means that all configuration with a split of 128 are possible, while for a split of 256, only the topology with a regrouping factor of 8 is achieved.

In the upstream direction, the transparent solution allows for a total split of 128. Other configurations are possible if the maximum distance is restricted. The transparent solution uses a conventional PIN (Positive Intrinsic Negative) detector in the burst mode receiver, which features a sensitivity of –33 dBm and a dynamic range of 22 dB. The LLC relieves the optical budget requirements with 4 dB. In the hardware upgrade version, the APD improves the sensitivity to –36 dBm, but limits the dynamic range to 15 dB. In combination with a LLC, configurations with a 256 split are feasible, though with a restriction on the differences in fibre length due to the dynamic range.

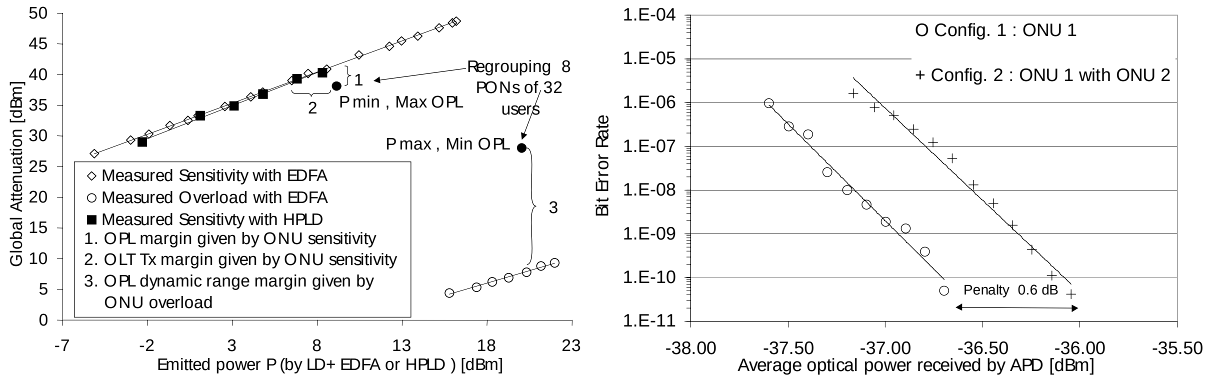


Figure 3: Results of BER measurements on extended split APON demonstrator.
Left: downstream for the transparent and the hardware upgrade implementations (BER<10^{-10}),
Right: upstream sensitivity for LT with APD and LLC.

3. Dynamic MAC protocols

In a shared medium, such as the PON, in which the upstream bandwidth from the ONU to the LT is shared by a TDMA (Time Division Multiple Access) mechanism, a MAC controller at the LT is required to arbitrate the access for each timeslot. In an APON, the timeslot is an ATM cell. There are several methods for implementing a centrally controlled MAC Protocol. A first method allocates the bandwidth to an ONU by generating a fixed rate of permits (also called grants) for that ONU based on signalling information. This is called a static MAC protocol. For services with a variable bit rate, the bandwidth efficiency can be improved by a dynamic MAC. In a so-called "unsolicited dynamic MAC", this can be realised by detecting unused upstream timeslots of a given ONU and consequently reallocating this part of the bandwidth to other ONUs. In order to achieve a faster adaptation to bursty bit rate variations , it is however better to let the LT generate permits, based on the requests received from the ONU via a request channel. If an efficient cell scheduling and buffering mechanism is used at the ONU side, it has already been shown by simulations that a dynamic MAC can be very efficient for transporting bursty TCP/IP traffic [5]. A static MAC protocol is considered in the G.983.1 version, while the dynamic MAC has recently been standardised in G.983.4.

The operation of a MAC protocol requires the transmission of a grant from LT to ONU, which indicates the ONU that is allowed to use an upstream time slot. It is even possible to make a subdivision of grants per QoS (Quality of Service) category in an ONU, also called T-Cont (Traffic Container). A T-Cont groups one or more connections from an ONU to the LT with similar service guarantees. The grants that identify a specific T-Cont are sometimes referred to as "coloured grants". Note that in G.983.1/2, the grants are assigned per ONU, not per T-Cont, which could be called "colourless grants". To improve the bandwidth efficiency for some types of T-Cont, it is beneficial to report the number of data cells in the queues at the ONU that are waiting for a permission to be transmitted in the upstream direction. This is called the request channel of the MAC.

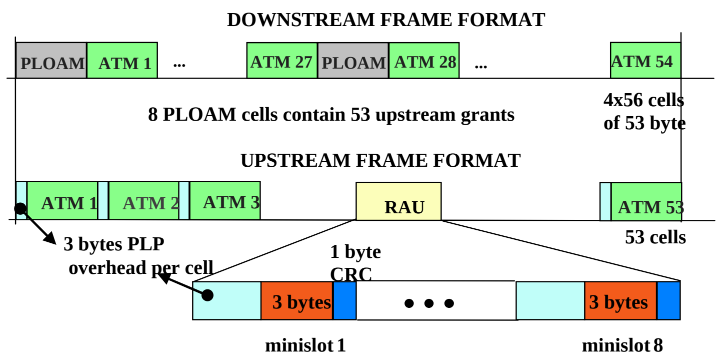


Figure 4: Frame format: Downstream PLOAM cells contain grant fields – Upstream minislots in the RAU contain requests.

The grants generated by the MAC Controller are encapsulated in the PON transport system in dedicated fields of the PLOAM cells (Physical Layer Operation Administration and Maintenance). Figure 4 shows the frame structure of the downstream and upstream for a 155/155 Mbit/s BPON. 2 downstream PLOAM cells per frame contain the grants for 53 upstream timeslots.

The request channel is realised by dedicated mini slot cells, which are sent per group of ONU in so-called multi-burst slot or RAU (Request Access Unit) at regular polling intervals. The multi-burst slot allows that one upstream timeslot (56 bytes) is used by a several ONU, each reporting in a particular, pre-assigned mini-slot. The request channel in the demonstrator was configured as 8 mini-slots in an upstream timeslot of (56 bytes) each consisting of 3 byte PLP (Physical Layer Preamble), 3 bytes request data, and 1 byte CRC (Cyclic Redundancy Check).

The implementation of the dynamic MAC functionality on the network required the introduction of a dynamic MAC chip-set, as shown in Figure 5. On the LT side, a MAC controller chip was introduced, while every ONU contains an ACRA (ATM Cell Routing and Adaptation) chip.

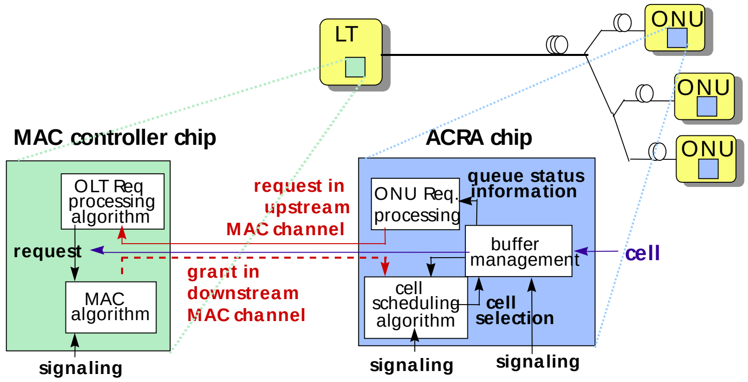


Figure 5: MAC components in BPON system.

The MAC controller at the LT contains a permit generator for each T-Cont per ONU. The permit generators can be purely rate based, purely request based, or a combination of both, depending on the T-Cont type. The implementation of the T-Cont types furthermore differs in the priority that the generated permits will obtain in the forwarding to the ONU. The realised prototype supports 4 T-Cont types per ONU. The MAC controller further more schedules the permits of the generators in order to send one grant per timeslot to the ONU. The ACRA chip at the ONU receives the grant. In the case of colourless grants, a scheduler in the ACRA decides about the queue to be emptied, thereby taking into account the priorities and service level agreements. In the case of coloured grants, only the queue(s) of a specific T-Cont can be selected. The ACRA chip furthermore performs frame aware buffer acceptance mechanisms and translates the queue status into the proper request information (e.g. increase of queue length or total number of cells waiting). The demonstrator platform is made configurable in order to evaluate various DBA options. More details about the DBA demonstrator are described in [6].

In order to evaluate the dynamic system behaviour, nearly all upstream bandwidth was allocated to 'background' ONUs, while only limited bandwidth was left available for the ONU under test. A Burst Level Traffic Generator /Analyser was used for analysis.

The T-Conts for the ONU under test have been configured as follows:

T-Cont 1: Highest priority fixed rate CBR (Constant Bit Rate) type,

T-Cont 2: Rate based permit allocation of specified minimum cell rate and request triggered permit rate change for additional bandwidth variations, e.g. VBR (Variable Bit Rate),

T-Cont 3: Request based permit allocation only, e.g. GFR (Guaranteed Frame Rate),

T-Cont 4: Lowest priority request based permit allocation only, e.g. best effort UBR (Unspecified Bit Rate).

The PON round trip delay was set to 216 µs, which corresponds to a range of 20 km. The intervals of the multi-burst slots were such that an ONU was polled for requests once every 144 µs. Different groups of tests were carried out focusing in different characteristics of the system. Two important results will be described here.

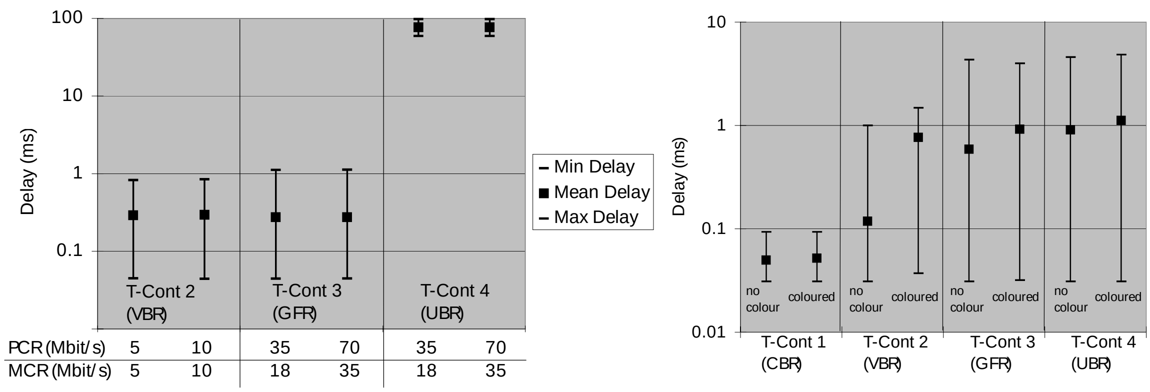


Figure 6: Left: impact of T-Cont priority on traffic delay – Right: impact of coloured grants on traffic delay.

Impact of priorities

Figure 6 – left shows the cell delay for connections belonging to different priorities of T-Conts. Each source is related to one T-Cont class, served by the MAC Controller. The scenario was performed for an average system load of 80%. The bit rates mentioned below the diagram (PCR: Peak Cell Rate, MCR: Minimum Cell Rate) describe the behaviour of the sources. They also specify the QoS parameter for the schedulers in case of T-Cont 2 and 3, but not in case of T-Cont 4. It is shown that connections of the same T-Cont class experience similar performance and close delay values, although the rates are different. The T-Cont classes 2 and 3 achieve a better performance than T-Cont 4, as they obtain a higher priority. The mean transmission delay for T-Cont classes 2 and 3 is almost similar. T-Cont 2 is meant for real-time VBR and therefor performs better in cell delay variation. T-Cont class 4 is a best effort service. Its traffic suffers from the system load as it observes the highest delay values. (T-Cont 1 as a CBR was not considered in this test scenario.)

Comparison of coloured versus colourless grants

An other experiment compared the efficiency of a MAC protocol based on grants per ONU versus grants per T-Cont in an ONU (Coloured). The results in Figure 6 - right show that there is no advantage in having the additional complexity of coloured grants. On the contrary, the average delay (for T-Cont 2, 3 and 4) is lower in the colourless case than the coloured grants.

4. Bandwidth upgrade by WDM

WDM is an attractive scheme to increase the bandwidth of an optical access system. WDM was already demonstrated in [8], as means to multiplex different APON streams in a FTTCab topology and configure the bandwidth per ONU in a flexible way. The recently approved standard G.983.3 defines an enhancement band from 1539 until 1565 nm for overlay services, in addition to bands from 1480 until 1500 nm for the downstream and from 1260 until 1360 nm for the upstream BPON signals. In current FTTH products, the enhancement band is used to carry video broadcast services.

In the present paper, a solution is described to overlay point-to-point WDM links which can be used, for instance, to offer Gigabit Ethernet services or a transparent link to the metropolitan network for high-end business users, while at the same time other subscribers remain connected to the services offered on the BPON. In this concept, an evolutionary upgrade of the capacity on a BPON is possible in which only the high-end users pay for the more expensive WDM technology.

The principle is explained in Figure 7. Each of the installed BPON ONU has a WDM filter integrated in the transceiver that blocks any signal with a wavelength in the enhancement band, as specified by the G.983.3 standard. One or more downstream DWDM (Dense WDM) signals, each carrying a point-to-point service, are multiplexed in the central office for example by an AWG (Arrayed Wave guide Grating) [7]. They are then broadcast in the enhancement band over the PON and received by the corresponding narrow band filter that selects one DWDM wavelength at a high-end subscriber. In the upstream direction, the high-end NT (Network Termination) transmits a signal at a specific wavelength that is demultiplexed at the central office towards a point-to-point LT (Line Termination) or passed on to the metro network. This approach has some interesting advantages compared to other WDM access architectures as e.g. proposed in [9]. The power splitter does not need to be replaced by a special temperature controlled multiplexer in the field. The number of wavelength pairs can be smaller than the number of branches. A wavelength pair is not bound to a given branch. The solution can be realised today with mature WDM technologies. Disadvantages are the perceived insecurity of WDM channels being broadcast in the downstream direction, which however can be solved by encryption at a higher layer, and the larger required optical budget, which can be solved by a shared optical amplifier in the central office or by limiting the number of branches as illustrated by the simulation results below.

Simulations were performed to determine the optical budget for a given maximum number of supported overlay channels. The model takes into account bi-directional transmission, adjacent and non-adjacent channel cross talk, the influence of the BPON signals, as well as reflections by the filters in the central office and at the customer premises, the multiplexer in the central office, and the ODN (Optical Distribution Network) as defined in G.983.1. Worst case situations were considered, taking into account the variations of different parameters like the insertion loss and launched optical power. The simulations were supported by lab experiments.

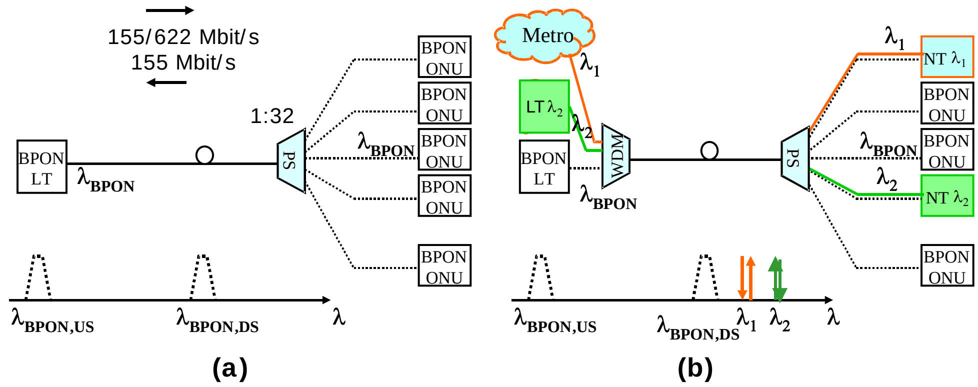
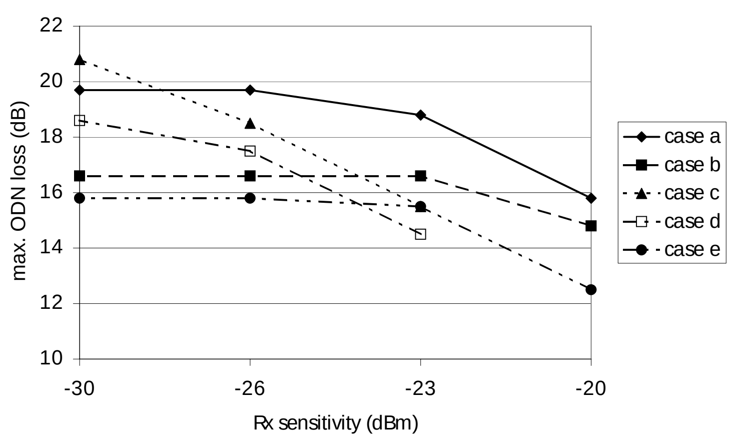


Figure 7: WDM upgraded BPON (PS: Power Splitter, US: Upstream, DS: Downstream).

Figure 8 shows the maximal ODN loss as a function of the receiver sensitivity. The inserted table shows the different cases that were simulated with parameters of commercial AWG components. Note that the results apply only to the DWDM part, the normal BPON part of the system is unaffected. For the large sensitivities (-20 dBm, -23 dBm), the optical budget is the limiting factor and the maximum ODN loss increases with improvement of the sensitivities. Below a certain sensitivity, the maximum allowed ODN loss no longer increases, because the linear cross talk then becomes the limiting factor. Depending on the branch of the ODN, the optical losses can differ as much as 15 dB due to differences in fibre length, non uniformity of insertion loss per splitter port, and tolerances of the insertion loss of other components in the optical path. Also the tolerances on the transmitted optical power add to the dynamic range of the signal at the receiver. The strong optical signal received from a branch that features a small optical loss can cause a prohibitive cross talk to the small signal arriving from a branch with a large optical loss. A minimum SIR (Signal to Interference Ratio) of 10 dB was used as a criterion.



case	max. # chan.	channel spacing in GHz	adjacent cross talk of AWG in dB	insertion loss of AWG in dB
a	2x2	400	25	2.5
b	2x4	400	25	3.5
c	2x4	200	30	5
d	2x8	200	30	6
e	2x8	200	25	6

Figure 8: Maximum loss of ODN for WDM point to point link in overlay to BPON (BPON Tx: -1,+2 dBm, WDM Tx: -1, +2 dBm).

The simulation results can be used to determine feasible architectures in which GigE (Gigabit Ethernet) point-to-point services are overlaid to BPON. A typical PIN based receiver for a GigE link has a sensitivity of about –26 dBm. Applying this to case c in Figure 8, the maximum ODN loss is 16.5 dB, which corresponds e.g. with a PON of maximum 7.6 km and a split of 1:8 for the DWDM users. Maximum 4 users in a cluster of 8 users can hence be hooked up to a GigE service with two wavelengths to support the bi-directional transmission. The clusters of 1:8 can of course be grouped to one BPON LT by an additional splitter in the central office. When an APD based receiver is used for the GigE link, the sensitivity can be as low as –30 dBm. Again in the example of case c, the maximum ODN loss is then 20.5 dB, which corresponds to a PON cluster of maximum 8 km and a split 1:16. If larger clusters are desired, optimised requirements for components like the AWG, optical amplification of the DWDM signals, or an alternating wavelength configuration will be required, as also proposed in [8].

A cost analysis has shown that WDM as a technology to offer point-to-point services in overlay to BPON is economically feasible in situations where there are no spare fibres available. Assuming list prices, the cost of all optical components in a WDM bi-directional link from Tx over the AWG and filters to Rx was about 4 times larger than two conventional optical transceivers for a link on a separate fibre pair. On the other hand, the cost to install additional fibres in an available duct or along available poles is at least several thousand Euro/km.

5. Conclusion

BPON is a standardised optical access technology suited for low cost FTTH deployment. The present paper reports on the feasibility of future extensions to the BPON, thereby remaining compliant with the BPON standard G.983 suite.

An extension of the optical splitting factor to 1:128 and 1:256 was demonstrated. The concept may be attractive to improve the cost sharing of the central office equipment in situations where the subscriber penetration is moderate compared to the number of homes that need to be passed.

Dynamic bandwidth allocation was realised in a prototype, showing an efficient statistical multiplexing of bursty services (e.g. IP) in the upstream direction of a BPON. The demonstrator distinguishes 4 T-Conts that each group connections with similar QoS requirements. The priorities and service levels of the different T-Conts are well respected and connections belonging to the same T-Cont get a fair share of the bandwidth.

It was shown that it is technically and economically feasible to upgrade the bandwidth to specific high end users by means of WDM overlay on BPON. It is typically possible to connect up to 4 subscribers to a GigE service out of a PON cluster consisting of 16 regular BPON ONUs.

Acknowledgement

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