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Design and Implementation of a Dynamic Bandwidth Protocol for TWDM-PON, and FPGA-Based LR-PON OLT and ONU Prototypes

Dissemination Level: PU

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Abstract:

TWDM-PON protocols for dynamic bandwidth assignment in the time domain and in the wavelength domain are investigated, and their outline implementation in FPGA hardware, on a proof-of-concept basis, is described. A LR-PON protocol is designed and implemented in FPGA-based OLT and ONU prototypes, which also supports the proof-of-concept TWDM-PON implementation. These protocols are designed in accordance with the requirements from WP2, WP3, WP4 and WP6.

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1 Introduction

This report describes the design of dynamic bandwidth protocols needed to operate a TWDM-PON, with the challenging large logical split (up to 1023-way) and logical reach (up to 125 km) proposed in DISCUS. This includes both dynamic bandwidth assignment (DBA) in the time domain, within a LR-PON, and dynamic wavelength assignment (DWA) between both LR-PON channels and non-LR-PON channels, i.e. point-to-point (PtP). The design and implementation of FPGA-based LR-PON OLT and ONU prototypes is also described (in Section 4), for demonstrating key features of the LR-PON protocol, including proof-of-concept aspects of DBA and DWA, and interactions with the control plane.

The protocol design is guided by the overall TWDM architecture, described in Section 3.1, which is defined in terms of the relationships between services, ownership, co-operation, bandwidth assignment protocols and laser tuning precisions. Three preferred wavelength referencing and calibration options are described, and the most promising solution (i.e. simplest) identified, from the protocol point of view.

Two distinct types of DBA are compared for their suitability in DISCUS in Section 2; the first is based on pointers and timers (free-running) and the second is based on Bandwidth Update Interval (pre-calculated). Suitability is in terms of bandwidth overheads and maximum balanced load (throughput) achievable, while satisfying G.987.3 recommendations for delay and bandwidth fairness.

Physical layer performance and impairments due to interferometric and linear crosstalk are invesigated in Section 3.2, for start-up, tuning, power levelling and normal operation. DWA protocols for ONU start-up, tuning and power levelling are described in Section 3.3, for their potential suitability in DISCUS. Suitability here is in terms of overcoming the effects of interferometric and linear crosstalk, in the wrong channel and in the correct channel, due to laser tuning precision and wavelength demultiplexer crosstalk isolation. Protocols considered include synchronous quiet windows, auxiliary management and control channel (AMCC), and a new mitigation protocol against interferometric and linear crosstalk caused by multiple ONUs starting up simultaneously. This is for use with low power/low bandwidth AMCC in a TWDM environment, in place of G.987.3's random delay protocol for preventing collisions during Serial Number Acquisition, in a TDMA environment alone. The mitigation protocol is also adapted for use with quiet windows, to enable AMCC at higher speed.

2 Dynamic Bandwidth Assignment

In DISCUS, the DS/US TDM/TDMA LR-PON protocol is based on that of XG-PON, but with suitable protocol changes for the longer logical reach (125 km) and logical split (1023). Dynamic bandwidth assignment (DBA) is necessary for multiplexing traffic efficiently in the US direction.

Section 2.1 begins with a basic reminder of DBA definitions in XG-PON, including T-CONT/Alloc-ID definitions, traffic descriptors and the way upstream transmission works in G-PON, using figures from G.987.3 [1]. Section 2.2 then discusses the delay and bandwidth fairness recommendations which DBA should meet in G987.3. In Section 2.3, the expected relative merits of two distinct types of DBA scheduling algorithm are examined, for use in the challenging large split and long reach environment of the DISCUS PON architecture. These are the GIANT project's algorithm [8] from G-PON, which is pointer and timer based, and a Bandwidth Update algorithm [12] from B-PON, which pre-calculates bandwidth assignments for the duration of a bandwidth update interval (DBA cycle). We wish to decide which of these is better suited to satisfying the delay and fairness recommendations in the challenging DISCUS PON architecture.

To this end, Section 2.4 calculates analytically the maximum balanced load that each algorithm can support, together with the bandwidth overheads. Maximum balanced load is equivalent to the maximum throughput, but is calculated under the assumption of no Alloc-ID queue build-up. Section 2.4 concludes by identifying the traffic conditions and requirements under which each algorithm is expected to be used. Results of DBA simulations performed to date are reported in Section 2.5, which are of the GIANT algorithm applied to the DISCUS PON architecture.

2.1 DBA Definitions from G.987.3

G.987.3 [1]states that dynamic bandwidth assignment (DBA) in XG-PON is the process by which the optical line termination (OLT) allocates upstream transmission opportunities to the traffic-bearing entities within optical network units (ONUs), based on dynamic indication of their activity and their configured traffic contracts. The activity status indication can be either explicit through buffer status reporting, or implicit through transmission of idle XGEM frames during the upstream transmission opportunities. In DISCUS, studies relate to status reporting.

In the upstream direction (see Figure 1), traffic multiplexing is a distributed process. The ONU's traffic-bearing entities are identified by their allocation IDs (Alloc-IDs). These can be represented by either a transmission container (T-CONT) or upstream ONU management and control channel (OMCC). Bandwidth allocations to different Alloc-IDs are multiplexed in time as specified by the OLT in the bandwidth maps transmitted downstream. Within each bandwidth allocation, the ONU uses the XGEM Port-ID as a multiplexing key to identify the XGEM frames that belong to different upstream logical connections.

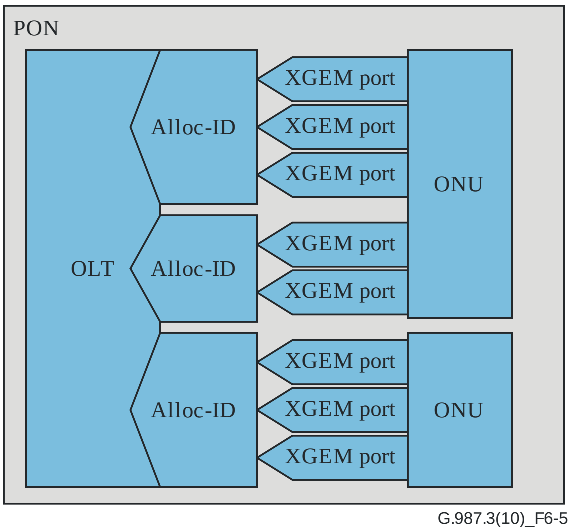

Figure 1. Upstream Multiplexing in XG-PON.

G.987.3 states "Regardless of the number of Alloc-IDs assigned to each ONU, the number of XGEM ports multiplexed onto each Alloc-ID, and the actual physical and logical queuing structure implemented by the ONU, the OLT models the traffic aggregate associated with each Alloc-ID as a single logical buffer and, for the purpose of bandwidth assignment, considers all Alloc-IDs specified for the given PON to be independent peer entities on the same level of logical hierarchy." See Figure 2.

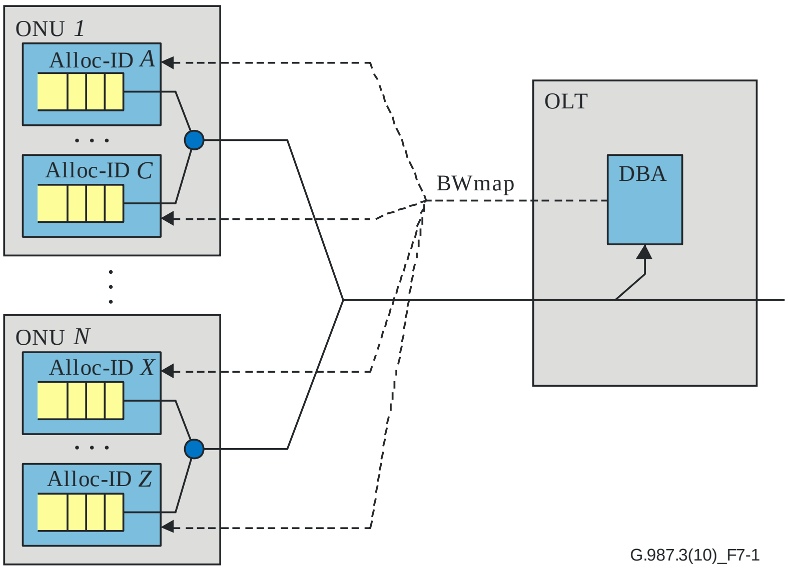

Figure 2. PON DBA abstraction in XG-PON.

Furthermore, "For each Alloc-ID logical buffer, the DBA functional module of the OLT infers its occupancy either by collecting inband status reports, or by observing the upstream idle pattern, or both. The DBA function then provides input to the OLT upstream scheduler, which is responsible for generating the bandwidth maps (BWmaps). The BWmap specifies the size and timing of upstream transmission opportunities for each Alloc-ID, and is communicated to the ONUs inband with the downstream traffic." Within DISCUS, we are investigating DBA algorithms that use status reporting from an upstream dynamic bandwidth report (DBRu).

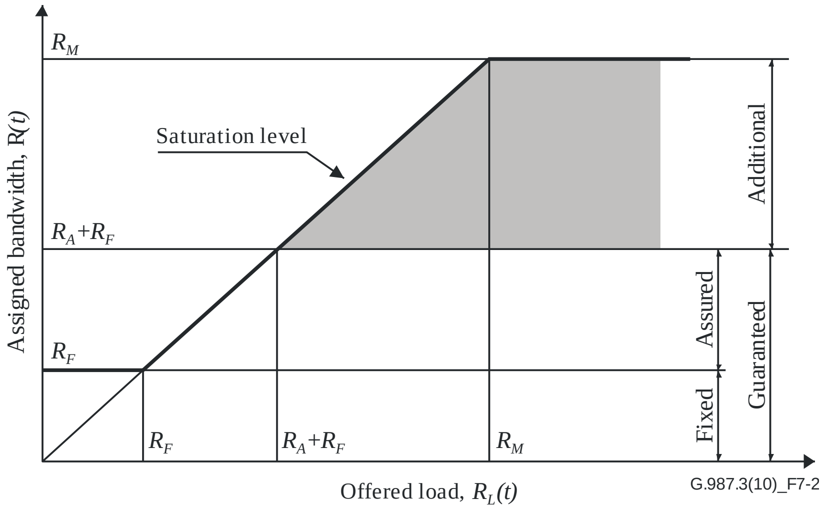

Figure 3. Assigned bandwidth components with respect to offered load

G.987.3 identifies four different types of assigned bandwidth, with a strict priority hierarchy:

1. Fixed bandwidth (highest priority) – assigned statically
2. Assured (A) bandwidth – assigned dynamically
3. Non-Assured (NA) bandwidth – assigned dynamically
4. Best-Effort (BE) bandwidth (lowest priority) – assigned dynamically

Fixed and Assured bandwidths constitute the Guaranteed bandwidth in Figure 3, and Additional bandwidth is either Non-Assured or Best-Effort. Additional bandwidth assignment criteria can be either rate-proportional, or based on provisioned priority and weights. Bandwidths are assigned up to a Maximum value. The only constraints on the combinations of bandwidth types allowed in an Alloc-ID are

a) Non-Assured and Best-Effort cannot be supported simultaneously

b) Non-Assured requires Guaranteed simultaneously

2.2 Delay and Fairness Recommendations (ABRT and DBACT)

Many dynamic bandwidth assignment (DBA) algorithms in the literature concentrate on mean packet delay as the over-riding delay parameter [2]-[9]. But there is no single value of mean packet delay recommended. However, ITU-T Recommendation Y.1541 [10] for IP-based services allows up to 15 msec delay in the non-IP (access) network, both upstream and downstream, for both class 0 and class 1 Hypothetical Reference Paths. The FSAN G-PON Common Technical Specification [11] provides for a low delay, low jitter, low PLR class of service, requiring 10 msec maximum delay + jitter upstream between UNI (User Network Interface, i.e. the interface directly connected to the user equipment) and SNI (Service Node Interface, i.e. the interface directly connected to the metro edge node in the network operator premises), including 3 msec jitter due to DBA.

More recently, an Assured Bandwidth Restoration Time (ABRT) is recommended for XG-PON in G.987.3 [1]. This is a target ABRT of 2 msec, and expected value of a few msec. ABRT is the worst-case (not mean) delay between the moment an Alloc-ID (T-CONT) increases its traffic demand (possibly from zero) to at least its Fixed plus Assured level, and the start of the first upstream frame in which the specified bandwidth is allocated on average (over K consecutive frames).

The DBA Convergence Time (DBACT) objectives in G.987.3 [1] are for meeting bandwidth fairness criteria for Non-Assured and Best-Effort bandwidths. They are 6 msec target, 10 msec expected. DBACT is the worst-case delay between a traffic change event at any ONU, and the first downstream frame, in a sequence of K frames averaging the frame-to-frame variations, in which the OLT adjusts the bandwidth assignments for all unsaturated ONUs, to within specified bounds (e.g. 20%) of the dynamic values given by the fairness reference model. The bandwidth fairness criterion between unsaturated Non-Assured bandwidth Alloc-IDs is

$$\frac{R_{NA}^{i}(t)}{R_{F}^{i}+R_{A}^{i}}=\frac{R_{NA}^{j}(t)}{R_{F}^{j}+R_{A}^{j}} \quad ...(1).$$

R_F, R_A and R_{NA} are the Fixed, Assured and Non-Assured bandwidths (rates in bit/sec). Thus surplus Non-Assured bandwidth should be assigned in proportion to the provisioned Fixed + Assured bandwidths of each Alloc-ID. The rate-proportional fairness criterion for Best-Effort bandwidth is

$$\frac{R_{BE}^{i}(t)}{R_{M}^{i}-\left(R_{F}^{i}+R_{A}^{i}\right)}=\frac{R_{BE}^{j}(t)}{R_{M}^{j}-\left(R_{F}^{j}+R_{A}^{j}\right)} \quad ...(2).$$

R_M is the maximum provisioned rate for the Alloc-ID. Thus surplus Best-Effort bandwidth should be assigned in proportion to the Alloc-ID's maximum allowable Additional bandwidth (when not assigned by priority and weight). See Figure 3.

2.3 GIANT and Bandwidth Update Algorithms

2.3.1 Choices and Decisions (why GIANT and Bandwidth Update)

Without a Bandwidth Update Algorithm, EU Project GIANT's [8] sequential DBA scheduling algorithm employing WRR (Weighted Round Robin) with timers and pointers could ensure fairness by adopting the proposal [9]:

$$\text{Peak Information Rate (PIR)} \propto \text{Fixed + Assured Rates} \quad ...(3).$$

However, applying this proportionality to the DBA reference model constrains the achievable values of provisioned Assured Rates. It is useful to be able to select PIR and Assured Rate independently, which a Bandwidth Update algorithm can do.

At high load the free-running NA bandwidth pointers of the GIANT algorithm will become de-correlated from the regular A bandwidth grants. This will result in A and NA payloads being transmitted in separate ONU bursts, which increases the bandwidth overheads, for a given service interval. A Bandwidth Update algorithm can ensure that A & NA payloads remain in the same ONU burst.

Furthermore, in a LR-PON with large potential numbers of Alloc-IDs with high peak rates as in DISCUS, the sequence of K frames, that average the frame-to-frame variations after the DBACT could cause very long delays:

a) from traffic change event to the 1st grant of the last Alloc-ID receiving a new bandwidth allocation, and

b) between successive NA or BE bandwidth grants.

For example, if all 16,368 Alloc-IDs were heavily loaded (admittedly unlikely, but possible), each one had e.g. 200 Mbit/sec Peak Rate (Assured bandwidth surplus grant bytes ABsur=37.5 kbytes), and ΣAssured bandwidths were 90% of PON capacity (excluding bandwidth overheads), then there would be sufficient Non-Assured bandwidth bytes available per frame for just one Non-Assured bandwidth allocation (1 Alloc-ID) per frame. Delays a) and b) would be ~2.0 seconds for service interval SImin=1.5 msec. So all undropped packets employing Non-Assured bandwidth would suffer long delays, far exceeding the 6-10 msec DBA Convergence Time, the 15 msec IP transfer delay (IPTD) objective in Y.1541, and the FSAN CoS packet delay requirements (longest 500 msec). So it is expected that the GIANT algorithm cannot ensure Non-Assured Bandwidth fairness in a heavily loaded LR-PON with large numbers of Alloc-IDs, without incurring excessively long packet delays.

A solution under consideration in DISCUS is to return to using a Bandwidth Update Algorithm, similar to the memoryless one in G.983.4 Appendix I.3 [12]. This calculates and matches the grant size to the number of active Alloc-IDs and available Surplus bandwidth, over a much shorter Bandwidth Update Interval. Mathematically, this is equivalent to the G987.3 DBA Reference Model. Every unsaturated Alloc-ID is then guaranteed to receive a fair bandwidth share within the Bandwidth Update Interval (i.e. the DBA cycle time e.g. 1.5 msec or 3.0 msec).

The intention is for the LR-PON's DBA algorithm to meet both the ABRT and DBACT objectives of G.987.3 [1], with acceptable packet delays.

2.3.2 GIANT DBA Algorithm

The GIANT DBA algorithm provides Assured bandwidth grants to appropriate Alloc-IDs every service interval (SI), if requested. Non-Assured and BE grants are given to appropriate Alloc-IDs whenever an SI timer has expired <u>AND</u> the Alloc-ID is next in turn according to a pointer. As stated above, because pointers could become de-correlated from the Assured bandwidth grants at higher loads, separate ONU bursts are expected for Assured grants and Non-Assured/BE grants.

2.3.3 Bandwidth Update DBA Algorithm

In the Bandwidth Update DBA algorithm, Assured, Non-Assured and BE bandwidth grants are calculated for an entire Bandwidth Update interval in advance, before the start of the interval. Non-Assured and BE bandwidth fairness between Alloc-IDs are guaranteed over the bandwidth interval. In G.983.4 [12], the bandwidth update interval was fixed, but the proposal in DISCUS is for it to be variable, to minimise the delays of newly arrived packets where possible. The

Bandwidth Update algorithm allocates all grants of all bandwidth types (Assured, Non-Assured and BE) of all Alloc-IDs in the same ONU within the same ONU burst. The Bandwidth Update algorithm is therefore expected to provide a higher maximum balanced load than GIANT.

2.4 Maximum Balanced Load Theory (including bandwidth overheads)

Beyond a certain PON load, mean packet delay (and packet loss ratio) increase rapidly. It is important to know the maximum balanced load at which this rapid increase begins, i.e. beyond which T-CONT queues build up and packets begin to be lost. Obviously, the higher the maximum balanced load is the better. An analytical method of calculating the maximum balanced load of LR-PONs, from the LR-PON parameters, is described in this section and in Appendix I. Instead of using mean packet delay as the delay criterion of merit, for which there is no preferred value, the ABRT is employed. Some of the techniques in the literature for minimising mean packet delays, such as predicting current bandwidth demand from earlier demand in a previous DBA cycle [2], and removing fairness between priority classes, by allowing high priority traffic within an ONU to use bandwidth grants already allocated to lower priority traffic within the same ONU [3], do not apply to the ABRT. Being worst-case, the ABRT must be met even when there is no lower priority traffic present.

Because DBA performance studies employ simulations, rather than analytical calculations, they have typically been applied to small LR-PON splits and T-CONT numbers. But in DISCUS we wish to support up to 1,023 ONUs, each with up to 16 T-CONTs, i.e. 16,368 T-CONTs altogether, over 125 km logical reach. Analytical calculations make such numbers very easy to deal with. This analysis compares two DBA algorithms: GIANT [8] and Bandwidth Update [9], in a 10 Gbit/sec LR-PON. The previous comparison in [9] between a GIANT-like algorithm allowing maximum bursting at all times, and a Bandwidth Update algorithm providing an improvement over that in G.983.4 G-PON [12], showed that both were similarly capable of increasing the achievable load beyond the G.983.4 capability. The mean packet delays were slightly, but not significantly, lower for the GIANT-like algorithm. Both algorithms employed the same service interval. But the Bandwidth Update algorithm is expected to provide a higher maximum balanced load than GIANT, because it can ensure that Assured and Non-Assured bandwidth grants can share the same ONU bursts, whereas in GIANT the Non-Assured bandwidth grants, using pointers, can become de-correlated from the Assured grants, requiring additional ONU bursts.

The detailed theory is given in Appendix I.

The estimated maximum balanced loads for the GIANT and Bandwidth Update algorithms are shown in Figure 4, as a function of service interval SI, for a 10 Gbit/sec upstream LR-PON with 125 km reach. The ONU burst overhead is assumed to be 228 bytes, consisting of 256 bits guard time, 512 bits preamble settling time, 1024 bits preamble for EDC and 32 bits delimiter. Mean packet size is 432 bytes, and ABmin of 76 bytes provides 405.3 kbit/sec Assured bandwidth to each of the 16,368 T-CONTs. As expected, the GIANT algorithm's need to have separate ONU bursts for Assured and Non-Assured bandwidth grants reduces the load it can support, relative to the BW Update algorithm. For a 125 km reach

LR-PON, with round trip time RTT = SI = 12 frames (1.5 msec), GIANT provides just 0.705 load (29.5% bandwidth overhead), compared with the BW Update algorithm's 0.82 load (18.1% bandwidth overhead). This relative advantage diminishes as the service interval increases.

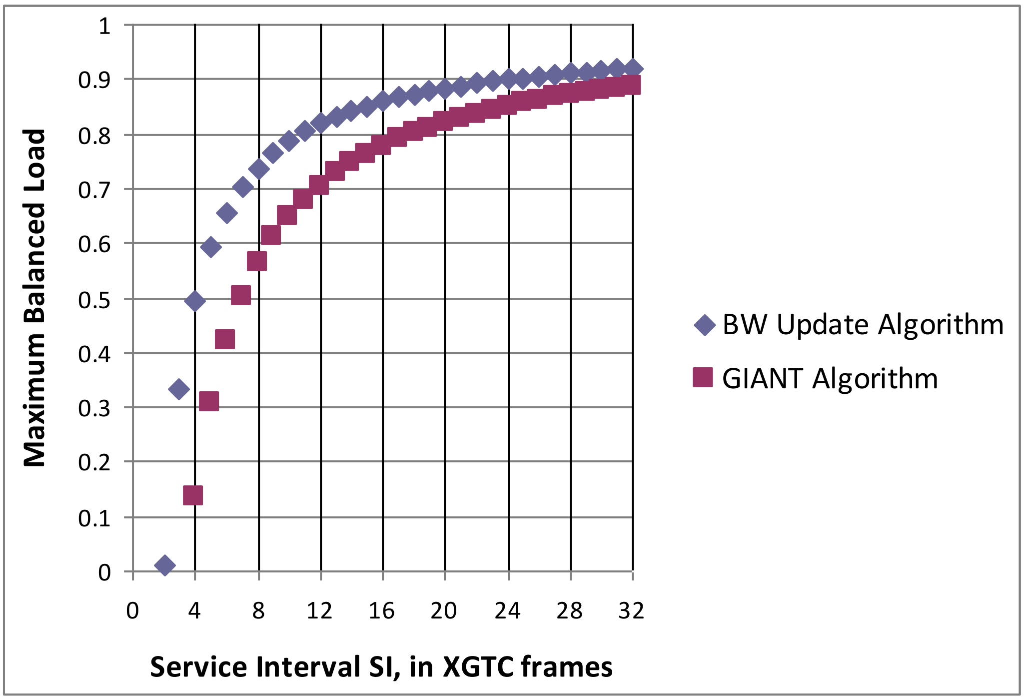

Figure 4. Maximum balanced loads of GIANT and BW Update algorithms, as a function of service interval SI, for 10 Gbit/sec, 125 km LR-PON with 1023 ONUs, each with 16 T-CONTs. Mean packet size is 432 bytes, and ABmin is 76 bytes.

However, the comparison between the two algorithms is not quite as simple as this, because each algorithm incurs a different ABRT for the same service interval SI. We will see that the BW Update algorithm loses its advantage, in terms of maximum balanced load, when compared as a function of ABRT.

For the GIANT algorithm, assuming that a T_CONT's DBRus and payloads are synchronised in the same ONU bursts, the ABRT is given by

$$\begin{aligned} ABRT_{GIANT} &= SI + RTT, \; for SI < RTT, RTT = i.SI \\ &= 2.SI + SI.INT\left[\frac{RTT}{SI}\right], \; for SI < RTT, RTT \neq i.SI \qquad \text{...(4).} \\ &= 2.SI, \; for SI \geq RTT \end{aligned}$$

However, for the Bandwidth Update algorithm, the worst-case delay occurs in an extreme situation, when all packets to be granted in an SI belong to T-CONTs that are concentrated together at the end of the list of Alloc-IDs to be considered within the SI. If all packets are uniformly distributed throughout the list, the DBRus would be transmitted approximately in the expected frame within the SI. But if all packets are concentrated in T-CONTs at the end of the list, the earliest one in the list would need to be transmitted within the SI after all the ONU bursts and DBRus of empty T-CONTs have been transmitted, which might be as few as 2 frames into the SI. So the earliest packets and their T-CONTs' DBRus will be brought forward in time by almost a whole SI. The worst delay occurs when a packet arrives in its T-CONT buffer after such an early DBRu has just been transmitted, so the packet arrival cannot be reported until the next DBRu in the next SI. To compound the problem, the appropriate DBRu in the next SI is transmitted in its expected location towards the end of the SI, perhaps because the packets in the next SI are concentrated, for example, at the start of the Alloc-ID list. Thus delay of 2 SIs is incurred before the successful DBRu is transmitted. There is a further RTT delay before the start of the SI in which the packet will be transmitted, and further SI delay if the packet is transmitted at the end of the SI. Therefore

$$ABRT_{Update} = 3.SI + RTT,\ forSI < RTT, RTT = i.SI \qquad ...(5).$$

But this value applies only when an integer number of SIs fit into the RTT. When they don't, i.e. for SI = 5,7,8,9,10 and 11 frames (where RTT = 12 frames), the ABRT increases to

$$ABRT_{Update} = 4.SI + SI.INT\left[\frac{RTT}{SI}\right],\ forSI < RTT, RTT \neq i.SI \qquad ...(6).$$

Furthermore, when SI≥RTT, it becomes

$$ABRT_{Update} = 4.SI,\ forSI \geq RTT \qquad ...(7).$$

These ABRT values are thought to be extremely unlikely to occur, but possible. They are employed in Figure 5. The more likely value when SI≥RTT is

$$ABRT_{Update} = 3.SI,\ forSI \geq RTT \qquad ...(8).$$

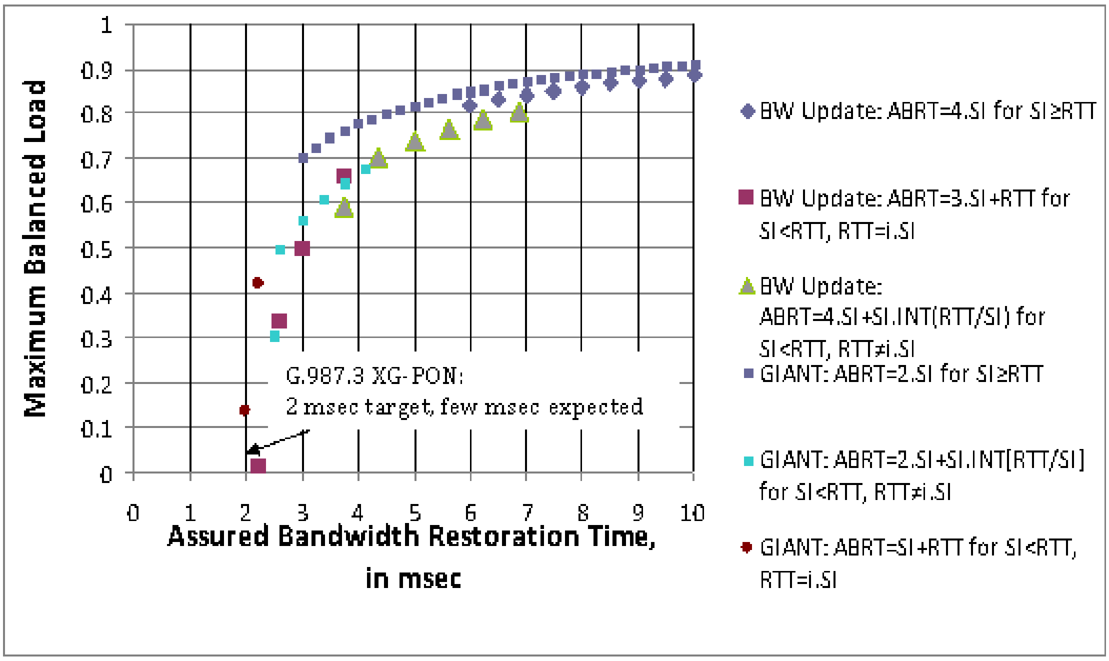

Figure 5. Maximum balanced load versus Assured Bandwidth Restoration Time, ABRT, for 10 Gbit/sec, 125 km LR-PON with 1023 ONUs, each with 16 T-CONTs.

Figure 5 shows that for a 10 Gbit/sec LR_PON, with 125 km reach and supporting 1023 ONUs each with 16 T-CONTs (A + NA bandwidth), for any required ABRT value, the GIANT algorithm provides higher maximum balanced load than the Bandwidth Update algorithm. It is only slightly higher for ABRT ≥6 msec. If $ABRT_{Update}$ were taken to be 3.SI, the Bandwidth Update algorithm would provide a slightly higher load for ABRT ≥4.5 msec.

To conclude, because the Non-Assured bandwidth pointers in the GIANT algorithm become de-correlated from the frames in which Assured bandwidth grants are made, resulting in additional ONU bursts for Non-Assured bandwidth grants, the Bandwidth Update algorithm always provides greater maximum balanced loads at the same service interval, as expected. However, when the worst delays possible under each algorithm must satisfy any given ABRT requirement, the GIANT algorithm provides higher maximum balanced load for all required ABRT values. This is despite having de-correlated pointers and more ONU bursts than GIANT.

Nevertheless, only the Bandwidth Update algorithm is expected to satisfy the DBA Convergence Time recommendation at very high loads, with acceptable delays.:

a) from traffic change event to the 1st grant of the last Alloc-ID receiving a new bandwidth allocation, and

b) between successive Non-Assured or BE bandwidth grants.

DISCUS proposes the Bandwidth Update algorithm, whenever delays a) and b) would be excessive for the Alloc-ID numbers used and their supported traffic. Otherwise, the GIANT algorithm is slightly preferable.

2.5 DBA Simulations

DBA simulations are being implemented in DISCUS, in order to confirm the theoretical predictions of the maximum balanced load theory (Section 2.4). This section reports simulation results achieved so far, which relate to the GIANT algorithm. As stated above, although GIANT provides greater maximum balanced load than Bandwidth Update, for all ABRT values, it is not expected to be the preferred DISCUS algorithm, for satisfying the DBA Convergence Time recommendation at very high loads with acceptable delays for sharing the surplus bandwidth fairly. But it provides a baseline for comparison.

The DBA simulations have been implemented at 10 Gbit/sec in the NS3 simulation package, using the XG-PON protocol. Figure 6 shows the transient time evolution of the GIANT DBA algorithm, from the start of the simulation runs, for service interval SI=12 fames. The transients settle down after ~ 1sec. of simulated time. The total BW overhead, including PHY, XGTC and XGEM overheads, is 26% at Load = 0.74 (blue curves), compared with the 29.5% bandwidth overhead at Load = 0.705 calculated from the Maximum Balanced Load theory of section 2.4. The simulations do not include the 256 bits guard time in the PHY overheads, which is an additional ~300 Mbit/sec, totalling ~29% bandwidth overhead overall. Theory and simulations are therefore in very good agreement.

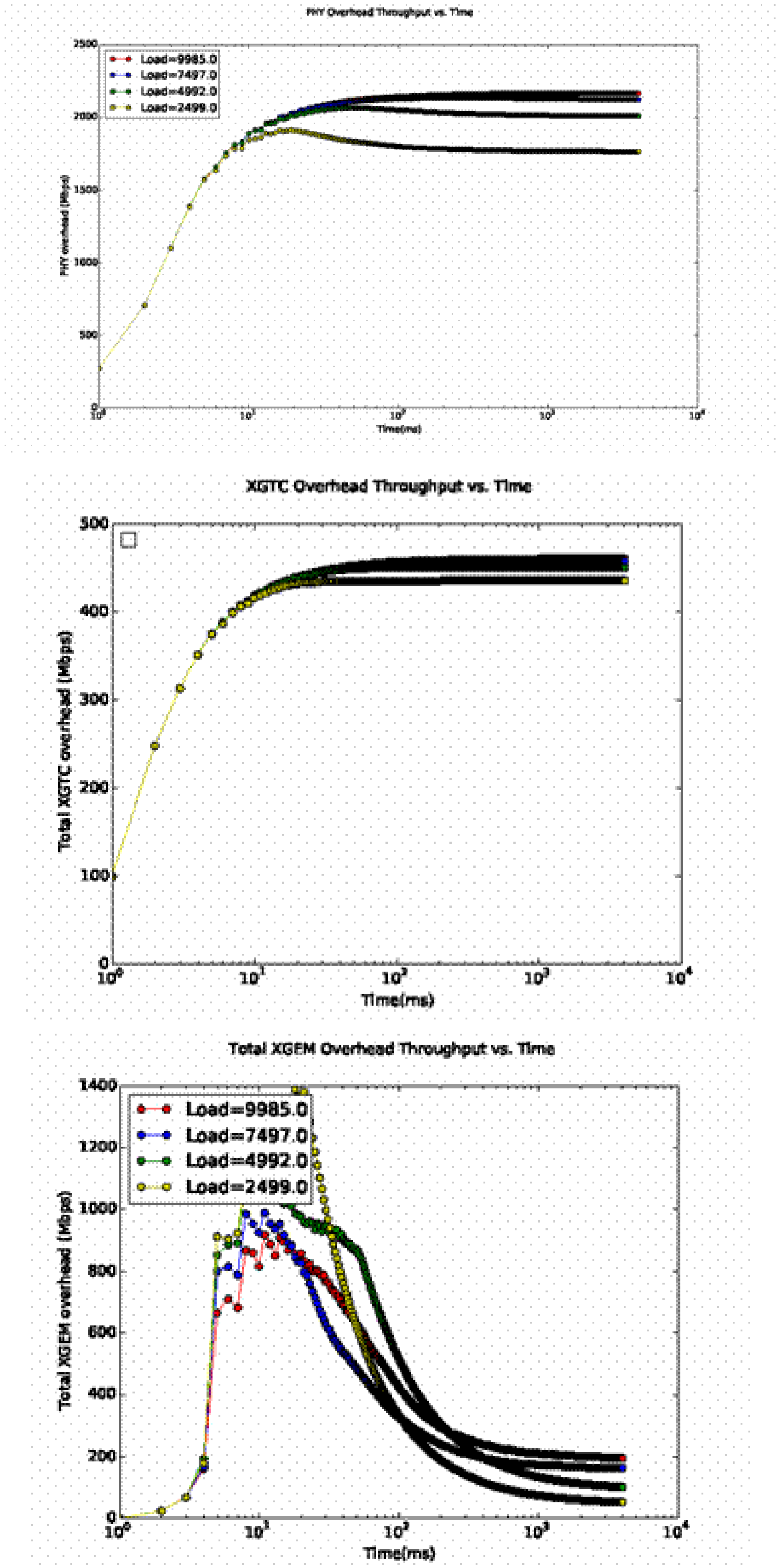

Figure 6. Transient time evolution of BW Overheads for the GIANT DBA algorithm, with 1023 ONUs, 16,368 T-CONTs, 10 Gbit/sec, 125 km reach, 432 bytes mean packet size and SI = 12 frames (1.5 msec).

Figure 7 shows the throughput of the GIANT DBA algorithm, for different service intervals. For SI = 12 frames, the reduction in throughput at higher loads is due to generation of an excessive number of idle frames at shorter service intervals. This is thought to be due to short Idle XGEM frames. Further simulations would be expected to reduce these by slightly adjusting the ABmin value of all Alloc-IDs.

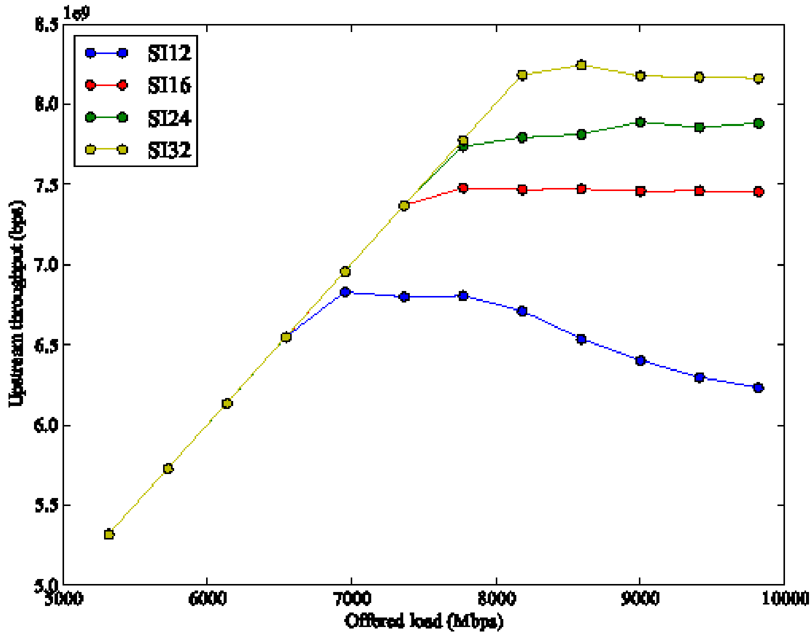

Figure 7. Throughput for GIANT DBA algorithm, for different service intervals SI = 12, 16, 24 and 32 frames.

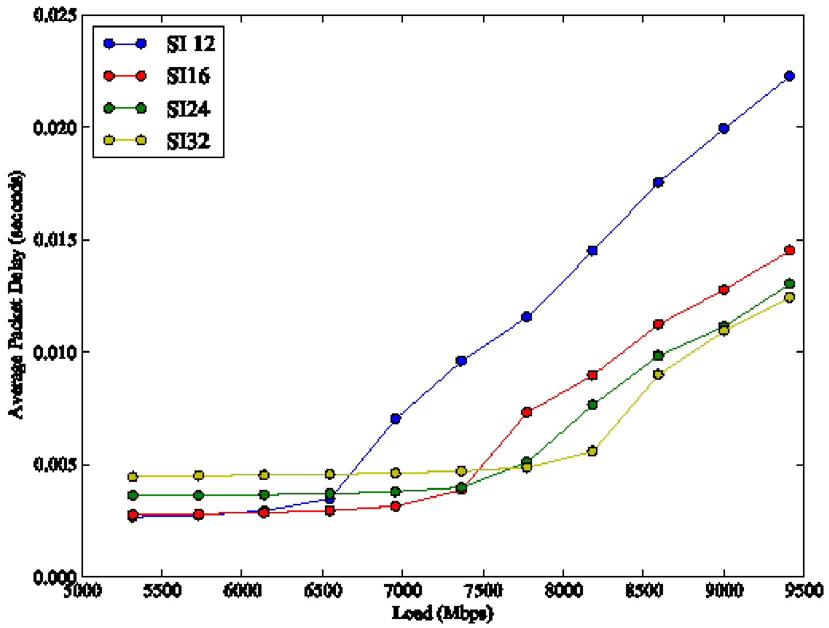

Figure 8. Mean packet delays for GIANT DBA algorithm, for different service intervals SI = 12, 16, 24 and 32 frames.

Figure 8 shows the mean packet delays of the GIANT DBA algorithm, for the different service intervals.

3 Dynamic Wavelength Assignment

3.1 Overall TWDM Architecture

This section provides an overview of the relationships between services, ownership, co-operation, bandwidth assignment protocols and laser tuning precisions. It begins (3.1.1) by discussing the wavelength usage and ownership models proposed in two DISCUS white papers in D3.2 [13], and describing technical solutions for assigning bandwidths in the time and wavelength domains, in terms of their relative bandwidth efficiencies, dependent upon the identity of the ultimate arbiter of contention: user, Service Provider (SP) or network operator. The full range of capabilities that a dynamic wavelength assignment (DWA) protocol must support is defined.

Next (3.1.2), the potential co-operation and protocol solutions required to support the range of possible ONU laser tuning precisions are identified.

Finally (3.1.3), three preferred wavelength referencing and calibration options are described, and the most promising solution identified.

3.1.1 Wavelength Services and Ownership Models Between Operators and Service Providers

Two DISCUS white papers [13] have described wavelength usage options, and business and ownership models, for the access network. The various wavelength usage options assign wavelengths to a) service and network providers, b) service types, c) shared wavelength between SPs and service types and d) individual users. The preferred option in DISCUS is option c), which allows full wavelength and resource sharing. Not locking wavelengths to individual SPs or service types provides the best statistical multiplexing gain and PON utilization, thus reducing the number of OLTs required and hence costs, power consumption and footprint of the metro-core node. It also maximises the opportunity to create a fairer competitive environment and to avoid a "digital divide" between dense urban areas and sparse rural communities.

Nevertheless, DISCUS can also support wavelength and bit-stream unbundling within the different wavelength usage options. Indeed, to enable any user in the access network to become a service provider in their own right, it might be advantageous to be able to assign a whole wavelength to an individual user/ONU. This would be point-point in both US and DS directions. But this does not contradict the preferred wavelength sharing option, with respect to other customer's access to multiple service providers (SPs) "on the fly". It merely moves the metro/core node's interface to the SP from the core network side of the access switch to the access network side. In addition, the PON should support business users with large bandwidth requirements of their own, for which a whole wavelength may be needed in each direction.

In the second white paper [13], the preferred business and ownership model is therefore the partial vertical integration of the network provider/operator and infrastructure provider, at least for the access network, optical switch and access switch in the metro/core node. The SP business would be completely separate, but could encompass IP layer service routers. All wavelength channels would therefore be "owned" and controlled by the network operator. Customers can gain access to multiple SPs at any time, using the time domain for dynamically assigning bandwidth and wavelength domain for capacity management.

<u>Time Domain Bandwidth Assignment</u>

There are several potential mechanisms for assigning bandwidth in the time domain, dependent upon who is the ultimate arbiter of contention between services and SPs: end user, SP or network operator. If the end user is the final arbiter, Dynamic Bandwidth Assignment (DBA) could allow users to access multiple SPs at any time, by supporting different SPs on different T-CONTs. But this is potentially the least efficient solution, possibly requiring each one to have its own Assured rate (i.e. Commited Information Rate: CIR) "pipe", thus restricting the total number of user-SP pairs that can be supported. Better efficiency would be achieved by supporting different SPs on different XGEM Ports on the same T-CONT, sharing a single user CIR value. To provide bandwidth guarantees to individual user-SP flows, only one of the individual XGEM Ports on the T-CONT must be allowed to operate at a time (in a given session).

Better bandwidth efficiencies are expected if the SP is the final arbiter of contention. The residential service model in D6.1 [14] proposes one VLAN per service per OLT per SP. Individual residential users share this VLAN, and its Assured bandwidth "pipe". If the SP uses connection admission control (CAC) for user access to this bandwidth, session-by-session, more users can be supported than are allowed simultaneous access. In the downstream direction, the LR-PON needs no contention resolution mechanism to achieve this, as all packets arriving at the OLT can be transmitted within the 10 Gbit/sec TDM stream. But upstream, the G987.3 DBA reference model provides no equivalent of the user-shared VLAN, and so would not benefit from the potential efficiency improvement. However, a possible sharing mechanism exists in the form of grouped assured bandwidth [15]. This could provide hierarchical scheduling of traffic between different users' T-CONTs within a group of T-CONTs associated with a VLAN.

The most bandwidth efficient solution is expected to be provided by the network operator, being the final arbiter of contention and guarantor of individual user bandwidth. This allows the entire LR-PON capacity to be considered as a single pool of capacity, without being sub-divided into smaller, aggregate bandwidth "pipes". Scenarios 1 and 2 of [16] use Software Defined Network (SDN) concepts to allow the SP to request bandwidth for individual user connections and sessions, as well as aggregates of user sessions, from the network operator. Thus it is the network operator who ultimately implements the CAC mechanism. In the upstream direction, this can be achieved by setting the CIR (and Peak Information Rate: PIR) values for each session or connection at the T-CONT.

Dynamic Wavelength Assignment

Dynamic Wavelength Assignment (DWA) protocols must support the following capabilities

- wavelength referencing
- registration and tuning at start-up
- in-service continuous monitoring & tuning of ONU laser & filter
- power levelling to reduce Xtalk during tuning, ONU registration & normal operation

for all the following systems across the wavelength channels:

- TDM/TDMA LR-PON
- TDM/TDMA LR-PON bandwidth/capacity management:
  - moving users to different TDM/TDMA LR-PON wavelength for growth
- TDM/TDMA LR-PON N:M Protection Switching:
  - tuning shared standby OLTs, possibly re-tuning drifting ONUs, within 100 msec LODS time-out if possible
- OLT-ONU point-point wavelengths:
  - bespoke service of 1 λ per user

3.1.2 Overview of Tuning Scenarios, Co-operation Levels and Protocol Options

The Broadband Forum working text WT-352 [17] is focused on the inter-communication messages required between OLTs for co-operation between OLT wavelengths, for ONU wavelength management within an NG-PON2 system. The need for co-operation between wavelength channels is assumed. But no specific communication protocol between OLT and ONU is mandated. Furthermore, the NG-PON2 wavelength plan (18) supports both Expanded Spectrum and Shared Spectrum options, i.e. separate and common wavebands for TWDM-PON and PtP channels.

In DISCUS, we are investigating the full range of co-operation and protocol (communication and higher) options required by different ONU laser tuning precisions, in both separate and common wavebands. DISCUS' preferred and fall-back options are identified.

There are three possible tuning precisions envisaged:

1. poor – uncalibrated (wrong channel, e.g. +/- 100 GHz)
2. good - calibrated (within correct channel, e.g. +/- 10-15 GHz) and
3. good - tightly referenced (within correct channel, e.g. +/- 5GHz)

For uncalibrated ONUs, there are four possible activation protocols at start-up (ONU activation). The simplest one of all would be to synchronise quiet windows between all LR-PON channels, allowing activation at full optical signal power. This needs LR-PON and non-LR-PON channels to be isolated in separate wavelength bands, or, if flexible intermingling of LR-PON and non-LR-PON channels is desired, a single, spectrally isolated LR-PON channel belonging to the network operator. If neither synchronised quiet windows nor an isolated LR-PON channel are desirable, then ONUs could simply be pre-registered. The OLT would poll the ONUs, to prevent multiple ONUs from starting up simultaneously, thus avoiding any potential interferometric crosstalk and service interruption (outage) problems. Interferometric crosstalk must still be prevented during OLT-controlled tuning, however, by transmitting US at low power and low bandwidth. If pre-registration is also undesirable, then a mitigation protocol becomes necessary, to reduce the impact of interferometric crosstalk from multiple ONUs, all starting up simultaneously in the same wrong channel. Such a protocol must therefore operate at even lower power and lower bandwidth. All of these activation options require co-operation between wavelength channels (possibly service providers). Co-operation is also required for tuning to the correct channel, despite the reduced level of interferometric crosstalk, if only one ONU is tuned at a time within any wavelength tolerance range.

In DISCUS' fall-back option, for ONUs that are calibrated in manufacture at one power level, and which are guaranteed to tune to within the correct wavelength channel, a good coarse tuning precision of e.g. +/-10-15 GHz, may not be sufficient to avoid interferometric plus linear crosstalk problems into the adjacent channel at higher power levels. So a mitigation protocol at low power and low bandwidth may also be needed for activating ONUs calibrated in manufacture, which can also avoid the need for co-operation between wavelength channels at start-up. Finer tuning needs no co-operation between channels, because coarse tuning precision is within the correct channel.

In DISCUS' preferred option, for ONUs that are tightly wavelength-referenced, using interleaved DS and US wavelength channels, local wavelength referencing and fine tuning are performed at the ONU. Activation and tuning can take place at full operating power level and full LR-PON speed in quiet windows.

These options are discussed in more detail below.

Impact of Tuning Precision

An issue raised in the first white paper is resolved by the preferred ownership model of the second. If the coarse wavelength tuning precision of an ONU Tx at start-up is poor, such that it starts in the wrong wavelength channel, and that channel is wholly owned by a service provider to which the ONU is not destined, there may be no way of identifying and registering itself, then being directed and tuned to the correct wavelength. Indeed, the wavelength channel may not even employ a TDM/TDMA LR-PON protocol. For first-generation systems, optical waveband separation between LR-PON and non-PON channels would allow synchronisation between quiet windows of the different LR-PON wavelength channels. This would avoid the need for any low-power, low bit-rate protocol or AMCC protocol, when ONUs are not calibrated and are allowed to tune to the wrong LR-PON channels during start-up. Of course, inter-wavelength communication would require service providers to co-operate between themselves, or via the network operator, using the control plane to exchange messages and transmit them downstream to enable registration, and to direct and possibly assist the ONU to tune to the correct wavelength. This would avoid the need for random ONU re-tuning. But if random ONU re-tuning is acceptable, service providers can protect themselves by employing just synchronised quiet windows, without any co-operation. But the flexibility to allow LR-PON and non-PON channels to be mixed arbitrarily in the same optical waveband would also be desirable. This would become possible when mitigation protocols against interferometric crosstalk have a mature, safe and cost-effective solution available, or calibrated ONUs are available at a reasonable price. A single network operator, which is the preferred ownership model of the second white paper, could monitor wavelength channels and provide the necessary signalling between service providers and to the ONU. The protocol must not interfere with the in-service wavelengths, if the ONU wavelength cannot be guaranteed at start-up. This report describes the necessary AMCC, interferometric crosstalk mitigation, tuning and power levelling procedures needed to achieve this. It is not necessary for the ONU to tune to the correct wavelength channel before it can register. Registration can take place first, followed by precise tuning and power levelling using feedback control from the OLT. This would allow a relatively poor coarse tuning precision to be tolerated, potentially minimising the cost of the tunable Tx.

Thus poor coarse tuning precision of ONU Tx wavelength into the wrong channel requires either a) co-operation between service providers to exchange signalling, or, preferably, b) a single network operator, to enable registration in the wrong channel and provide feedback control from the OLT. Being in the wrong channel, unless all wavelength channels are TDM/TDMA LR-PON protocol channels, and they all employ synchronised quiet windows, power levels at start-up must be reduced sufficiently to prevent any interferometric and linear crosstalk from disturbing the working system. This is in addition to any power levelling required to accommodate any differential reach before the first upstream amplifier. An alternative mitigation protocol to synchronous quiet windows is described, which greatly reduces the number of simultaneous interferers (ONU bursts) that can collide in the same time slot, using a back-off procedure. The power levels and transmission speeds required at start-up can be very low, resulting in potentially long activation and power levelling times, if multiple ONUs are expected to attempt activation simultaneously.

Pre-registration of ONUs can prevent multiple ONUs attempting simultaneous activation. Individual pre-registered ONUs that are not yet activated could be polled by the OLT, one at a time, and offered an activation opportunity. This cannot be at full operational power, in the case of poor coarse tuning precision. But with only one potential interferometric crosstalk interferer at a time, the low power level and low bandwidth can be significantly higher than for multiple interferers. Of course, either a single network operator or co-operation between service providers is necessary.

More precise coarse tuning precisions on start-up are less problematic. Good tuning precision to well within the channel passband, close to the centre wavelength, would enable an ONU to register using the normal LR-PON quiet windows (synchronised quiet windows or pre-registration not needed). It is also hoped that at least some intermediate tuning precision values, lying somewhere between channel centre and half way between channel centres, i.e. in the correct channel, could use normal quiet windows for activation and tuning without any power reduction to mitigate the effects of interferometric and linear crosstalk.

Beyond such a tuning precision, feedback control from the OLT is still necessary. The added benefit of having a single network operator is that wavelength monitoring and feedback control of the ONU Tx can be used to set up any transmission protocol, not just TDM/TMA LR-PON. Feedback messages can be via a LR-PON protocol channel downstream initially, then once the Tx is correctly tuned, the ONU (if using just one Tx/Rx pair) can tune its Rx to the correct downstream channel. The ONU must have means for switching over from a LR-PON protocol to the required transmission system. In practice, it is more likely that a customer using other transmission systems and protocols would have two Tx/Rx pairs, one permanently capable of communicating over a TDM/TDMA LR-PON protocol.

A much simpler solution to all of the above would be if very good tuning precision were achieved by local wavelength referencing at the ONU. There is then, hopefully, no need for monitoring and feedback control at the OLT. Wavelength interleaving of US and DS channels is proposed to enable this (see Figure 11).

3.1.3 Preferred Wavelength Referencing & Calibration Solutions

A number of different solutions to provide the ONU with absolute wavelength referencing for the tuneable Tx are described in detail in D5.8 [19]. The various solutions are compared in terms of the technical issues that need to be addressed: rogue wavelength behaviour, fine tuning and SMSR control. The cost and complexity of the ONU is also considered as it is crucial to develop a realistic solution for access networks. Here we describe the three most promising candidates of all the solutions considered.

<u>Tx Tuneable filter with coarse calibration of tuneable laser at manufacturing and feedback from OLT</u>

Accurate wavelength monitoring could be implemented at the OLT since the cost will be shared by all the users in the PON. The OLT could then provide feedback to the ONU using the downstream channel with information regarding the tuning of the upstream wavelength. The scheme could be easily used to track slow drifts of the upstream wavelength, if it is already within the bandwidth of the assigned channel. The protocol communication through the downstream should be fast enough to track the slow drift of the wavelength due to temperature changes or ageing in the laser. At start up a different procedure should be used, where the ONU starts at very low power until it is discovered by an OLT and receives information that it is tuned within its assigned bandwidth (Sections 3.2 and 3.3). If feedback from the OLT is used on its own, rogue wavelength behaviour could only be recognised when a collision has already occurred and then stopped by means of the protocol.

A tuneable filter could be used at the output of the ONU transmitter as a way to implement a passive rogue wavelength block. The filter would need to be tuned to the channel assigned to the ONU, which would require a reference wavelength from the OLT or an absolute reference or calibration within the ONU. Another advantage of the tuneable filter in the ONU is that it would eliminate the out-of-band side mode, virtually eliminating the SMSR issue and easing the problem of maintaining good high SMSR while tuning the laser.

Another option to reduce the possibility of rogue behaviour could be the coarse calibration of the tuneable laser at manufacturing. A large contribution to the cost of tuneable laser is the wavelength/power calibration in manufacturing, which is directly related to the time that the calibration takes for each laser. As an example, a laser with 80 channels over a 50GHz grid, with a fine tuning of ±5GHz, might require up to 30 minutes to be calibrated precisely in wavelength for one power level. Due to the interdependence between output power and wavelength, the calibration would need to be performed at each power level. Moreover in order to obtain such wavelength accuracies the tuneable laser should already be packaged before it is calibrated and sometimes even assembled with the control electronics.

In the scheme proposed here the calibration should be precise enough to make sure that the initial wavelength is within the channel assigned. An advantage of this coarse calibration is that it would be considerably faster since only one power level could be calibrated at each wavelength, which could reduce the overall calibration time from hours to a few minutes.

Figure 9 shows a possible implementation in the ONU of these solutions. The coarse calibration of the laser could be used to bring laser and filter (monitoring transmitted or dropped power) within the correct channel band. Fine tuning is then performed by using information feedback from the OLT. This configuration would have the advantage of improving the SMSR of the tuneable laser ensuring that, even if during the tuning a non-optimal SMSR mode is selected, the SMSR at the output of the Tx would not be compromised. The tuneable filter used in conjunction with coarse calibration would also avoid the rogue wavelength behaviour at start-up.

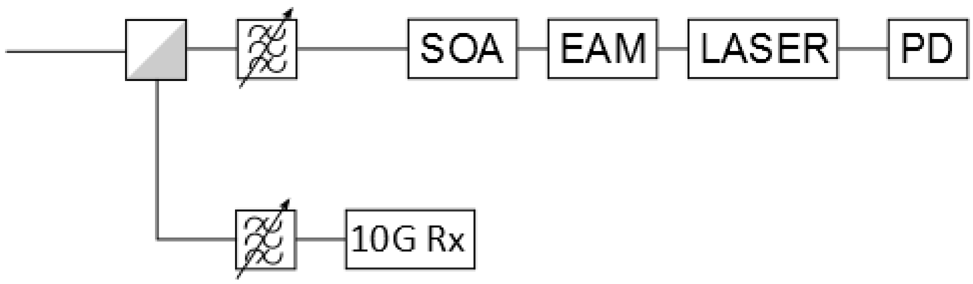

Figure 9. ONU configuration that implements the tuning scheme with Tx tuneable filter with coarse calibration of tuneable laser at manufacturing and feedback from OLT.

<u>Tx Tuneable filter with the DS channel as a reference using filter FSR and feedback from OLT</u>

This scheme (Figure 10) combines the use of three ideas: tuneable filter at the Tx matched with the Rx filter, the downstream (DS) channel spaced by one free spectral range (FSR) of the filter from the upstream (US), and a feedback from the OLT on the tuning. If DS and US channels are spaced by one FSR then in principle the filters can be tuned together (thermally for example). The DS can then be used as the precise reference to tune both filters. The tuneable laser can then be tuned coarsely as in the previous scheme by measuring the power transmitted or dropped by the filter.

This scheme relies on the accuracy and stability of the FSR of the filter, which is not a parameter that is usually specified accurately, but we believe that a filter could be specifically designed with an accurate and reproducible FSR. However, realistically the Tx tuneable filter will only be coarsely tuned to the correct wavelength and hence fine tuning of the laser is still necessary. This might be done by feedback from the OLT where the wavelength of the signal might be accurately measured.

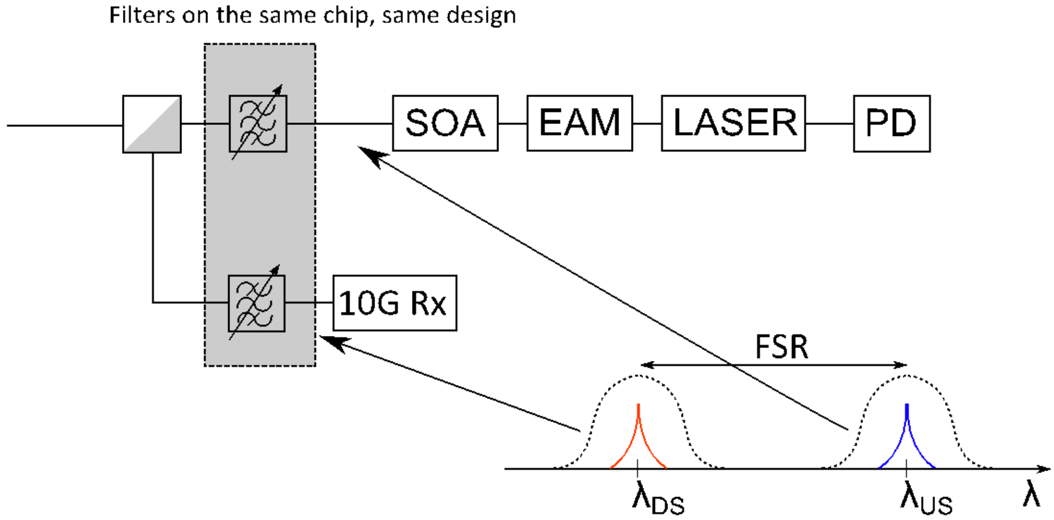

Figure 10. ONU configuration that implements the tuning scheme with Tx Tuneable filter using the DS channel as a reference, filter FSR, and feedback from OLT.

<u>Tx Tuneable filter and the two section wavelength/power monitor using DS channels as wavelength reference</u>

A solution similar to the previous one can be implemented where US and DS channels are interleaved on a 50GHz grid (Figure 11). In this case DS channels adjacent to the US channel are used as references to tune the tuneable filter in the transmitter. The SOA can be used as a detector to tune the Tx filter to DS channels. By interpolating the wavelength setting, the filter can then be tuned to the correct US channel.

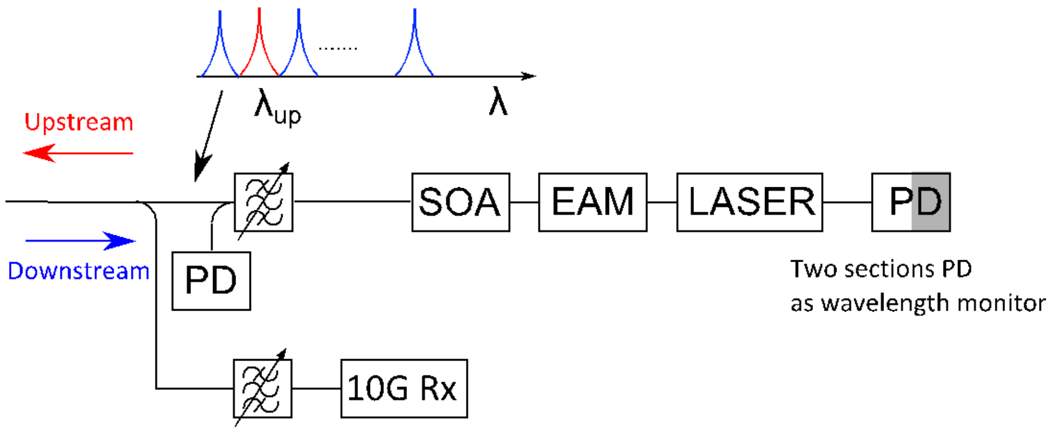

Figure 11. ONU configuration that implements the tuning scheme with Tx tuneable filter and the two section wavelength/power monitor using DS channels as wavelength reference

The DS channels can also be used to provide an absolute reference for a two section wavelength monitor, which works on the principle that the ratio between the photocurrents of a two section semiconductor absorber is dependent on the wavelength of the signal absorbed. The ratio is monotonically increasing with the wavelength and, if it is calibrated with an absolute reference, it can be used to track drifts in the tuneable laser wavelength, or possibly to coarse and fine tune the laser in the channel. One of the advantages of this structure is that it can be easily integrated with the slotted FP tuneable laser. A split contact SOA could also be used as a two section wavelength monitor when the SOA is in the off-state for blanking. A split contact SOA could be used as a two section wavelength monitor or alternatively a split contact monitor photodiode could be used (as in Figure 11). In the second case the SOA and the laser should be biased above transparency to allow the reference DS wavelength to reach the wavelength monitor. This solution could also have the advantage of selectively amplifying only one polarisation, reducing the potential polarisation dependence of the wavelength monitor.

Once the wavelength monitor is calibrated using two (or more) DS wavelengths, it can be used to measure the tuneable laser wavelength. The tuneable laser can then effectively self-calibrate using the wavelength monitor as a reference. By turning the SOA gain off and because of the presence of the filter in the Tx, the tuning of the laser can be performed safely avoiding the emission of a rogue wavelength into the rest of the network.

<u>Comparison of the various solutions</u>

The three solutions described here have good prospects of being implemented in a low cost ONU. The first one is the simpler in terms of ONU design, but requires accurate wavelength monitoring to be implemented at OLT. It also requires the PON protocol to convey tuning messages between the OLT and ONU. As described in Section 3.3.3, if no assumption can be made about the absolute precision of the tuneable laser calibration, and hence at start-up the laser could be within the bandwidth of the wrong channel, a special protocol should be implemented in order to avoid rogue wavelengths of the ONUs at startup. This protocol is relatively complex and also it would increase the time required by the registration procedure.

The second solution avoids the issue of rogue wavelengths at startup by using the DS channel and the tuneable filter FSR as a reference. The ONU has similar complexity as in the first solution, but it requires the design of a tuneable filter with a precise FSR. On top of this the fine tuning would still require a feedback from the OLT, which should contain accurate wavelength monitoring.

The third solution is the most complex from the ONU point of view. However, compared to the previous two solutions, it would not require any wavelength monitoring equipment at the OLT nor protocol control over the ONU wavelength. Since it avoids the issue of rogue wavelengths at startup it would also not impact the registration procedure. Since for all the solutions we assume a level of photonic integration of the ONU components, the relatively complex ONU could possibly be manufactured at low cost.

For these reasons we believe that the third is at the moment the most promising solution. There are, however, still technical issues that need to be investigated. For this reason within Task 8.4 we are planning to implement (or partially implement) this solution in order to analyse it experimentally. Within Task 8.4 we are also implementing the protocol messaging between OLT and ONU that would allow the feedback of tuning information necessary for the first two solutions.

Manufacturability of ganged & non-ganged Tx/Rx tuneable filters on same chip

Considering now the fabrication aspects of integrated components (Tx, Rx, filters ...) to address DWA aspects in access networks could rely on a Silicon photonics approach. Indeed this platform has reached a good maturity level and the low cost is guaranteed through the large scale of silicon on insulator (SOI) diameters (>200mm) that offers large volume of components per wafer. Within DISCUS, we already validated such a fabrication approach where tunable filters were fabricated on 200mm SOI wafers at CEA-Leti (Figure 12). The fabrication process relies on silicon waveguides (450nm wide and 220nm high), covered with silica. The filter is based on a ring resonator (RR) which has a racetrack resonator shape, with 5µm radius turns. The coupling coefficient between the RR and the input/output waveguides is 0.05. For measurement purposes, the integrated filter input and output ports are linked to vertical grating couplers. Above the RR, metallic heaters are processed. The heater resistor is 97 Ω.

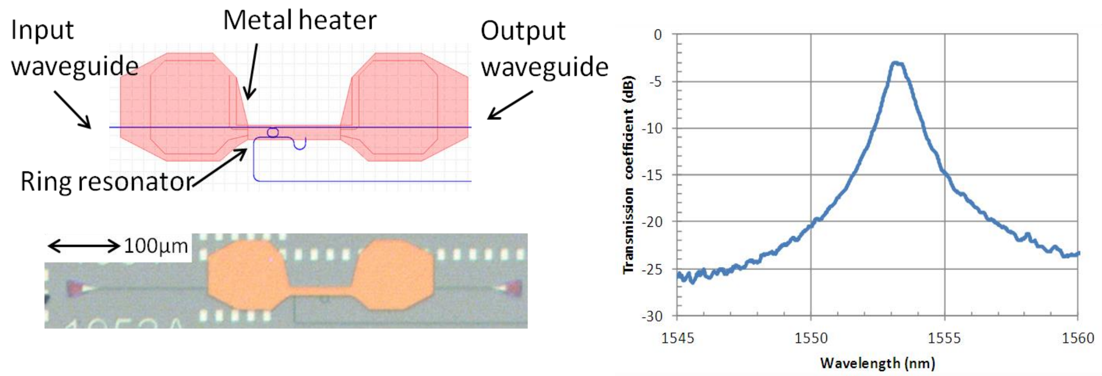

Figure 12. Top left : Tunable filter chip layout. Bottom left : Photograph of the chip. Right : Transmission spectrum of the output port of the ring resonator.

A more complex filter configuration could also be implemented in such a platform with low risk. Indeed, the ring resonator used in our proposed solution has a wide spectral range and the design parameters (geometry of the waveguide, thickness...) allow handling several wavelength bands (O-, C- and L-bands). Power splitters could also be implemented on this platform using for example coupled waveguides.

3.2 Physical Layer Performance & Impairments

3.2.1 Interferometric Xtalk and the Relation to ONU Laser Parameters

As discussed in deliverable D4.6 [20], cross-talk induced by optical network units (ONU) reduces the achievable receiver sensitivity in the upstream path. In this section, we will briefly remind the reader of the various cross-talk effects affecting the ONUs when they are already registered and ranged. Thus, these cross-talk effects happen in the operation phase of the upstream path. Additionally, we are extending our previously performed analysis by the number of upstream (US) wavelength channels as well as the used amplifier types, i.e.

erbium-doped fiber amplifier (EDFA) or semiconductor optical amplifier (SOA), for the multi-stage tree architecture.

In general three crosstalk cases can be distinguished in a TWDM-PON upstream path. The first case: "AWG" is shown in Figure 13(a). The limited total channel isolation of the wavelength-demultiplexer (WM) filter in front of the optical line terminations receiver (OLTs-Rx) causes a power leakage onto the test ONU channel from active adjacent and active non-adjacent ONUs-transmitter (Tx) reducing the signal-to-power-interference ratio (SIR, inter-channel X-talk) for the test channel to be received (dashed line represents the receiver filter for the channel under test). In the second cross-talk case: "when not enabled (WNE)" the residual output power of all not-burst-enabled ONUs accumulates at the power splitter. Thus, the available OSNR for the burst-enabled (active) test ONU signal is reduced, see Figure 13(b). The rival power can be either from background amplified spontaneous emission (ASE) noise of directly modulated laser (DML) or from not ideally suppressed signal carriers of externally modulated laser (EML) as used in the DISCUS project. However, in the WNE scenario it is assumed that the cross-talk beat noise of the rival and of the test ONUs falls within the electrical receiver bandwidth of the corresponding OLT-Rx, so that interferometric (intra-channel) cross-talk causes a power penalty. The third case: "out-of-channel optical power (OOC)" is shown in Figure 13(c). The limited side mode suppression ratio (SMSR) of the ONUs-Tx laser causes the noise power from adjacent and non-adjacent burst-enabled ONUs to reduce the available optical signal to noise ratio (OSNR) for the test ONU channel. This in-band effect causes also a power penalty given by the interaction of the electrical fields as explained for the first cross-talk case (WNE).

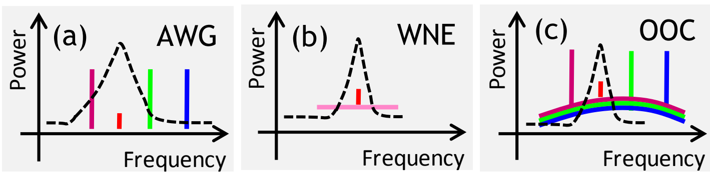

Figure 13. Reminder of the various crosstalk cases in the upstream path of TWDM-PON.

It should be noted that the "AWG" cross-talk is the dominant effect as long as a high power dynamic in the optical distribution network (ODN) of the long-reach (LR) PON is appearing. In the DISCUS approach, the mechanism of power levelling, i.e. the power reduction of the ONU-Tx in terms of signal carrier and simultaneously of the rival output noise power, is considered to be applied in all cases. This is made possible by the ONU laser manufacturing from Tyndall, because the laser comprises a slotted tunable laser section, an electro-absorption modulator (EAM) section as well as an SOA section. Here the SOA section can be used to compensate the losses of the EAM section and to adapt to the desired output power of the laser (ONU) by changing the SOA gain via the bias current. The use of power levelling relaxes the requirements of the AWG filter adjacent and non-adjacent channel isolation drastically so that the intra-band cross-talk effects WNE and OOC become dominant. In the following, the investigation of these two cross-talk cases are extended to the previous presented work in [20] in terms of the number of active wavelength channels and the comparison of EDFA and SOA technology for the multi-stage tree architecture. Once the rival output power density is calculated, these figures are transferred into commonly used transmitter specifications related to the different cross-talk cases (assuming identical polarization states of the Tx's), the burst-extinction (BU-ER) and the side-mode-suppression ratio (SMSR). The BU-ER is defined as the ratio of the average output power when the ONU-Tx is burst-enabled and the residual output power when the ONU-Tx is not burst-enabled. The SMSR is defined as the ratio of the signal power to the rival power (exploited at the center frequency of the OLT-Rx bandwidth for the ONU under test within a resolution bandwidth of 0.1 nm). In our study, the SMSR is assumed to be constant over the entire considered spectrum, which is obviously an acceptable assumption for a limited number of US wavelength channels, e.g. 4 (4*100 GHz = 400GHz → approximately 4 nm total spectral width, and it can be considered as a worst-case assumption for 50 US wavelength channels, e.g. 50*100 GHz = 5000GHz → approximately 50 nm total spectral width].

In the following, we investigate the cross-talk of a typical long-reach and high-split TWDM-PON scenario in the US path. We consider that the metro/core node (M/C node) to local exchange (LE) distance is 90 km, the LE comprises a 2:4 splitter and that the optical distribution network is 10 km long and each arm comprises a 1:128 splitter. This scenario represents the urban network deployment case of DISCUS. The ONUs laser always apply power levelling to adapt the output power to the minimum power level required to successfully detect the signal at a bit-error-ratio (BER) of 1E-3. The optical amplifiers used are either EDFA or SOA based.

The network model, which we use to determine the OSNR behind the last amplifier in the row (configuration: just one EDFA or in total 5 SOAs (one SOA per splitter arm (i.e. 4SOAs) and another common amplifier behind the splitter (i.e. 1 SOA))) is a very simple one assuming a time-invariant and constant gain for different signal input power levels, an unsaturated gain and a gain-dependent ASE noise contribution. Equation (9) presents the OSNR for the case of the cascaded amplified splitter using SOAs. The signal power behind the LE is P_{signal}, the noise power per 0.1 nm behind the LE is P_{noise}, the gain of SOA1/2 (splitter arm) is $G_{SOA1/2}$, the split loss of the 2:4 splitter is $S = 7$ dB, the ONU transmitter power is $P_{ONUsignal}$, the losses of the ODN (including fiber and splitter losses (excluding the 7 dB from the 2:4 splitter)) are L, the rival power from the ONU transmitter (in 0.1 nm) evaluated at the 2:4 splitter port inputs (EDFA) or the SOAs input located at the 2:4 splitter branches is $P_{ONUrival}$, N describes the number of branches of the splitter within the LE (here $N = 4$), and $P_{ASE1/2}$ describe the ASE contributions within 0.1 nm from the SOA1/2.

$$\mathrm{OSNR}_{\mathrm{SOA}} = \frac{P_{\mathrm{signal}}}{P_{\mathrm{noise}}(0.1\mathrm{nm})} = \frac{G_{\mathrm{SOA2}} S G_{\mathrm{SOA1}} L P_{\mathrm{ONUsignal}}}{G_{\mathrm{SOA2}} S G_{\mathrm{SOA1}} P_{\mathrm{ONUrival}} + G_{\mathrm{SOA2}} S N P_{\mathrm{ASE1}} + P_{\mathrm{ASE2}}} \quad ...(9).$$

The ASE power and the excess noise factor F are calculated by using equation (10):

$$P_{\mathrm{ASE}} = 2hfn_{\mathrm{sp}}\left(G-1\right)w_{0.1\mathrm{nm}}; \quad F = 2n_{\mathrm{sp}} \quad ...(10).$$

Here h is the Planck constant 6.626E-34 Js, f is the signal carrier frequency 193.3 THz, n_{sp} is the inversion factor, G is the gain and $w_{0.1nm}$ is the considered spectral width of the ASE noise. In case the EDFA technology is used, equation (9) has to be modified by $G_{SOA2} \bullet G_{SOA1} = G_{EDFA}$, $P_{ASE1} = 0$, $P_{ASE2} = P_{EDFA}$.

First, we investigate if the use of the SOAs and EDFA along the upstream path is feasible in terms of delivered OSNR. We analyze if an OSNR of 17 dB for *rival-free operation* can be achieved allowing for 1 dB OSNR path penalty and for 1 dB OSNR penalty induced by rival noise. Here, we assume that the ONU minimum output power is +1.5 dBm ($P_{ONUsignal}$), the fiber losses are 0.35 dB/km, comprising also losses for splices, and that the losses per split-stage are 3.5 dB. The receiver of the OLT requires a power of -35 dBm and a minimum OSNR of 15 dB as per the linear burst-mode receiver requirements at 10 Gbit/s, see deliverable D2.1 [37].

The OSNR in front of the M/C node is simulated. In Figure 14(a,b) the OSNR versus the ODN loss as well as the OSNR versus the rival noise power density is presented for the case that SOAs with 15 dB gain and a noise figures NF of 7 dB and an EDFA with a gain of 30 dB and a NF of either 7 dB (EDFA 1) or 4 dB (EDFA 2) are used. The test ONU signal is amplified along the amplifier chain, the optical amplifiers are always on all the time and the rival power is launched into the 2:4 amplified splitter branches. Note that each ONU has a power level of -35 dBm at the receiver.

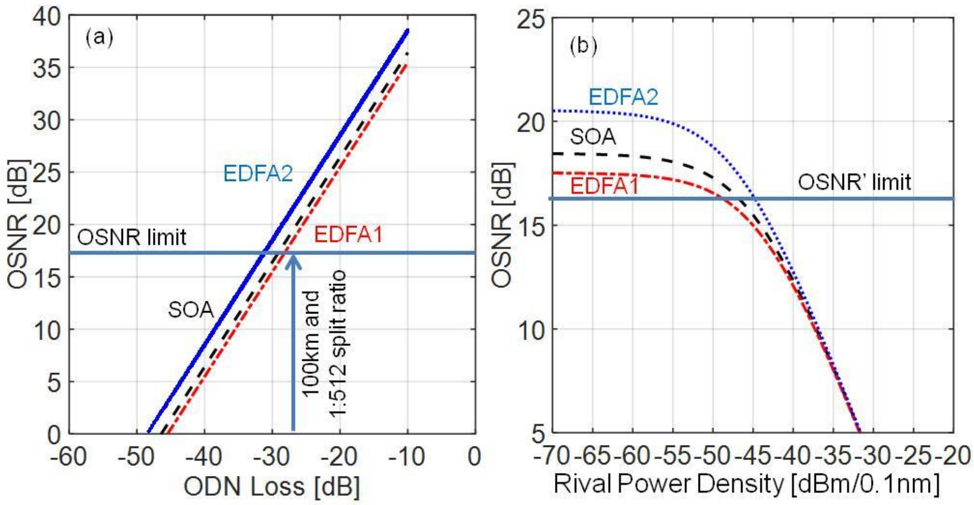

Figure 14. Calculated OSNR as a function of the ODN loss for three different amplifier / amplifier configurations in (a) and the OSNR as a function of the rival power density for a given ODN loss of 28 dB (128 split (additional 7 dB for the 1:4 splitter are already included within the calculation) and 10 km) in (b).

Obviously, the 17 dB OSNR limit for an ODN reach of 10 km (3.5 dB loss) and a split ratio of 1:128 (24.5 dB, 4x) are achieved independently of the amplifier technology. The highest OSNR is obtained as expected with the EDFA2 offering the lowest NF. The SOA cascade provides slightly better results compared to the EDFA1, because of the advantage of distributed amplification. To evaluate the acceptable amount of rival power from the ONU, the influence of the total rival power on the OSNR is tested for each amplifier and an ODN loss L of 28dB (128 split and 10 km, see Figure 14(a)). The acceptable rival power density at an OSNR limit of 16 dB is -46/-44/-48 dBm/0.1nm for the SOA/EDFA1/EDFA2.

The obtained rival power density limitations for the various amplifier cases need to be related to the ONU transmitter parameters. Thus, first the accumulated rival power at the input to the optical amplifier (SOA) or input to the split branch (EDFA) is distributed to the number of rival ONUs, i.e. n_{rival}. The rival ONUs can be either the number of ONUs assigned to the same sub-PON (identical wavelength) in the WNE case or the number of active WDM channels (burst-enabled ONUs) in the OOC case. The rival power at the ONU transmitter $P_{\text{ONUTxrival}}$ is calculated in case 0 dB of ODN dynamic is present, because power levelling is applied (using a log-scale):

$$P_{\text{ONUTxrival}} = P_{\text{ONUrival}} + L - n_{\text{rival}}, \qquad \text{...(11).}$$

The BU-ER and the SMSR are obtained by $P_{\text{ONUsignal}} - P_{\text{ONUTXrival}}$ (using a log-scale).

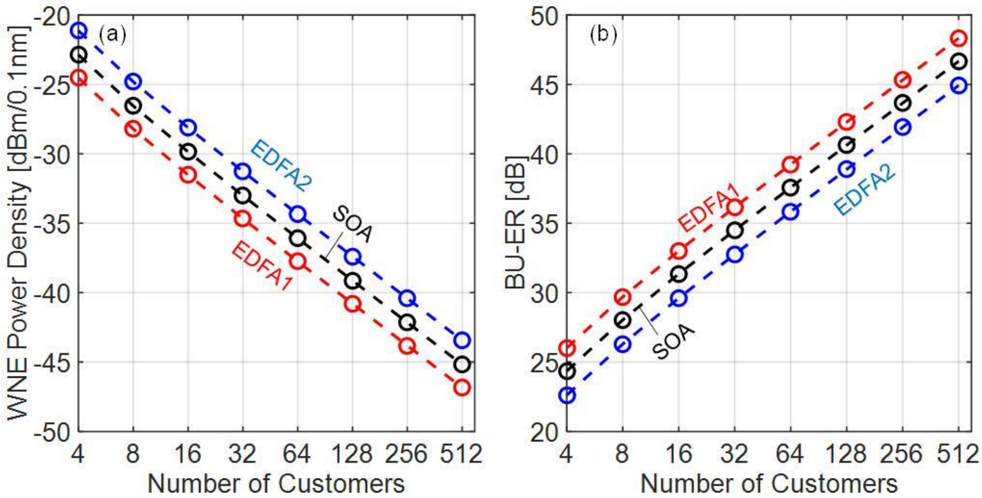

Figure 15. Results for the WNE cross-talk case. In (a) the power density as a function of the assigned ONUs to the sub-PON (wavelength) is presented for the three amplifier scenarios. In (b) the related BU-ER is presented.

The results in Figure 15 present the WNE case. In (a) the required power density as a function of the number of customers assigned to a specific sub-PON is shown. Obviously, the demand on the WNE power density increases with an increasing number of rival ONUs. The requirements can be presented also in terms of BU-ER, see (b). In case all ONUs (i.e. 512) available in the DISCUS LR-PON network are assigned to the same sub-PON wavelength the BU-ER requirement is about 50 dB. The tuneable slotted Fabry-Pérot laser fabricated by Tyndall within the DISCUS project comprises an EAM section for modulation as well as an SOA section for amplification and gating. A typical EAM modulation suppression is in the range of 20 dBm, thus, the SOA gate needs to offer a suppression of about 30 dB which seems feasible. Final tests of the ONU laser performance will be carried out in WP5 and WP8. In case that the total suppression of EAM and SOA is not sufficient, the laser bias current between burst-enabled and not burst-enabled modes can be reduced accordingly to meet the needs of the WNE cross-talk case.

The results in Figure 16 present the OOC case. In (a) the required power density as a function of the number of wavelength channels (simultaneous active ONUs on different wavelength channels) is shown. Obviously, the demand on the OOC power density increases with an increasing number of rival ONUs. The requirements can be presented also in terms of SMSR, see (b). In case 100 ONUs are switched on simultaneously (number of investigated channels here exceeds the number of wavelength channels discussed within the DISCUS project, i.e. 40...50 US channels) the SMSR requirement is slightly higher than 40 dB. The tuneable slotted Fabry-Pérot laser fabricated by Tyndall should offer an SMSR in the range of > 35 dB (see deliverable D5.3 [21]) which will be sufficient for the 40...50 US channels discussed within the DISCUS framework.

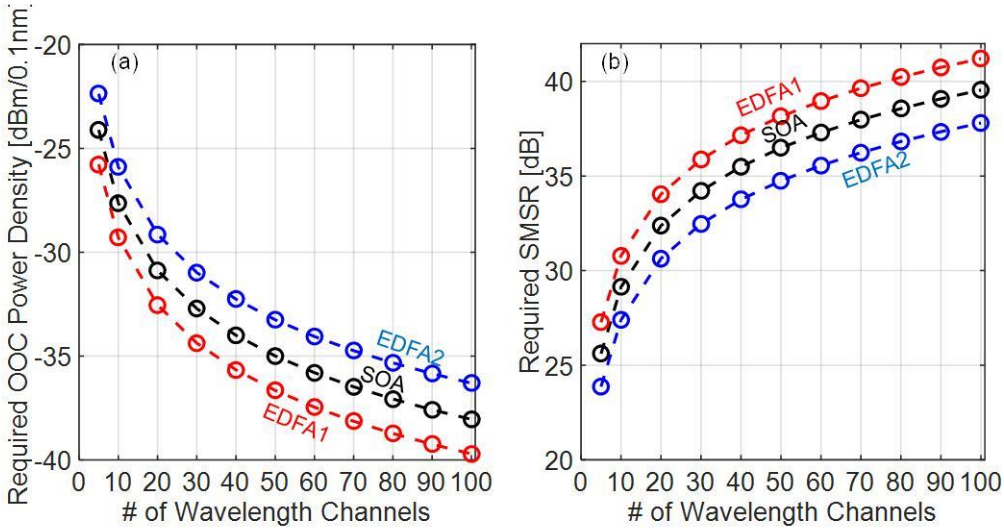

Figure 16. Results for the OOC cross-talk case. In (a) the power density as a function of the burst-enabled ONUs operated on different wavelength channels is presented for the three amplifier scenarios. In (b) the related SMSR is presented.

3.2.2 Interferometric Xtalk into the Wrong Channel

<u>Introduction</u>

If synchronised quiet windows are not used, then when ONUs attempt to register and tune to their correct channel at start-up, if their tuning precision is poor, they may tune to an incorrect channel to begin with, and cause interference with the working channel. In the worst case, a number of ONUs may tune randomly to wavelengths within the electrical passband of the working channel, causing interferometric crosstalk between themselves and the working channel.

The impact of interferometric crosstalk on the BMRx performance of an amplified LR-PON is assessed, for 1,024-way split and 125 km reach. Two models of interferometric crosstalk are compared: a) worst-case eye closure and b) statistical variance in the crosstalk photocurrent in the OLT BMRx, which is added to the variances due to sig-ASE noise and ASE-ASE noise in the amplifier.

The reduction in ONU launch power level needed to incur 1dB and 0.1 dB power penalties in BMRx sensitivity are assessed, as a function of the number of interferometric crosstalk interferers.

<u>Power Penalties with Optical Amplifier</u>

The following analysis applies when an optical amplifier is placed before the receiver, and the amplifier gain is sufficiently large for the beat-noise powers to dominate shot-noise powers [22], and optical power at the receiver remains large enough for the amplifier's sig-ASE and ASE-ASE noise terms to dominate the receiver's shot noise and thermal noise. Two types of analysis of the interferometric crosstalk are compared: worst-case eye closure and statistical. For both analyses, the required Q value, is given by

$$Q = \frac{RG(P_1 - P_0)}{\sigma_1 + \sigma_0} \qquad \text{...(12).}$$

For the worst-case analysis, we therefore have from Appendix II, for k simultaneous interferers:

$$P_0 = \alpha P_S + k^2 P + 2k\sqrt{\alpha P_S P}\,; \qquad P_1 = P_S + k^2 P - 2k\sqrt{P_S P}$$

$$\overline{P}_0 = \alpha P_S + kP \qquad \overline{P}_1 = P_S + kP$$

$$\sigma_1 = \sqrt{2hfB\left[2n_{sp}\overline{P}_1(G-1)G + n^2{}_{sp}hf(G-1)^2\Delta f_{opt}\right]}$$
$$\sigma_0 = \sqrt{2hfB\left[2n_{sp}\overline{P}_0(G-1)G + n^2{}_{sp}hf(G-1)^2\Delta f_{opt}\right]} \qquad \text{...(13).}$$

Therefore, for R=1 A/W, the worst-case analysis value for Q is

$$Q_{WC} = \frac{G\left((1-\alpha)P_S - 2k\left(1+\sqrt{\alpha}\right)\sqrt{P_S P}\right)}{\sqrt{2hfB\left[2n_{sp}\overline{P}_1(G-1)G + n^2{}_{sp}hf(G-1)^2\Delta f_{opt}\right]} + \sqrt{2hfB\left[2n_{sp}\overline{P}_0(G-1)G + n^2{}_{sp}hf(G-1)^2\Delta f_{opt}\right]}}$$
...(14).

There is no variance associated with the interferometric crosstalk, because the very smallest eye opening is being considered where fluctuations are at the extremes of their range.

Number of interferers, k	Power Reduction $10\log_{10}(P/P_S)$ dB for 1dB Power Penalty	Power Reduction $10\log_{10}(P/P_S)$ dB for 0.1dB Power Penalty
1	-28.3	-47.7
2	-34.3	-53.7
6	-43.8	-63.3
10	-48.2	-67.7
1023	-88.4	-107.9

Table 1 ONU power reductions required to ensure maximum power penalties of 1dB and 0.1dB in working channel, due to interferometric crosstalk from k ONUs starting up simultaneously in the same wrong channel: worst-case eye closure analysis.

As the number k of simultaneous interferers increases, the interfering power P from each ONU must be reduced, to maintain a required maximum power penalty. Table 1 shows that the power reduction required at start-up grows quadratically with the number of simultaneous interferers, i.e. eye closure ∝ $2k\sqrt{(P_S P)}$. With 1023 interferers, we need -88.4 dB reduction for 1dB penalty, and -107.9dB for 0.1 dB penalty. The worst-case analysis is far too pessimisitc, as it safeguards against the worst eye closure whose probability of occurring is extremely low. These results are for the following parameter values: spontaneous emission factor n_{sp} = 1.774 (5.5dB NF), Q = 3.09 assuming FEC, electrical bandwidth B = 7.5 GHz, optical bandwidth Δf_{opt} = 25 GHz, amplifier gain G = 1000.

Conversely, for conventional statistical analysis as in [23], the interferometric crosstalk is handled as a variance as follows

$$P_0 = \alpha P_S + kP; \qquad P_1 = P_S + kP$$

$$\sigma_1 = \sqrt{2kP_S PG^2 + (k^2 - k)P^2G^2 + 2hfB\left[2n_{sp}P_1(G-1)G + n^2{}_{sp}hf(G-1)^2\Delta f_{opt}\right]}$$

$$\sigma_0 = \sqrt{2k\alpha P_S PG^2 + (k^2 - k)P^2G^2 + 2hfB\left[2n_{sp}P_0(G-1)G + n^2{}_{sp}hf(G-1)^2\Delta f_{opt}\right]}$$

$$Q_{STAT} = \frac{G(1-\alpha)P_S}{\sigma_1 + \sigma_0} \qquad \text{...(15).}$$

Only the mean eye closure is used, not the worst case. Table 2 shows that for a statistical analysis, the power reduction required at start-up grows linearly with the number of simultaneous interferers, because it does not need to safeguard against the worst eye closure, i.e. Xtalk variance $\propto 2kP_sP$. With 1023 interferers, we need -53.2 dB instead of -88.4 dB reduction for 1dB penalty, and -62.7 dB instead of -107.9dB for 0.1 dB penalty. The same parameter values apply. The statistical analysis is therefore used to assess the performance of the mitigation protocol of section 3.3.3.

Number of interferers, k	Power Reduction 10log10(P/P_S) dB for 1dB penalty	Power Reduction 10log10(P/P_S) dB for 0.1dB penalty
1	-23.0	-32.6
2	-26.1	-35.6
6	-30.8	-40.4
10	**-33.1**	-42.6
1023	-53.2	-62.7

Table 2. ONU power reductions required to ensure maximum power penalties of 1dB and 0.1dB in working channel, due to interferometric crosstalk from k ONUs starting up simultaneously in the same wrong channel: statistical analysis.

The receiver sensitivity without any interferometric Xtalk $P_{S,NoIntXtalk}$ = -38.3 dBm. Therefore when incurring a maximum 1 dB power penalty, the receiver sensitivity with interferometric Xtalk needs to be $P_{S,sens}$ = -37.3 dBm. See Figure 18. Assuming that P_S is at most 4 dB dynamic range above this, to maintain a 3 dB margin and tolerate at most 1 dB polarisation variation over the first 10 km to the amplifier/splitter node, then the maximum signal power at the amplifier input is $P_{S,max}$ = -33.3 dBm. This value is used in section 3.2.4 to calculate the bandwidth reduction factor B'/B needed to detect a low power signal at start up, in the presence of interferometric Xtalk from a working channel at this full power.

The mitigation protocol in section 3.3.3 suggests that if 1023 ONUs all start up simultaneously, the protocol can limit the number of ONU bursts that collide in the same time slot to 10, with a sufficiently low probability of more than 10 ONUs starting up simultaneously. For k=10 simultaneous interferers (Table 2), the maximum power level that can be tolerated with 1 dB power penalty due to interferometric Xtalk is $P_{max} = P_{S,sens} - 33.1 = -37.3-33.1 = -70.4$ dBm (see Figure 18). But without such a mitigation protocol, and k=1023 simultaneous interferers, we would require an additional 20.1 dB power reduction (Table 2) i.e. $P_{max} = -90.5$ dBm.

The power budgets from ONU to first amplifer, for 512-way and 1024-way splits, are shown in Table 3. For a 512-way split, with $P_{S,max} = -33.3$ dBm and maximum loss of 38.2 dB, a maximum launch power of +4.9 dBm is required. Assuming +5.0 dBm launch power, 100% of all 512-way LR-PONs would be able to tolerate a 1 dB penalty due to interferometric Xtalk. 1024-way split LR-PONs would require another 3.4 dB launch power to ensure 100% coverage of all LR-PONs. Statistically, a good percentage of LR-PONs would support 1024-way split without this additional launch power. To guarantee 100% coverage with +5.0 dBm launch power would require coherent transmission.

	512-way Split			1024-way Split		
Component	Quantity	Min. Loss dB	Max. Loss dB	Quantity	Min. Loss dB	Max. Loss dB
Circulator	1	0.2	0.6	1	0.2	0.6
Connector	2	0	1.0	2	0	1.0
Splice	6	0	1.8	6	0	1.8
1:4 Splitter	3	16.2	21.3	2	10.8	14.2
1:8 Splitter	1	7.95	10.5	2	15.9	21.0
Fibre	10 km	2.0	3.0	10 km	2.0	3.0
Total Loss		26.35	38.2		28.9	41.6

Table 3. Power budgets from ONU to first amplifer, for 512-way and 1024-way splits.

3.2.3 Interferometric + Linear Xtalk from Correct Channel into Adjacent Channel

The impact of interferometric + linear crosstalk into the adjacent channel is considered with and without the use of quiet windows for start-up in the correct channel. Quiet windows cannot necessarily be used, if the low power/bandwidth channel continues transmitting outside the quiet windows. Quiet windows cannot be used in any case if the ONU laser's coarse tuning precision is poor, i.e. tunes to the wrong wavelength channel. But for tuning precision within the correct channel, if the low power/bandwidth start-up transmission bursts are turned off outside the quiet windows, much higher low bandwidth transmission speeds become possible.

Without Quiet Windows at Start-Up

When ONUs attempt to register and tune to their correct channel at start-up, if their tuning precision is good enough, they will tune to their correct channel to begin with. But, if synchronised quiet windows are not being used, even if they tune with perfect precision to the centre of the channel, the finite linear crosstalk isolation into the adjacent channel will cause interference into the neighbouring channel. Although the crosstalk will not be interferometric with the adjacent channel's signal, because the frequencies differ by more than the receiver's electrical bandwidth, in the worst case, a number of ONUs may tune randomly to wavelengths that are within the electrical passband of each other (within the correct channel), causing interferometric crosstalk between themselves, which is detected with additional linear crosstalk isolation in the adjacent channel's receiver. For flat-topped, 50 GHz channel-spaced AWG wavelength demultiplexers [24], worst-case crosstalk isolation between demultiplexer channels can be as high as 25 dB (X = 316.2) at the centre of the channel passband (tuning precision +/- 0 GHz), or as low as ~6 dB (X = 4) if tuning precision is only good enough to tune to the edge of the channel passband (+/- 25 GHz). If the corresponding values [25] for narrowband (Gaussian), 100 GHz spaced AWGs translate to 50 GHz spacing, they would be 26 dB (X = 398) and ~ 10.7 dB (X = 11.7).

Hence, even if ONU laser tuning precisions are good enough to ensure tuning within the correct wavelength channel, power reduction (levelling) may be necessary on start-up, to control the level of interferometric crosstalk into the adjacent channel, dependent on the tuning precision and number k of ONUs expected to start up simultaneously in the same channel, and within each other's electrical bandwidth. But because of the linear crosstalk isolation X into the adjacent channel, the required power reductions are expected to be significantly less than for interferometric crosstalk into the wrong channel in Section 3.2.2 above. As the tuning precision (of all ONUs) tightens from band edge (+/- 25 GHz) to +/- 0 GHz, and crosstalk isolation increases to 25 or 26 dB, the required power reduction lessens further. The major question is whether there is a value of guaranteed tuning precision for all ONUs, at which the required power reduction becomes zero, i.e. $P=P_S$, so that ONU activation can take place at full power P_s in quiet windows in the correct channel. Further studies would be needed to decide this possibility. It is likely to depend on whether a worst-case eye closure analysis or statistical noise analysis applies. If quiet windows can be used, then because power levelling is also necessary (due to the ODN dynamic range), the back-off procedure in quiet windows must ensure an extremely low probability of ONUs failing to register at each power level, as ensured in the mitigation protocol (Section 3.3.4.1).

It is expected that tuning precisions that are good (within correct channel), but not tightly specified close to the channel centre, could be up to +/- ~10-15 GHz. For such tuning precisions, low power/low bandwidth reception is still expected to be necessary, to prevent excessive interferometric crosstalk into the adjacent channel, so registration at high power in quiet windows is not possible within their correct channel.

Furthermore, the impact of interferometric + linear crosstalk within the correct channel must also be considered. As the tuning precision tightens from the band edge, the impact on this channel gets worse, because the crosstalk isolation X reduces as the laser wavelengths approach the channel centre. Furthermore, even with a stated tuning precision at the band edge, i.e. +/- 25 GHz, or as good as +/- 10-15 GHz, there is no guarantee that the k interfering lasers will not actually exhibit much smaller wavelength error. In the limit, they could possibly (but with very low probability) all be within the electrical passband of the correct channel. In practice, therefore, if power reductions are required, even if tuning precision is as bad as to the channel edge, the correct channel must employ the same low power/low bandwidth (B') scheme as for interferometric crosstalk into the wrong channel (Section 3.2.2).

Another reason why the correct channel's low power/bandwidth Rx must use the same low bandwidth scheme, as for interferometric crosstalk into the wrong channel, is if both tuning precisions co-exist in the same PON, i.e. ONUs with good tuning precision (up to the channel edge) and ONUs with poor tuning precision (into the wrong channel). This is because the correct channel's low power/bandwidth Rx does not know which precision the ONUs will exhibit.

However, initial theoretical calculations suggest that if only k=1 ONU starting up at a time needs to be protected against, and the tuning precision is +/- 15 GHz with up to 12 dB linear crosstalk into the adjacent channel, then the value of P_{max} required by the adjacent channel is -35.2 dBm, which lies within the Rx margin for $P_{S,max}$ (see Figure 18). This would allow start-up in the correct channel to take place at high power (not quite maximum power) at full LR-PON speed. But low power/bandwidth reception must still be employed for protection against k=2 or more simultaneous interferers.

Using Quiet Windows at Start-Up

If the ONU's coarse laser tuning precision is good enough to be within the correct upstream channel at start-up (e.g. +/-10-15 GHz), such that downstream LR-PON protocol messages can be trusted to relate to the correct upstream wavelength channel, then it becomes possible to employ the working channel's quiet windows for transmitting activation requests/attempts.

The statistical theory for interferometric + linear crosstalk into the adjacent channel is (from Appendix III):

$$P_0 = \alpha P_S + \frac{kP}{X}, \qquad P_1 = P_S + \frac{kP}{X}$$

$$\sigma_1 = \sqrt{2\frac{(k^2-k)P^2}{X^2}G^2 + 2hfB\left[2n_{sp}P_1(G-1)G + n^2{}_{sp}hf(G-1)^2\Delta f_{opt}\right]}$$

$$\sigma_0 = \sqrt{2\frac{(k^2-k)P^2}{X^2}G^2 + 2hfB\left[2n_{sp}P_0(G-1)G + n^2{}_{sp}hf(G-1)^2\Delta f_{opt}\right]}$$

$$Q_{STAT} = \frac{G(1-\alpha)P_S}{\sigma_1 + \sigma_0} \quad \text{...(16).}$$

There is no interferometric mixing between the k simultaneous low power bursts and the adjacent working channel, because they are very far apart in wavelength. Mixing occurs only between the k interferers themselves. Assuming 15GHz wavelength error from the centre of the correct channel, and hence 35GHz from the adjacent channel centre (for 50 GHz channel spacing), and assuming worst-case linear crosstalk isolation X of 12dB in the adjacent demultiplexer channel, the low power channel is limited to P_{max}=-50.2 dBm, to ensure that up to k=10 simultaneous interferers can be tolerated by the adjacent channel. Such a power level is far too high to remain transmitted outside the quiet windows, as the correct channel can tolerate only -70.4 dBm with k=10 simultaneous interferers, i.e. the same as for the wrong channel in Section 3.2.2. The mitigation protocol used for start-up in quiet windows must therefore be different to that without using quiet windows in Section 3.3.3.

All these options, with and without the use of quiet windows at start-up, are summarised in Figure 17, together with further options raised in Section 3.3.4. For good tuning precision of +/-10-15 GHz within the correct channel, start-up using quiet windows is preferred to start-up at much lower power level and bandwidth (not shown), and is DISCUS' fall-back option. But the overall preferred wavelength referencing and calibration option uses interleaved US and DS wavelength channels, to provide tightly specified tuning precision.

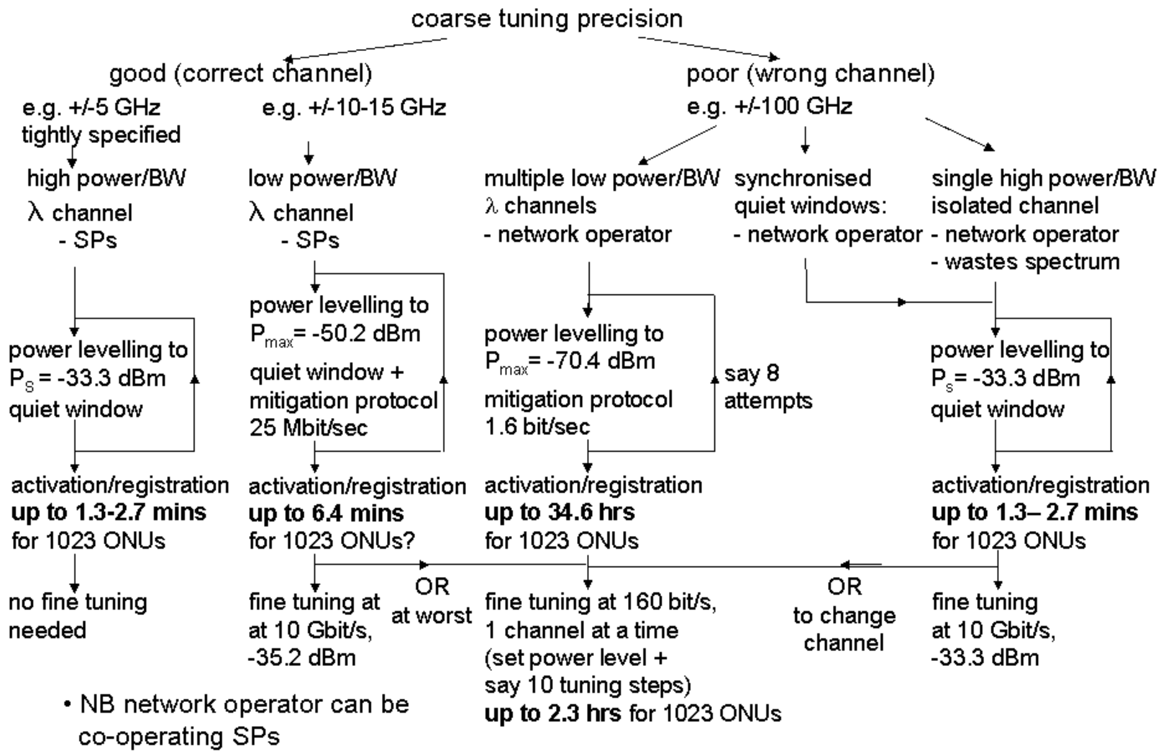

Figure 17. Start-Up and Tuning Options.

There are further problems that need to be solved for power levelling at start-up, in the relationship between laser calibration, available dynamic range in the low power/bandwidth Rx (Section 3.2.4), and accommodation of the ODN dynamic range. See Section 3.2.5.

3.2.4 Theoretical BMRx Performance at Low Power & Low Bandwidth

This sub-section discusses the theoretical BMRx performance achievable, both when poor ONU tuning precisions could result in start-up occurring in the wrong channel, so that quiet windows cannot be used, and when ONUs start up in the correct channel, allowing quiet windows to be used. It is assumed here that synchronous quiet windows are not employed across all wavelength channels.

Start-Up in Wrong Channel: No Quiet Windows

Having reduced the ONU transmit powers during initial start-up (section 3.2.2,), in order to reduce impairment in the working channel due to interferometric Xtalk to an acceptable power penalty, it now becomes necessary, in case multiple ONUs with poor tuning precision tune to the same incorrect channel to begin with, to reduce the receiver bandwidth from the full high-speed bandwidth B to a much lower value B', to enable the ONU to signal its identity (e.g. serial number), and possibly its desired wavelength channel identity, to the OLT. The OLT can then register the ONU, and begin to control tuning of the ONU to the correct wavelength and raising its power to operational level. A statistical analysis is used to calculate the required bandwidth B' and corresponding signalling bit-rate achievable.

When only one ONU is attempting to start up at low power P, there is only one interferer potentially causing interferometric Xtalk in the low bandwidth receiver: the working channel with much higher optical power P_S. This is because it is the wrong channel, and we are assuming that either quiet windows are not synchronised between different wavelength channels, or the working channel does not employ an LR-PON protocol.

Under these circumstances, the mean working signal is filtered by the bandwidth reduction term √(B'/B), and the interferometric crosstalk between working signal P_S and low power signal P is dealt with as variance terms, which, as with the working signal variance, is filtered by the ratio B'/B, as follows:

$$P_1 = P + P_S\sqrt{\frac{B'}{B}} \qquad\qquad P_0 = P_S\sqrt{\frac{B'}{B}}$$

$$\sigma_1 = \sqrt{2\frac{B'}{B}P_S P G^2 + 2\frac{B'}{B}P_S{}^2 G^2 + 2hfB'\left[2n_{sp}P_1(G-1)G + n^2{}_{sp}hf(G-1)^2\Delta f_{opt}\right]}$$

$$\sigma_0 = \sqrt{2\frac{B'}{B}P_S{}^2 G^2 + 2hfB'\left[2n_{sp}P_0(G-1)G + n^2{}_{sp}hf(G-1)^2\Delta f_{opt}\right]}$$

$$Q_{STAT} = \frac{GP}{\sigma_1 + \sigma_0} \qquad \text{...(17).}$$

The theory adapts Mestdagh's [22] amplifier spon-spon noise mixing theory to our purposes, using the supposition that in full bandwidth B (7.5 GHz) there are 4M^2 (= B/B') optical power cross-terms that can be detected, but only 4M terms detectable in narrow bandwidth B'. 2M of these are dc terms, leaving 2M terms if ac coupled. The result is $\sigma^2 = 2(B'/B)(G.Ps)^2$, if there is no modulation. It is hoped that either phase modulation or OOK modulation will halve this to $\sigma^2 = (B'/B)(G.Ps)^2$. This is the value used for the rest of this document. Further study is needed.

It is expected that $P_1 - P_0$ equals P precisely. But this may not matter. For example, if P_1 is reduced because P_S reduces during the 1 state, σ_1 also reduces significantly, possibly providing a higher Q value overall than for constant P_S. This needs checking.

For the spon-spon noise (last) term, the optical bandwidth Δf_{opt} should be increased to ensure that low power signals can be detected when the coarse tuning precision is at its worst. For example, if the precision is +/- 50 GHz, i.e. to the centre of the adjacent channel, then Δf_{opt} should be increased to say 150 GHz. This implies that the low power, low bandwidth channels should use separate, wider wavelength demulitiplxers or optical filters than the working wavelength channels. The first interferometric Xtalk variance term in σ_1, which is due to the electrical spectrum of P_S mixng with P, similar to sig-spon noise, is reduced by the bandwidth ratio B'/B. It is small compared with the sig-spon noise term itself. But the second interferometric Xtalk term, due to the spectrum of P_S mixing with itself like spon-spon noise, becomes the dominant noise term. This causes B' to become extremely narrow.

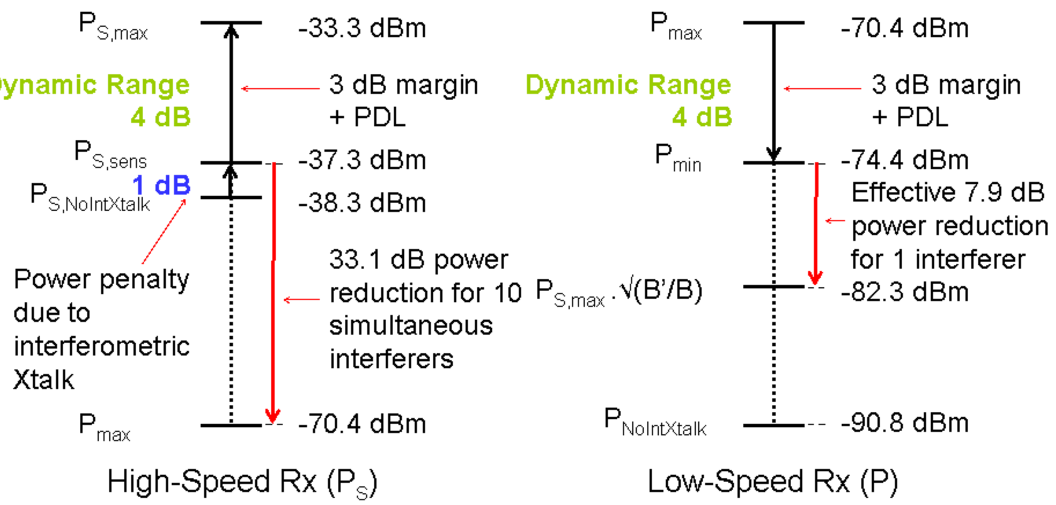

Figure 18. Dynamic range and power levels at amplifier input, to tolerate 10 simultaneous interferers in working channel, and 1 interferer in low power/low bandwidth channel. Quiet windows are not used.

Using P_{max} = -70.4 dBm from section 3.2.2, which allows 10 simultaneous interferers to be tolerated in the working channel, the lowest possible received power level in the low bandwidth channel is further reduced by the 4 dB dynamic range to P_{min} = -74.4 dBm. See Figure 18. To detect data with 10^{-3} error rate (Q=3.09) at this power level, in the presence of interferometric Xtalk from the working channel at its highest possible power $P_{S,max}$ = -33.3 dBm, the bandwidth B' must be reduced to 1.2 Hz, equivalent to 1.6 bit/sec data rate. This is a bandwidth ratio B'/B of 1.6×10^{-10}. With this bandwidth, the receiver sensitivity without interferometric Xtalk $P_{NoIntXtalk}$ would be -90.8 dBm. But this is of no relevance, because the working channel will always have ONU bursts present during the long bit intervals of the low bandwidth channel. The effective optical power level of the narrowly filtered working signal is $P_{S,max}.\sqrt{(B'/B)}$ = -82.3 dBm.

Hopefully it will be feasible to work at such a low bit rate. It is the mitigation protocol in section 3.3.3 that prevents far lower bandwidths and data rates from being necessary (photon counting). Without it, if 1023 simultaneous interferers had to be tolerated, the bandwidth of the low power channel would need to be reduced to 5.6×10^{-5} Hz. But the on-off-keying (OOK) calculated here will probably not be used. A more practical solution would be to shift the transmission in frequency, e.g. to a few MHz, to avoid problems around DC. At such low frequencies this could be done easily in a DSP both at Tx and Rx. The ONU registration times achievable with a 1.6 bit/sec data rate are discussed in section 3.3.3.

<u>Start-Up in Correct Channel: Using Quiet Windows</u>

During a quiet window, there is no working signal P_S at high power to cause interferometric crosstalk with the low power channel. But in practice there is likely to be interferometric crosstalk during a quiet window, due to all the ONU lasers on the LR-PON not being turned perfectly off, and interfering with the successful ONU laser that has avoided collision. The successful ONU's power level, which has a minimum sensitivity P_{min} = -54.2 dBm (Figure 19), now becomes the signal level P_S. The remaining 1022 ONUs produce interferometric crosstalk between themselves, and with the successful ONU. The low bandwidth Rx performance, into low bandwidth B', is given by

$$P_1 = P_S + kP \qquad P_0 = \alpha P_S + kP$$

$$\sigma_1 = \sqrt{2kP_S PG^2 + (k^2 - k)P^2G^2 + 2hfB'\left[2n_{sp}P_1(G-1)G + n^2{}_{sp}hf(G-1)^2\Delta f_{opt}\right]}$$

$$\sigma_0 = \sqrt{2k\alpha P_S PG^2 + (k^2 - k)P^2G^2 + 2hfB'\left[2n_{sp}P_0(G-1)G + n^2{}_{sp}hf(G-1)^2\Delta f_{opt}\right]}$$

$$Q_{STAT} = \frac{G(1-\alpha)P_S}{\sigma_1 + \sigma_0} \qquad \text{...(18).}$$

With k=1022 ONUs producing interferometric crosstalk, it is possible to receive successfully at P_S = -54.2 dBm (with Q_{STAT} = 3.09), at a speed of 25.0 Mbit/sec (B' = 18.8 MHz), provided that all interferers have their power levels reduced to P_{OFF} ≤ -103.3 dBm (at amplifier input). This represents a ≥70 dB total power reduction requirement (ON/OFF ratio) from the full working power level of -33.3 dBm. Δf_{opt} is assumed to be 50 GHz.

25.0 Mbit/sec is a huge improvement on the 1.6 bit/sec achievable without quiet windows, in the wrong channel. In fact, it can be increased further to 55.6 Mbit/sec, by increasing the ON/OFF ratio to 80 dB. 59.1 Mbit/sec is the absolute maximum rate, with infinite ON/OFF ratio. These higher activation speeds require a different approach to using the mitigation protocol in Section 3.3.3, for reducing collision probabilities. Because the protocol time slots (containing ONU activation bursts) can be completed within a single quiet window, the protocol can be more like the conventional random delay protocol in XG-PON, albeit not at full PON speed.

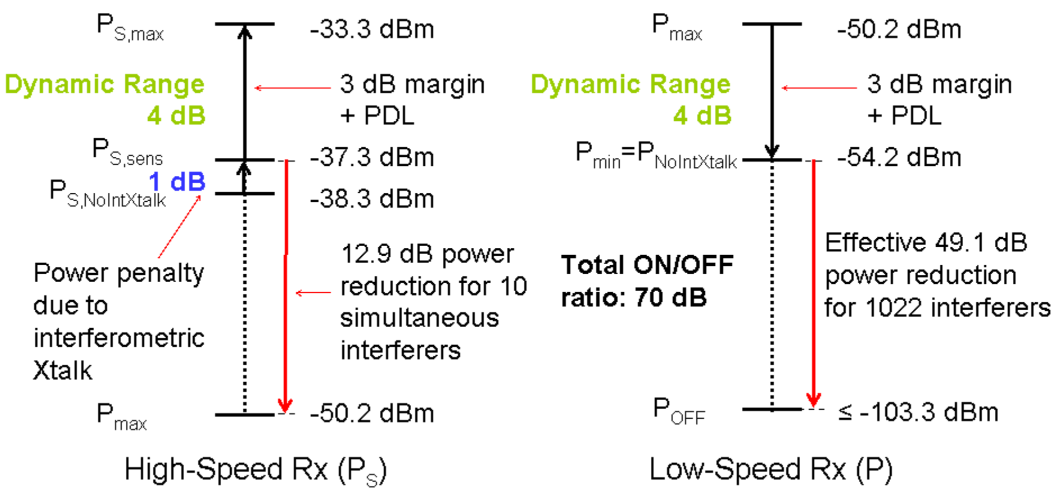

Figure 19. Dynamic range and power levels at amplifier input, to tolerate 10 simultaneous interferers in adjacent channel, and 1022 interferers in low power/low bandwidth Rx in correct channel. Quiet windows are used.

Outside the quiet windows, all ONUs must be turned OFF, to prevent interferometric crosstalk into the working channel. Because the working power level is -33.3 dBm, the required ON/OFF ratio is just ≥58 dB, ensuring ≤-91.3 dBm from each ONU at the amplifier.

3.2.5 *Power Levelling Issues*

This section discusses power levelling issues at start-up and during tuning. These include the Time-Gap method of Telecom Italia and Polytechnic University of Turin [26], [27].

At Start-Up Without Quiet Windows

Regardless of laser tuning precision, and whether or not quiet windows are used, ONU laser powers must be increased, for each activation attempt, until the ONU is discovered by the OLT.

It is proposed that ONU lasers should be calibrated at only one power level for each wavelength channel, to reduce manufacturing costs. This introduces severe difficulties for power levelling, in the relationship between laser calibration, available dynamic range in the low power/bandwidth Rx (Section 3.2.4) and accommodation of the ODN dynamic range.

As stated in Section 3.2.3, ONUs with good tuning precision (at one power level), e.g. to +/- ~10-15 GHz, cannot activate/register at full working power P_S, to prevent interferometric + linear crosstalk into the wrong channel. Furthermore, they must employ the same low power/low bandwidth scheme as for tuning into the wrong channel, in case interferometric crosstalk occurs with the working signal P_S in the correct channel.

The dynamic range available in the low power/low bandwidth Rx is just the 3 dB margin in Figure 18. But the power level may need to be raised incrementally by at most the full ODN dynamic range of 12.7 dB (Table 3), in order to become detectable. The wavelength will therefore change. Unfortunately, until the power level becomes detectable, the wavelength shift due to power change cannot be corrected by feedback from the OLT, as described in Section 3.3.4.1. But that section also describes how it is hoped that the wavelength shift could be corrected by local feedback control in the ONU, by transferring the laser precision to the Tx tuneable filter. Therefore, at higher power levels, the wavelength error could perhaps be maintained at +/-10-15 GHz. This would increase the number of distinct wavelength channels that can be used by the mitigation protocol in Section 3.3.3 at start-up, perhaps from 32 to 96, and hence provide a threefold reduction in the calculated protocol run times.

It would be beneficial if the low power/bandwidth Rx margin could be increased to accommodate the 12.7 dB ODN dynamic range. A potential way to achieve this might be to employ the Time-Gap method of Telecom Italia and Polytechnic University of Turin. This allows the working signal P_S to be turned off during (sampled) measurements, so is hoped to allow a sufficiently low power level to be detected (-87.1 dBm), that would incorporate the 12.7 dB dynamic range. But in a LR-PON, turning off the signal means that all ONUs must be turned hard off, with an ON/OFF ratio sufficient to allow -87.1 dBm to be detected in the presence of interferometric crosstalk due to k=1022 interferers. For example, an ON/OFF ratio of 101 dB, to -134 dBm at amplifier input, allows B'=1.0 Hz and a bit rate of 1.33 bit/sec. But this is at the expense of employing the entire 125 microsec frame during registration attempts. If just 10% of each frame (12.5 microsec) is "wasted" instead, which should degrade just the Non-Assured and BE traffic during start-up protocol runs, then overall the bit rate becomes 0.13 bit/sec. This is lower than the 1.6 bit/sec calculated without incorporating the ODN dynamic range and without Time-Gapping. Furthermore, 101 dB ON/OFF ratio is impractical. Thus it appears that Time-Gaps cannot eliminate the need to raise power levels in order to activate/register.

Interestingly, if laser power levels were raised for each activation attempt, so not incorporating the ODN dynamic range in the low power Rx margin, and tuning precision were +/-10-15 GHz, the Time-Gap method would enable the overall bit rate to increase to ~2.75 kbit/sec. This is equivalent to 275 bit/sec overall bit rate using 10% of each frame, providing a 172-fold reduction in the protocol run times in Section 3.3.3. But this requires a 90 dB ON/OFF ratio, which is also likely to be impractical.

<u>At Start-Up With Quiet Windows</u>

The power levelling requirements for start-up in quiet windows (at 25 Mbit/sec) are made less severe by the mitigation protocol in Section 3.3.3, which is modified for use with quiet windows. It enables the number of ONU lasers, involved in power levelling and coarse wavelength calibration at any time, to be reduced from the total number attempting to start up simultaneously (1023 at most), to a much smaller number. For 1023 ONUs, the mitigation protocol allows activation at 25 Mbit/sec to provide , for example, 10 time slots for serial number bursts in each quiet window. Therefore 1023 ONUs require 103 quiet windows to complete a round of registration attempts. While the expected number of ONUs per quiet window is just 10, there is a statistically high probability of more than 10 ONUs choosing to burst in the same quiet window. The design number used here is k=37. This provides similar overall outage probability to that designed in the mitigation protocol for use without quiet windows (for poor tuning precision into the wrong channel).

In the first protocol run (7 rounds) of registration attempts, ONUs burst at their pre-calibrated (in manufacture) power levels, i.e. with +/-10-15 GHz tuning precision and therefore within the correct wavelength channel. In subsequent protocol runs at higher power level increments, ONUs intending to burst in the next quiet window must calibrate their tuning precision at the new power level (e.g. 2 dB increments) in readiness for the quiet window. All other ONUs must turn their power level hard OFF, to -103.3 dBm at amplifier input (70 dB total ON/OFF ratio required).

At the new raised power level, tuning precision reverts to poor, e.g. +/-100 GHz, which could be in the wrong channel. Nevertheless, the worst interferometric crosstalk potentially occurs in the correct channel, if all 37 ONUs happen to be within +/-10 GHz of each other, and of the working channel, causing mixing with the high power signal P_S. For the working channel to tolerate this interferometric crosstalk, the maximum power level of ONUs during re-calibration at raised power level must be $P_{max} \leq$-76.8 dBm at amplifier input. Since the power level required for bursting in a quiet window is -50.2 dBm, ONUs must possess at least -76.8 – (-50.2) = 26.6 dB ON/OFF attenuation, which can be turned ON without affecting the laser wavelength during the burst. This attenuation cannot be provided by the laser, SOA or EAM, because all of these may affect the laser wavelength.

The ON/OFF attenuation must be located after the Tx tuneable filter and its photodiode coupler, because these are used for wavelength re-calibration. So potentially it could be implemented in the same silicon on insulator (SOI) wafer as the Tx tuneable filter itself. Perhaps it could be an ON/OFF coupler/splitter, or even another tunable filter, tuned off by 8-10 nm to provide the attenuation (see Figure 12). The fast tuning speed of this tunable filter is <20 μsec for 10 nm tuning. So a short, additional guard time of 20 μsec could be inserted before each ONU burst, extending the quiet window considered in Section 3.3.3 by 200 μsec for 10 time slots to 1.503 msec.

With 26.6 dB attenuation in place, and the laser power level raised by 2 dB, the laser wavelength is re-tuned under local control within the ONU, so as to be centred on the Tx tunable filter passband, and hence re-calibrated to the +/-10-15 GHz (good) tuning precision provided in manufacture.

Within the quiet window itself, and within the time slots in which an ONU is not bursting, the attenuation needs to be even higher. This is because the working power level P_S in quiet windows is reduced to -50.2 dBm from -33.3 dBm at amplifier input, to tolerate interferometric crosstalk into the adjacent channel from up to 10 interferers in the same time slot. With k=37 interferers in the quiet window, the maximum power level for each one, tolerated by the 25 Mbit/sec Rx, is -88.9 dBm at amplifier input. Hence -50.2 – (-88.9) = 38.7 dB ON/OFF attenuation is required. Hopefully, the additional 12.1 dB attenuation from -76.8 dBm to -88.9 dBm can be provided by a component that affects the laser wavelength, such as the EAM or SOA. Although the laser may potentially tune to other wavelength channels, they can tolerate the same -76.8 dBm power level as the correct channel, and there will be several dB attenuation provided by the Tx tunable filter roll-off to assist against rogue behaviour. After successful activation, the ONU turns itself hard OFF, until the OLT begins to provide feedback control for fine tuning and power levelling.

Thus, after successful activation, ONUs are calibrated to +/-10-15 GHz over a range of power levels up to -50.2 dBm at amplifier input. They must still be calibrated up to full working power level before, after or during fine tuning, under feedback control from the OLT. Alternatively, perhaps the further -33.3 – (-50.2) = 16.9 dB attenuation could also be achieved without affecting the laser wavelength, using additional, or higher attenuation, optical coupler/switch or tunable filter in SIO. This would leave only fine tuning, and possibly fine power levelling, to be controlled by feedback from the OLT.

During Tuning

For the fine tuning itself, if this can be achieved without the laser tuning precision worsening, during the procedure, from its calibrated +/-10-15 GHz, hence remaining within the correct wavelength channel, it might be possible to fine tune at full working power level. As discussed in Section 3.2.3 in relation to start-up, if only k=1 ONU is being tuned at a time, and the tuning precision is +/-15 GHz with up to 12 dB linear crosstalk into the adjacent channel, then the value of P_{max} required by the adjacent channel is -35.2 dBm, which lies within the Rx margin for $P_{S,max}$ (see Figure 18). This would allow fine tuning in the correct channel to take place at high power (not quite maximum power) at full LR-PON speed.

If laser tuning precision worsens during the fine tuning procedure, perhaps because the power level has to be changed, then fine tuning could be performed at lower power, but not necessarily as low as for poor tuning precision.

Future work is needed to define precise procedures for fine tuning and possibly for fine power levelling under feedback control from the OLT.

3.3 DWA Protocols

This section provides detailed descriptions of three potential DWA protocol options: synchronised quiet windows, auxiliary management and control channel (AMCC) and the new mitigation protocol against interferometric crosstalk at ONU start-up.

The initialization, activation and operation of various ONUs in a TWDM-PON need specific measures to be functional. The various ONUs-Tx can be operated on different wavelength channels, which are related to their respective, independently operating OLTs. This way, the ONU initialization and activation needs either wavelength calibrated ONU laser sources, or the synchronization of ranging windows across all OLTs, or the use of an auxiliary management and control channel (AMCC) to avoid rogue ONU behaviour in wavelength and time domain deteriorating system performance with every new ONU entering the network. For the operation of the ONUs a received signal strength indicator (RSSI) measurement to determine the relative burst power levels in conjunction with a specific filter shape can be used in the OLT-Rx to align and fine tune the respective ONU-Tx to the centre of the desired wavelength channel.

The operation of an AMCC channel can be improved by means of a mitigation protocol to protect against interferometric crosstalk. This ensures that no more than 10 ONUs can simultaneously collide in the low power/low bandwidth channel (with acceptable outage probability for the high power working channel), no matter how many ONUs attempt to start up simultaneously, even up to 1023.

In the following, these mechanisms are described in detail.

3.3.1 Synchronised Quiet Windows

ONU initialization and activation need to be adapted from the standardized TDM-PON technique. The challenge is to initialize a new ONU without disturbing ONU's that are already in operation. Wavelength non-calibrated ONU transmitters provide the lowest cost implementation, but the wavelength of a new ONU is then unknown at start-up and it could potentially interfere with the ongoing PON traffic.

Next we describe a method to initialize and activate a non-calibrated ONU on a TWDM-PON [28]. Before the activation of an ONU begins, the ONU must tune its receiver for optimal downstream (DS) data reception. This phase does not interfere with the current traffic on the PON, since all ONUs can receive the DS data simultaneously.

Once the ONU is able to receive DS physical layer operation and maintenance (PLOAM) messages from the OLT, the US wavelength of the ONU can be tuned. For this we use the standard quiet windows (ranging windows), which are standardized in for example reference [29], [30]. The main adaptation of the standardized quiet windows for TWDM-PON is that these quiet windows must occur synchronously on all US wavelength channels.

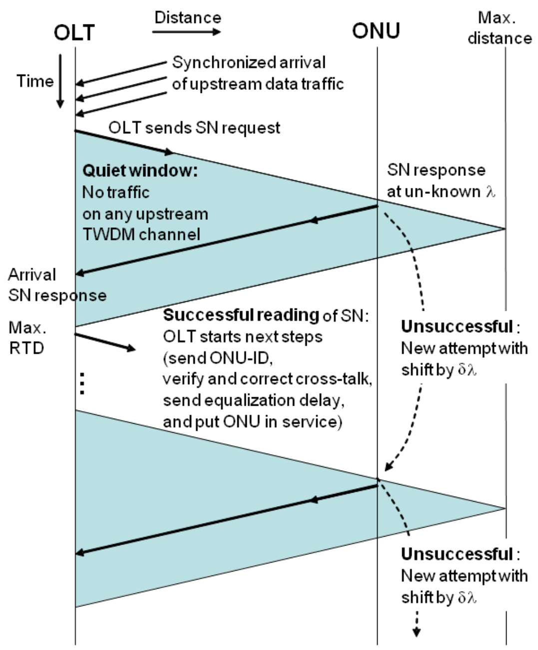

Figure 20. Illustration of ONU initialization protocol for TWDM-PON; SN: serial number, RTD round-trip time.

Figure 20 shows a flow diagram of the initialization protocol steps for TWDM-PON [31]. This follows the standardized initialization methodology except for the wavelength shifting steps that are added. The ONU passively listens to the DS to achieve synchronization. Then after receiving a serial number (SN) grant PLOAM message, the ONU responds by transmitting its SN during a synchronized quiet window. In case of a successful reading of the SN by the OLT the ONU moves to the next step where it receives its ONU-ID, gets fine-tuned, and calibrates the equalization delay so it can range. When the OLT does not have a successful reading of the SN, the ONU will not get a response back. The ONU then starts a coarse search algorithm where it shifts its wavelength and waits until the next opportunity to transmit the SN to the OLT. These steps are repeated until the ONU achieves communication with the OLT.

After SN detection, RSSI measurements at the OLT-Rx are used to fine tune the ONU's US wavelength. By dithering the US wavelength and comparing RSSI values a maximum output of the Gaussian-shaped receiver filter can be detected, thereby selecting optimal tuning before the ONU becomes operational. Figure 21 shows the fine tuning and dithering process. After fine-tuning is done the ONU is put into operation.

During operation dithering stays active to track the wavelength when (slow) ambient temperature changes occur. These fine tuning adjustments involve minuscule wavelength changes (< 2 GHz) that do not affect other operating TWDM-PON wavelength channels and are made during the time allocated to the ONU for US transmission.

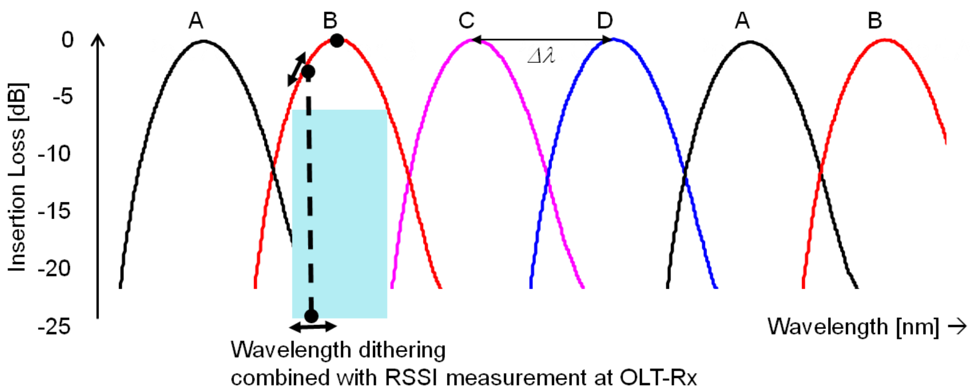

Figure 21. Fine tuning and dithering of the ONU-Tx wavelength.

Ranging procedure similar to one already standardized for GPON and XGPON can be used in TWDM-PON, but the synchronization of the quiet windows across all US wavelength channels has to be applied in case non-calibrated lasers are used. This section describes methods on how to achieve this synchronization across the OLTs.

Two possible cases can be identified, OLTs in same location, i.e. M/C node, and OLTs on the same TWDM-PON network in different locations (not applicable for DISCUS networks, but nevertheless briefly outlined in the following). The first case is the easiest as the time-of-day (ToD) interface, which is standard on most telecom equipment, can be used. Mature technology, e.g. phase locked loop based clock synchronization is available to interface with ToD. Contrary, when OLTs are not co-located ranging window synchronization is a bit more complex. With an accuracy of ± 10 ns, global positioning system (GPS) time signals are the most accurate possibility for clock synchronization. A GPS receiver can be incorporated at each OLT location. However the GPS receiver requires good visibility of the sky. Additionally, there may be government regulations to be considered too, which means that the publicly useable GPS can be switched to a lower accuracy—for political, strategic, generally non-telecom related reasons. Another possibility to synchronize OLTs in different locations is to employ the precision time protocol (PTP) [32]. With a sub-microsecond accuracy the PTP protocol is used to synchronize clocks throughout a computer network.

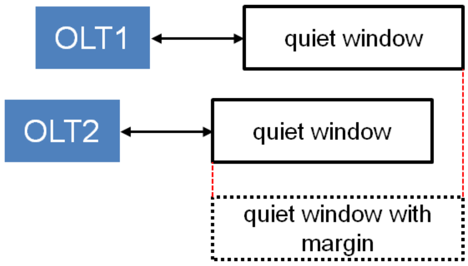

Figure 22. Synchronization accuracy for OLTs, which are in different locations.

Once the clocks are locked at each OLT, the quiet windows still need to be synchronized in absolute time. A distinction can also be made between handling co-located and isolated OLTs for this synchronization. In the first case the quiet windows can synchronize using the time at the OLT as is, the inaccuracy can be handled with very small safety margins. In the second case one needs to take a larger margin into account or alternatively one could measure the distance, or 'range' the OLTs with a more accurate method. Figure 22 illustrates how one can add a margin to the quiet window to accommodate inaccuracies, if this extra margin is acceptable from an overhead point of view. The quiet window must be 1000 µs (round-trip time) to accommodate a 0…100 km PON reach. If the distance between OLTs is exemplarily 10 km this would require an additional 100 µs margin.

The rate at which quiet windows occur must coincide for each wavelength of the TWDM-PON implementation. If we consider the case of including a 10 km margin for OLTs, which are not co-located, then a 1100 µs quiet window is needed for a PON with reach of 0…100 km. Note that a 1000 µs quiet window will anyway be chosen for a 100 km link length (if any are applied), since the quiet window will have to be a multiple integer of 125 µs, because the 8 kHz frame rate has to be preserved for service related reasons. In that case with a quiet window rate of 1 per second the resulting overhead is 0.11% only. In case the quiet window rate is increased to 10 per second the overhead is 1.1 %. Both overhead values are reasonably low and seem to be tolerable.

3.3.2 Auxiliary Management and Control Channel (AMCC)

In general the ONU-Tx wavelength must be aligned properly with the desired US wavelength channel. If the ONU-Tx wavelength is not calibrated during manufacture, the ONU-Tx should be calibrated automatically while starting up. However, during calibration the ONU-Tx must not interfere with US signals in operation. Thus synchronized ranging windows, as introduced above, can be used for ONU-Tx wavelength calibration. Alternatively, another method without the need for ranging windows can be applied, i.e. the auxiliary management and control channel (AMCC), allowing for communication between OLT and ONU. Here, the starting ONU-Tx transmits the AMCC at a low bit rate channel (e.g. 64 Kbit/s or few Mbit/s) with an on-off-keying or even using phase-shift keying modulation, and at a low laser output power level. AMCC is expected to be used with lasers that are coarsely calibrated in manufacture, and with lasers having DS/US filters locked a FSR apart, as proposed in Section 3.1.3. In general, the ONU-Tx wavelength can be also calibrated without synchronized ranging windows or the need for AMCC, but with the requirement of ranging windows on each of the sub-PON wavelengths. Then, a wavelength referencing scheme is required, e.g. using adjacent DS channels as precision references (where DS and US channels are interleaved), as in Section 3.1.3. Note that the various mechanisms can also be combined in case that it seems to be preferable and necessary.

In this section, we focus on the AMCC method. Its advantage is that it is not protocol specific and that ranging windows can be avoided. However this approach suffers from interferometric cross-talk with US ONUs already in operation. The reason to investigate the AMCC within the DISCUS framework is the desire to avoid synchronized ranging windows at start-up, because not only the various wavelength channels of the 10 Gbit/s TWDM-PON system can be active, but also e.g. 100 Gbit/s high speed systems on other wavelength channels that do not offer ranging windows. Of course, a possible solution can be to restrict the maximum ONU laser wavelength operating range by design and manufacturing (typically few nm wavelength uncertainty are possible) and additionally to have a wavelength guard band between the TWDM-PON wavelength and the pre-calibrated high-speed (100 Gbit/s) channels.

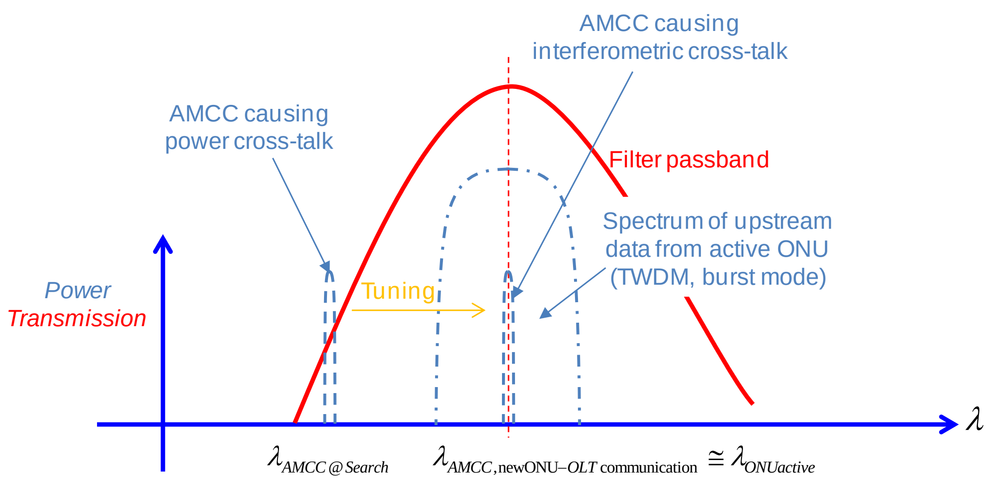

Figure 23. AMCC channel to activate an non-calibrated ONU without ranging windows in a TWDM-PON network (figure modified from TI input).

Figure 23 presents the process for the AMCC. It shows the spectrum of an active 10 Gbit/s ONU laser whose wavelength is well aligned to the filter passband of the wavelength channel under test. The AMCC signal of an ONU in the activation phase can start at any wavelength position in the upstream band (non-calibrated, no control of laser batch and no referencing scheme assumed). The ONU laser carrying the AMCC channel can come up at the filter edge causing power cross-talk into the active ONU channel as well as possibly into neighbouring wavelength channels. However, at such positions the power level of the AMCC channel will be too low to be detected by the OLT-Rx. Here, we assume that either an optical power splitter behind the optical pre-amplifier in front of the M/C switch or an electrical power splitter within the OLT-Rx is used to direct the AMCC signal (at ONU activation) or the 10 Gbit/s signal (at operation) into the separate receiver branches. The selection of optical or electrical splitters for the AMCC and the 10 Gbit/s ONU US signal has to be done related to the modulation format of the signals. In the case that the OLT-Rx is not able to receive the AMCC channel the ONU laser will tune its wavelength slowly until the OLT-Rx is able to detect the signal and the ONU-Rx receive feedback on that from the OLT-Tx. In the case that the ONU laser in the activation phase tuned its wavelength to the filter passband it will interfere with the active ONU laser on the identical wavelength, i.e. interferometric cross-talk is caused. Assuming that the communication between ONU and OLT is successful, the ONU can be ranged by using PLOAM messages in DS and AMCC in upstream. In case, the ONU is granted to become active, it is changing from the AMCC channel mode into the data mode, i.e. transmitting 10 Gbit/s bursts. The exchange of operation and maintenance messages between OLT and ONU and vice versa is performed by PLOAM messages while the ONU is active.

To acquire a basic knowledge of the worst-case scenario in terms of interferometric cross-talk, we perform a set of measurements. Here, we investigate the influence of a low bit rate AMCC channel on the 10 Gbit/s data channel as well as the influence of the 10 Gbit/s data channel onto the AMCC channel.

In our experiments, we first use a test 10 Gbit/s channel operated in continuous mode with a PRBS sequence of 2^{15}-1 generated by a DML which offers an extinction ratio (ER) of 4 dB at the receiver. The “rival” AMCC channel is mimicked by an external cavity laser source which is either modulated with an on-off-keying 101010 bit sequence of 50 kHz or it is left unmodulated. The setup comprises both lasers, individual attenuators in both arms of a 2:2 splitter and the receiver consists of a 15 dB gain and 7 dB noise figure SOA, a Gaussian shaped filter with 100 GHz grid, an APD photodiode and a BER-tester. The alignment of the laser frequency offset relative to the lowest possible offset is measured by an electrical spectrum analyzer (ESA), and the maximum and minimum interference between the channels in terms of polarization is achieved by independent polarization controllers in each splitter arm.

Figure 24(a) shows the power penalty of the 10 Gbit/s signal channel at a BER of 1E-3 as a function of the “rival” AMCC channel power for three cases, i.e. an AMCC channel which is unmodulated and has an offset frequency of about 1.5 GHz compared to the 10 Gbit/s carrier wavelength (black curve), an AMCC channel which is modulated with a 50 kHz OOK modulation and is co-polarized to the signal (blue curve) or orthogonally polarized to the signal (red curve). The receiver sensitivity of the undisturbed 10 Gbit/s OOK signal is about -32.0 dBm at a BER of 1E-3. We allow for a 1 dB power penalty, which requires an AMCC power of -57 dBm in the worst case for OOK modulation and of -54 dBm for the case of the unmodulated carrier (“BPSK-like”). The ratio between the data channel and the accumulated power for the AMCC channels is about 25 dB and 22 dB. However, in case of minimum received power level at the OLT-Rx of -

35 dBm for the 10 Gbit/s, the accumulated power of all AMCC channels has to be in the range of -60 dBm. This power level has to be distributed to the worst-case scenario in which 511 ONUs try simultaneously and on the identical wavelength channel to start-up, i.e. the power level needs to be reduced by 27 dB leading to an AMCC receiving power level per ONU of about -87 dBm (with best case polarization: -75 dBm). These receiving power levels seem to be too low to successfully receive the AMCC channel with an amplified system using 50 GHz...100 GHz wide channel filters at the OLT. However, including additional means on the protocol side can significantly help to reduce the requirements. An interferometric crosstalk mitigation protocol, described in Section 3.3.3, could be used to prevent ONUs, that are starting up and hence transmitting low power data simultaneously, from all colliding within the same wavelength channel at the same time. For example, when no more than 10 ONUs are simultaneously allowed to collide, the requirements for the AMCC channel at the receiver are -70 dBm (max. Requirement) down to -58 dBm (min. requirement). These figures seem to be achievable. To reduce potential collisions, ONUs that enter the start-up phase simultaneously randomly distribute themselves across the spectrum. Using our receiver model introduced in deliverable D4.2 [33], we expect that a receiver sensitivity of about -50 dBm at 155 Mbit/s or -67 dBm at 64 kbit/s at a BER of 1E-3 is achievable for the AMCC channel in case that the identical optical amplifiers, identical optical filters, but just another photoreceiver for the AMCC channel is used compared to the 10 Gbit/s data signal. However, it should be mentioned that these additional measures will cause an increase of the start-up time of the overall LR-PON (see discussions in following sections 3.3.3 and 3.3.4).

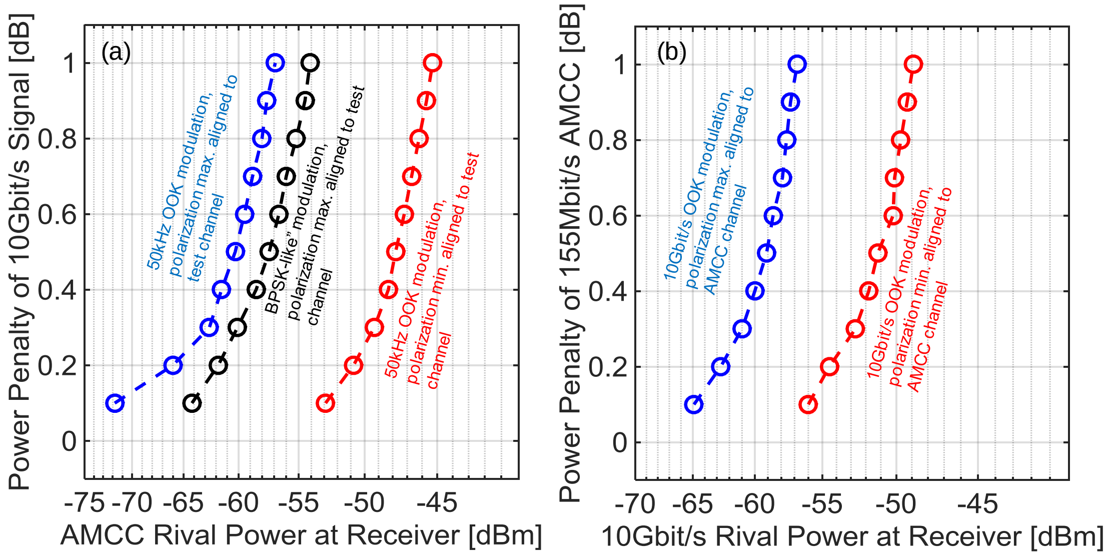

Figure 24. Measurement results for rival channels at start-up. (a) Influence of an AMCC channel on the 10 Gbit/s data channel and (b) influence of the 10 Gbit/s data channel on the AMCC channel.

The influence of the AMCC channel on the 10 Gbit/s data channel, and vice versa, are measured in Figure 24. For our analysis, in this case a 155 Mbit/s AMCC channel is implemented with a DML operated with OOK modulation and an ER of 4 dB. The 10 Gbit/s OOK rival channel is generated by a XFP offering an ER of 10 dB. The receiver sensitivity of the undisturbed 155 Mbit/s OOK signal is -48 dBm at a BER of 1E-3 using a pre-amplifier receiver with a 100 GHz grid

Gaussian filter. In case that we allow for a 1 dB power penalty, the 10 Gbit/s data signal needs to be at a power level of -57 dBm in the worst case situation at the receiver, see Figure 24. This means that the 10 Gbit/s channel has to have a power level which is 10 dB below the AMCC channel. This situation cannot be realized, because the 10 Gbit/s data channel is active (burst-enabled ONU) and has to be received at a minimum power level of -35 dBm. Figure 25 shows the influence of the 10 Gbit/s data signal on the 155 Mbit/s AMCC channel in the electrical domain using an ESA: in (a) the undisturbed AMCC channel is shown and from (b) to (d) the power of the 10 Gbit/s “rival” channel is increased causing significant interferometric cross-talk. The offset frequency is almost 0 Hz. In order to tolerate the active 10 Gbit/s data signal, the bandwidth of the AMCC channel must be reduced. Section 3.2.4 suggests that a data rate of 1.6 bit/sec should be achievable with -70 dBm AMCC channel power (for tolerating 10 simultaneous interferers), and Section 3.3.4.1 suggests 160 bit/sec with -60 dBm (tolerating just one interferer).

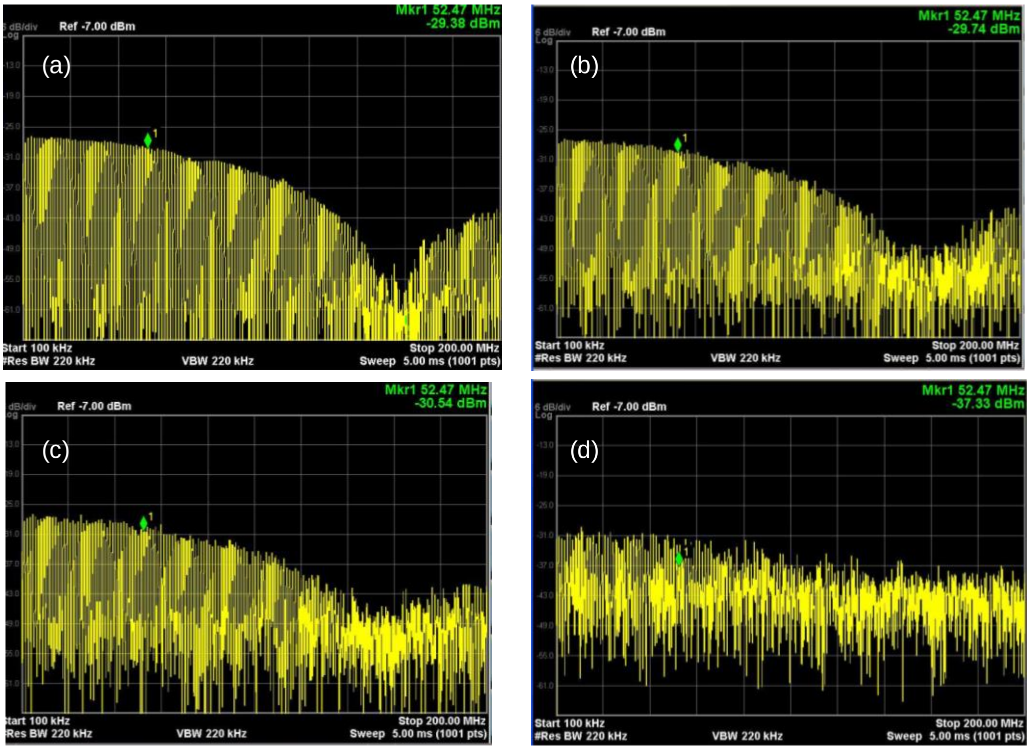

Figure 25. shows the influence of the 10 Gbit/s data signal on the 155 Mbit/s AMCC channel: in (a) the undisturbed AMCC channel is shown and from (b) to (d) the power of the 10 Gbit/s “rival” channel is increased causing significant interferometric cross-talk.

Potential alternative solutions to the above challenge would be to introduce short time gaps [26], [27], or to use quiet windows in which no 10 Gbit/s ONU data signal will be present, and thus the AMCC channels can be measured without disturbance. Section 3.2.5 gives a specific example using 12.5 microsec time gaps in every frame (during start-up), where an AMCC channel data rate of 275 bit/sec might be supportable, for tolerating 10 simultaneous interferers in a 10 Gbit/s channel. But lasers need a 90 dB ON/OFF ratio to achieve this, which may be impractical. Section 3.2.4 estimates that an AMCC channel might be able to operate at 25 Mbit/sec using quiet windows, at a power level no greater than -50.2 dBm, by adapting the interferometric crosstalk mitigation protocol to prevent too many ONUs from colliding in the same time slot within a quiet window. The necessary laser ON/OFF ratio is 70 dB, and 56 Mbit/sec is achievable with 80 dB ON/OFF ratio.

3.3.3 LR-PON Mitigation of Interferometric Xtalk at Start-Up

This sub-section presents a mitigation protocol, to offset the impact of interferometric crosstalk at start-up, by reducing the probability of collisions between activation bursts. Two approaches are given, one without the use of quiet windows for use when ONU laser tuning precision is poor, allowing start-up in the wrong channel, and the other with quiet windows, when tuning precision is good enough to guarantee start-up within the correct channel.

<u>Without Quiet Windows at Start-Up</u>

On start-up, an ONU attempts to tune its laser to an intended wavelength channel. Initial tuning precision could be poor, such that it transmits in the wrong wavelength channel. If LR-PON and non-LR-PON channels share the same waveband, for flexibility reasons, there might be no quiet windows in this channel (non-LR-PON protocol). But even with separate wavebands, if quiet windows are not synchronised across the LR-PON channels, the quiet window start times will be unknown to the ONU. Without the use of quiet windows, the ONU's laser power level must be reduced at start-up, to prevent excessive interferometric Xtalk into the working channel. The presence of this transmission must be detected at the OLT, and individual ONUs identified so they can be individually controlled for precise tuning. But there could be a number of ONUs all starting up and transmitting at the same time. A protocol is required that can prevent multiple ONU bursts from colliding with each other in the same time slot, to maximise the probability of successful detection of all of them.

A dynamic time and wavelength assignment (DTWA) mitigation protocol is described, for use in a low power, low bandwidth channel, or set of channels, to mitigate the effects of interferometric Xtalk, by reducing the probability of collisions. ONUs randomly choose a time slot and wavelength channel in which to transmit their start-up request, e.g. serial number response. Variants of the protocol are described using different combinations of numbers of wavelength channels, time slots per channel, total number of time slots across all channels and numbers of rounds of attempts.

Furthermore, by operating away from DC, e.g. around 1 MHz, it becomes possible to employ multiple sub-carrier frequencies as well as wavelength channels, i.e. time, frequency and wavelength. But a greater number of low power signals P would then interfere within a wavelength channel. An initial analysis suggests that the reduction in power level P, needed to ensure the same outage probability of the working signal P_S as calculated below, requires a greater reduction in the low speed data channel rate, than would be offset by the reduction in the true number of physical time slots needed when multiple frequencies are employed. This suggests that a net increase in protocol run times might result when using sub-carrier frequencies. Further detailed studies would be needed to confirm this.

The mitigation protocol, using time and wavelength domains alone, achieves very low probability of interferometric crosstalk impairing a working channel, even if all 1023 ONUs are attempting to register simultaneously. This itself is believed to be extremely unlikely ever to happen during the lifetime of a LR-PON, except perhaps on first installation, when it first goes live. But this is a special situation that could be planned for. Furthermore, even if all 1023 ONUs attempt to register simultaneously, and their tuning precision is so poor (e.g. +/- 50 GHz) that they could be centred in wrong channels, the likelihood that all ONUs will be tuned to the same wrong channel, and to within the electrical passband of the channel, so that interferometric Xtalk occurs, is highly unlikely. It is in all likelihood unnecessary to safeguard against such an extreme possibility.

Nevertheless, similar precautions are taken in G.987.3, using random delays to reduce the probability of collisions due to multiple serial number responses arriving at the same time. So a protocol can be implemented to ensure that such an extreme scenario can never happen, and which can also be tailored to any expected smaller number of simultaneous interferers. The proposed protocol has some similarity to the random delay, back-off procedure, for serial number acquisition and ONU registration in the XG-PON protocol, but in this case the ONUs choose randomly between a number of time slots, which can be distributed across a number of wavelength channels. This is a form of blind re-tuning, but across multiple wavelengths and time slots, rather than towards the desired wavelength channel. It is more controlled than if each ONU were simply trying to tune to one particular wavelength channel, so perhaps not tuning very far away in wavelength during the process. The mitigation protocol could make use of the entire available spectrum. Use of multiple wavelengths reduces the total time needed to implement all the time slots in the protocol. ONUs transmit at low power level, so that the working channels do not need to implement quiet windows for initial registration, and can continue working. If successfully detected, and the ONU identities (e.g. serial numbers or other identities) are received correctly, they will receive acknowledgement (e.g. ONU-ID) via their correct downstream channel (which they have previously tuned to). Unsuccessful ONUs will back off, i.e. in this case randomly choose a different time slot, possibly in a different wavelength channel, and try again in a subsequent round of attempts. Even in the above very worst case of 1,023 ONUs all attempting to register simultaneously, the probability of more than a small defined number of ONUs attempting to register in the same time slot, and consequently in the same wavelength channel, can be made very small.

To detect an ONU burst from a laser with poor coarse tuning precision of +/- 50 GHz, the wavelength channels used at low power and low bandwidth must be wider than the normal working channels, e.g. 150 GHz. This implies a different wavelength demultiplexer, or set of optical filters, to the working channels, using an optical tap. In this example, one low power/bandwidth channel contains 3 working channels of 50 GHz spacing.

Let there be a total of T time slots (1023), which could be distributed amongst a number of wavelength channels (e.g. 10 and at most ~32 in this example), so that the total number of time slots T available to choose randomly across the entire spectrum equals the total number of ONUs on the LR-PON, N. In a given round of registration attempts, the probability that k ONUs out of n ONUs taking part in the round are randomly attempting to register in a given one of the T time slots, i, is given by the Binomial distribution, i.e.

$$\Pr ob(k) = \binom{n}{k} p^k . (1-p)^{n-k} \qquad ...(19).$$

where p=1/T is the probability that a given ONU chooses time slot i.

Figure 26 shows the probability that k ONUs are attempting to register in time slot i, of 1,023 available time slots, in each round of attempts. In round 1, all 1,023 ONUs are simultaneously attempting to register on the LR-PON. The probability that precisely k=1 ONU is attempting to register is 0.368. Only k=1 results in successful registration. k=0 is unsuccessful because no ONUs are present, and all k≥2 are unsuccessful because of ONUs colliding. In practice, unlike serial number acquisition in XG-PON, the ONU burst duration at low bandwidth exceeds the RTT, so it is not possible for more than one ONU burst to be detected successfully within the same time slot; multiple ONU bursts will always overlap in time. Therefore, in the first round of registration attempts, 0.368xT=376 ONUs out of 1,023 can successfully register. The remaining 647 attempt to register in a second round. The number of ONUs successful and remaining in each round is also shown for each round. Thus, even if all 1023 ONUs begin to attempt registration at the same time, they should all be successfully registered in just 6 rounds. N.B. These are expected numbers, on average.

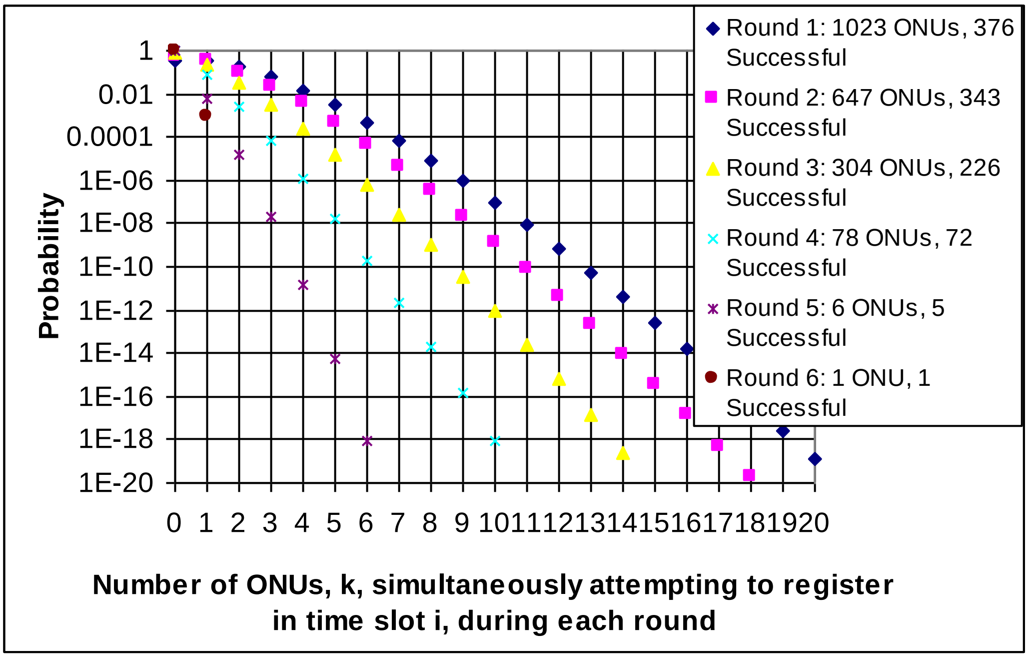

Figure 26. Probability that k ONUs are attempting to register in time slot i, of 1,023 available time slots, in each round of attempts.

This protocol enables all 1023 ONUs to attempt registration simultaneously, while preventing them all, or at least large numbers of them, from causing interferometric crosstalk into the same wavelength channel. Table 2 shows that the power reduction need be just -33.1 dB, if up to 10 interferers are tolerated in the same wavelength channel. Figure 26 shows that the first round of attempts dominates the probabilities. The probability that more than 10 ONUs interfere simultaneously in any time slot is 9.61×10^{-9}. Because there are 1023 time slots, the probability that any time slot will suffer impairment due to interferometric crosstalk in the first round is 1023x9.61x10^{-9} = 9.83x10^{-6}, even if all 1023 ONUs attempt to register simultaneously. Over all 6 rounds the probability is 9.92 x10^{-6}. This is the worst-case probability of a working channel outage (see Table 4). But the probability of all start-up ONU laser wavelengths overlapping interferometrically in the electrical bandwidth of the same working channel is quite low. So in practice, the probability of a working channel outage would be lower than this worst case.

The power reduction of -33.1dB, to accommodate up to 10 simultaneous interferers, results in a data rate reduction from 10 Gbit/sec in the working channels to 1.6 bit/sec in the low power/low bandwidth channels (section 3.2.4). The ONU burst length on start-up is assumed to be 16 bytes long, which is more than sufficient to contain a 10-bit burst header, one of hundreds of billions of different serial numbers and 10-15% FEC overhead. Therefore the time slot duration needs to be 16x8/1.6 = 81.0 sec, for 1023 ONUs starting up simultaneously. If any working wavelength channel suffers impairment, i.e. an outage, due to interferometric Xtalk caused by ONU clashes, throughout the entire 6 rounds of the protocol, this is the duration of that outage.

Assuming time slots are distributed between 10 low power/low bandwidth wavelength channels, the total time to complete 6 rounds is 6x103x81 = 13.9 hours. With 32 low power/bandwidth channels it would take 4.3 hours (see Table 4. These times are perhaps consistent with those needed on first installation of the LR-PON, if the network operator wishes to complete an automatic start-up of the entire LR-PON within a day.

Maximum Number of ONUs	Number of Protocol Runs	Working Channel Outage Probability: Worst Case	Working Channel Outage Duration	Start-Up Protocol Duration per Run
10	103	0	0	8.1 min
32	32	2.1x10^{-6}	81.0 sec	8.1 min
128	8	7.2x10^{-6}	81.0 sec	32.4 min
512	2	9.5x10^{-6}	81.0 sec	129.6 min
1023	1	9.9x10^{-6}	81.0 sec	259.2 min

Table 4. Working channel outage probabilities due to ONU collisions, outage durations and start-up (registration) protocol durations for increasing maximum numbers of ONUs expected to start up simultaneously.

After first installation of the LR-PON, many ONUs may already have been registered (and tuned), but not all will have been purchased and installed. This will occur from time to time, but it is unlikely that large numbers of ONUs will start up simultaneously. Table 4 gives the estimated working channel outage probabilities throughout the lifetime of the LR-PON, outage durations and start-up protocol durations, as a function of the maximum number of ONUs expected to start up simultaneously. Obviously, for no more than 10 ONUs starting simultaneously, there is never any working channel outage, because the system is designed to tolerate interferometric Xtalk from 10 ONUs. All working channel outages last for 81.0 sec., i.e. one time slot duration. The start-up protocol duration for each run is 8.1 min. for up to 32 ONUs expected to start up simultaneously. This is because each time slot is assumed to use a separate low power/bandwidth channel, so that only 1 time slot is required per round, and each run requires 6 rounds. Beyond 32 ONUs expected, no more low power/bandwidth channels are available (assuming they span 96 working channels over 38 nm), so the number of time slots per round increases. The number of protocol runs represents the number required to register all 1023 ONUs, assuming that the worst situation is where they are spread over the smallest possible number of runs, consequently generating the highest possible outage probabilities.

The very worst-case working channel outage probability of 9.9×10^{-6}, which is for 1023 simultaneous ONUs, corresponds to just 1 LR-PON out of ~100,000 LR-PONs (or 51.2 million homes and businesses) causing one 81.0 sec outage of 1 working channel during the lifetime of all ~100,000 LR-PONs. This is an acceptable outage probability.

It is not so likely that those network operators, who believe it necessary to safeguard against as many as 1023, 512 or even 128 ONUs starting up simultaneously, after first installation, would accept the corresponding 4.3hr, 2.2hr or even 0.54hr start-up (registration) protocol run durations.

Using Quiet Windows at Start-Up

When ONU laser tuning precision is good enough to guarantee start-up in the correct wavelength channel, to within +/-10-15GHz, a low power/bandwidth transmission speed of 25.0 Mbit/sec is expected to be possible (Section 3.2.4) for activation, assuming that all ONUs not attempting to activate within the same quiet window can be turned down by an ON/OFF ratio of at least 70 dB below the full working power level.

Assuming the same ONU burst length on start-up as at 1.6 bit/sec, i.e. 16 bytes, the duration of each protocol time slot at 25.0 Mbit/sec is 5.12 μsec. This is approximately one tenth of the random delay of 48 μsec used for serial number acquisition in G.987.3 [1], so it should be quite acceptable to employ 10 protocol time slots within a quiet window. For a LR-PON with 125 km differential fibre distance, the quiet window would need to be 1.3 msec in total duration, adding the 1.25 msec for the variation of round-trip propagation delay and 2 μsec for variation of ONU response time. Therefore a round of the start-up protocol will take 103 quiet windows to complete (if 1,023 ONUs are yet to start up), and the protocol run of up to 7 rounds will take 721 quiet windows.

The mitigation protocol cannot allow ONUs to attempt to start up in every quiet window. Each ONU randomly chooses only one time-slot in which to transmit in each round of the protocol. Furthermore, any ONU wishing to start up must wait for the beginning of a complete mitigation protocol run of 721 quiet windows, before bursting. It is allowed to burst in as many rounds as necessary to be successfully detected. The LR-PON protocol must signal downstream to all ONUs the start of a new protocol run, and new ONUs must wait for this signal, before transmitting in their randomly chosen quiet windows and time-slots within them.

If quiet windows are opened for this purpose once a second, each protocol run will take 12.0 minutes, and 8 runs at different power levels will take 96 minutes. This could be reduced to 9.6 minutes if quiet windows are opened every 100 msec. The resulting bandwidth inefficiency of 1.3% is quite acceptable when such large numbers of ONUs are all starting up simultaneously. Indeed, even more frequent quiet windows could be used, as no ONUs are yet active. The protocol run time could be reduced by a factor 3 by extending the quiet window by just 102 μsec to 1.4 msec. The maximum delay experienced by any ONU attempting to start up would be 2x9.6/3 = 6.4 minutes. As the number of ONUs yet to start up reduces, the number of time slots required per protocol run reduces in proportion, as do the overall protocol run times.

3.3.4 Tuning and Power Levelling Procedures

The following tuning and power levelling procedures combat interferometric and linear Xtalk, at start-up (activation, registration and tuning), in normal operation (in-service continuous monitoring & tuning of ONU laser & filter) and when changing channel, for poor tuning precision, the preferred solution of local wavelength referencing, and for the fall-back solution of feedback control from the OLT. They also take into account the traditional type of power levelling needed to accommodate differential reach at start-up and normal operation.

3.3.4.1 Poor Tuning Precision

Raising Power Level to Register at Low Power/Bandwidth

At start-up, an ONU in the wrong wavelength channel attempts to register at low power level, using the mitigation protocol in section 3.3.3, before it can be fine-tuned. If the ONU's transmission is not detected at the initial low power level (P_{max} – DR), e.g. if it's loss to the first amplifier is at the high end of the LR-PON dynamic range (12.7 dB for 1024-way split from Table 3), the ONU will raise its power level incrementally, until it can be detected. This might be achieved in e.g. 2 dB steps, so that after a number of attempts, the power level lies within the dynamic range of the BMRx. This could take 8 attempts, increasing the start-up protocol durations in Table 4 8-fold, to 64.8 mins for up to 32 ONUs starting up simultaneously.

However, if the ONU is not detected successfully, when at a power level that should be detectable, due to collisions with one or more other ONUs transmitting in the same time slots in every round of the mitigation protocol, then it will increase its power level even higher and cause an outage in the working channel. There is no way to communicate with the ONU to prevent this. If the probability in a mitigation protocol run of not successfully registering the ONU is too high, its power level would have to be prevented from rising too high, by adding the 12.7 dB dynamic range of the LR-PON to that of the BMRx. Unless the Time-Gap method of Telecom Italia and Polytechnic University of Turin could be used (Section 3.2.5), which seems unlikely, this would require the low bandwidth B' to be reduced even further to 3.4×10^{-3} Hz, causing ~290-fold increase in start-up protocol duration. Fortunately this is not necessary, because the probability of not registering the ONU in a protocol run can be reduced to any desired level by increasing the number of rounds. 7 rounds are believed to be sufficient.

Therefore, it can be made sufficiently safe for the ONU to increase its power level incrementally, until it is detected successfully. But if the ~8-fold increase in start-up protocol duration is not acceptable, for any of the maximum numbers of ONUs expected to start up simultaneously in Table 4, then the only other option that can be considered, from the full range identified in Figure 17, is a single network operator's high power/bandwidth isolated channel.

A single network operator must provide one LR-PON wavelength channel that is isolated from all other wavelength channels, e.g. at one end of the wavelength window. The spectral gap should most likely be 150 GHz, i.e. missing out two wavelength channels. All ONUs must transmit their serial numbers upstream in this isolated channel, which can be considered as the correct wavelength channel, so can transmit at the full 10 Gbit/sec LR-PON speed.

Raising Power Level to Register at High Power/Bandwidth

At start-up, an ONU with poor coarse tuning precision, potentially in the wrong wavelength channel, and therefore using either synchronized quiet windows or a single, high power/bandwidth isolated channel under the control of the network operator, can be allowed to attempt to register during a quiet window. The ONU's power level can be raised incrementally until it is successfully detected at the full 10 Gbit/sec speed. This might take up to 8 attempts to register at different power levels. The number of quiet windows required per attempt is essentially equivalent to the number of rounds of the mitigation protocol. If, for example, a serial number acquisition window is opened once per second, it will take a number of seconds for an ONU to be detected successfully, with an acceptably low probability of being unsuccessful. It is believed that this can be rendered astronomically low within 10 to 20 seconds. 8 attempts should therefore take no longer than a few (1.3-2.7) minutes to register. Of course the laser wavelength at each power level may be different (within say +/-100 GHz), so that successful activation could occur in any of several nearby wavelength channels when using synchronised quiet windows, or within a much wider wavelength passband (say 200 GHz wide) when using the network operator's single, high power/bandwidth isolated channel.

Fine Tuning and Power Levelling

After successful registration, fine tuning and, for ONUs that have registered at low power/bandwidth, power levelling to full operational power P_S are required. Fine tuning might need to be performed first (certainly for poor tuning precision), before raising power level to P_S. This is to prevent interferometric and linear Xtalk problems into the adjacent channels, or within the correct channel.

If the ONU started up in the wrong channel (due to poor tuning precision), then for the OLT to control tuning and power level, it must first be made aware of the destination channel identity. One option is for the ONU to transmit its desired channel's identity to the OLT, when the OLT grants an ONU burst at low power in one of the low bandwidth channels. This burst would last for just one time slot (81.0 sec). If all 1023 ONUs have started up simultaneously, and there are 32 low power/bandwidth channels, all 1023 would take another 43.2 mins to transmit this information. Alternatively, all ONUs could first start up in a default LR-PON, owned by the network operator. Once full communications are established there, the SDN control plane could control new connection requirements.

Of course the most severe power level reduction is required with poor coarse tuning precision into the wrong channel, when tuning through working channels to reach the desired one. Although the transmitter's SOA is turned off while the laser is tuned, so the laser is not swept across the channels, it could appear in a working channel when the SOA is turned on. But if the OLT tunes only one ONU at a time through working channels, higher power levels P_{max} can be tolerated than for serial number acquisition, as there would be no more than k=1 interferometric interferer. With working signal sensitivity level $P_{S,sens}$ = -33.3 dBm (for 1 dB penalty), the maximum allowed power for 1 interferer is P_{max} = -60.3 dBm, and the minimum possible is P_{min} = -64.3 dBm. This is only ~10 dB higher power than with 10 interferers. But it would allow the low bandwidth B' to rise to ~120.1 Hz (≡ 160.1 bit/sec), i.e. 101 times faster than during serial number acquisition. This increase is possible if there are still ONUs unregistered, because the registration mitigation protocol is not run at the same times as tuning and power level measurements. Far higher values of P_{max} and B' would be possible for DISCUS' fall-back solution in Section 3.3.4.2.

For an ONU with poor tuning precision into the wrong channel, the OLT instructs the ONU to raise its power level by ~10 dB to a level producing at most –60.3 dBm at amplifier input. In order to check the power level, the ONU is then instructed to transmit one burst. It would be beneficial if the duration of this burst needed to measure the power level, and all others at this level, could be further reduced, by transmitting less than the 16 bytes used for serial number acquisition. Nevertheless, for the duration of 16 bytes at 160.1 bit/sec, a power measurement of one ONU would take just 0.8 sec. In the worst case, if (nearly) all 1023 ONUs need initial tuning to the same working channel, their power levels must be measured sequentially, and it would take ~1023x0.8 = 818 sec = 13.6 min to make one power measurement on every one. It is expected that ~10 tuning steps may be needed for fine tuning, each using a power level measurement. So the total time to tune 1023 ONUs could be as much as 2.3 hrs. This is far less than the 34.6 hrs for serial number acquisition and raising power levels initially. For DISCUS' fall-back solution with +/-10-15 GHz coarse tuning precision, far shorter tuning times are possible (Section 3.3.4.2).

One approach for the OLT to tune ONUs is not by measuring wavelength directly, but by measuring the power level received through a wavelength demultiplexer channel, and sending +/- $\Delta\lambda$, i.e. wavelength shift, instructions to the ONU. But unfortunately, tuning the laser can cause its power level to change, and altering the power level can cause its wavelength to shift. The two are interdependent. Therefore a power level measurement made through a wavelength demultiplexer channel would be unable to distinguish between power changes due to wavelength tuning and those due to resultant laser power level changes. A potential way of unscrambling this interdependence would employ two measurements at the OLT. A low power and low bandwidth Rx is used, as for start-up, that can detect in the presence of a high power, high speed signal, over a spectral range with a flat spectral response. This allows the true change of power resulting from tuning the laser to be measured. This information is used to correct the power level change measured through the demultiplexer passband, to obtain the true change due to tuning alone, up and down the demultiplexer slope. Thus laser power level and wavelength tuning can be correctly controlled by the OLT.

An alternative approach would be to use a wavelength discriminator at the OLT. But there are various issues with the 2 section wavelength monitor as proposed in Figure 11, when used at the OLT. The major one is polarisation dependence. Non-linear behaviour could also be an issue with a second high power signal present. Other open questions include relative and absolute precision and temperature dependence. Another solution would be to use a wavelength locker (an FP etalon for example), but that would have the same issues as the Gaussian shaped filter in terms of power/wavelength interdependence. Other types of channel/wavelength monitor would be too slow for this application, as they tend to "scan" the wavelengths one by one (using various methods), similar to a spectrum analyser.

Further study is needed to determine precisely how to control the raising of the power level from between -73.0 dBm and -60.3 dBm to P_S = -33.3dBm (as measured at amplifier input). This is only 27dB. But the poor tuning precision means that the laser could be tuned to the wrong channel as power level is raised. Furthermore, it certainly cannot be raised to full power, unless the ONU is actually scheduled an ONU burst by the LR-PON's bandwidth map. This cannot be done until a sufficiently high power level is reached, where low power Rx measurements are no longer needed. A method of spanning this power level gap is needed, that still guarantees wavelength tuning precision. A possible solution could be to insert an ON/OFF attenuator after the laser, as suggested in Section 3.2.5 for start-up in quiet windows, which has no effect on laser wavelength. The fine tuning achieved under feedback control from the OLT at -60.3 dBm would then be maintained when the attenuator is switched ON.

3.3.4.2 Fall-Back Solution: Feedback from OLT (separate US/DS λ bands)

The DISCUS fall-back solution assumes good tuning precision into the correct channel (e.g. +/-10-15 GHz). The fall-back solution also assumes that lasers are calibrated at one power level per wavelength only, to reduce laser costs. The laser's tuning precision at this power level is transferred firstly to the Tx tuneable filter in the ONU (Figure 9), by tuning this locally in the ONU to be centred on the laser wavelength. Holding the filter at this wavelength, the tuning precision is then transferred back to the laser when its power level is raised, to correct any resulting shift in wavelength, by tuning the laser locally back to the centre of the filter passband. Thus the tuning precision can be maintained at all power levels, from a single calibrated level. Therefore wavelength shifts due to power level changes need not be corrected by feedback control from the OLT during start-up (activation/registration), but locally in the ONU. Further detailed procedures are described in Section 3.2.5 for start-up in quiet windows, and for raising power level from -50.2 dBm to -33.3 dBm during start-up. Of course feedback control from the OLT will be necessary for fine tuning and perhaps fine power levelling at operational power level. These are also discussed in Section 3.2.5.

3.3.4.3 Preferred Solution: Local Wavelength Referencing/Calibration (interleaved DS/US channels)

For local wavelength referencing and calibration, using interleaved DS/US channels, it is expected that the tuning precision could be as good as $\Delta\lambda$ = +/- 5 GHz. This is also expected to be within the 1 dB bandwidth of the wavelength demultiplexer passband. With the preferred Tx structure of Figure 11 (Section 3.1.2), tuning the laser is not expected to change the power level, and vice versa. The good tuning precision and low demultiplexer loss are expected to make finer tuning unnecessary. So feedback control would not be needed for tuning. Therefore just power levelling may be needed. But feedback control of power levelling would not be necessary, if the probability of successful activation at each power level is guaranteed to be extremely high, as discussed in Section 3.3.4.1.

Furthermore, ONU activation (start-up) can employ quiet windows at full working power level of -33.3 dBm, if the adjacent channel crosstalk of the wavelength demultiplexer can be guaranteed to be ≥ 29 dB. This will allow the adjacent channel to remain uninterrupted, in the presence of interferometric crosstalk from 10 ONU lasers attempting to start up in the same time slot within a quiet window. This can be guaranteed by the ≥30 dB non-adjacent channel crosstalk of 50 GHz-spacing AWG demultipexers, when US and DS channels are interleaved, i.e. when adjacent US channels are 100 GHz apart, representing non-adjacent channels in the demultiplexer.

4 Protocol Implementation in FPGA Hardware

In this section we outline the LR-PON protocol implementation on FPGA. The protocol hardware was initally targetted to run on Xilinx 10G NetFPGA boards [34], but after some testing it was found that the 10G NetFPGA boards were unsuitable for the raw PON data as they had hard wired phy layers attached to all of the 10G ports. During year two of the DISCUS project the Xilinx VC709 board [35] became available and the PON protocol hardware was retargetted at the VC709 boards. Unlike the NetFPGA boards the VC709 board implemented the 10G phy layer on the FPGA and so the channels could be controlled to allow 10G raw LR-PON data to be transmitted over the 10G ports. To enable the use of this board for LR-PON protocol testing we implemented an interface layer between the various physical components of the board and the LR-PON protocol as shown in Figure 27. The interface layer is primarily used to enable communication between external components and the LR-PON protocol hardware. It consists of the data backplane, the PON physical layer interface, the tunable laser/filter control interface, the control plane interface and the PON component controller.

The data backplane consists of a 10Gb Ethernet PHY layer and MAC which is connected to one of the four SFP+ cages on the VC709 board. All data to be delivered or that has been received is forwarded to the core architecture via this link. The PON physical layer interface is used to pass the PON data from the LR-PON protocol to the PON phsical layer over one of the 10G SFP+ interfaces. The data on this link is encoded by the LR-PON protocol and is forwarded between PON components without any further encoding/encapsulation. Data from this interface is therefore in the raw PON format. The tunable laser/filter control interface is used for DWA operation on the PON. The tunable laser is controlled across a i2c bus and the tunable filter is controlled over a labview interface. The details of this interface differ depending on whether the system is running off-the-shelf laser/filter components or the DISCUS components. The control plane interface will be discussed in detail in Section 4.4. The control plane interface allows the LR-PON to be managed in a dynamic way using openflow type commands. Finally the PON component controller is a microprocessor which is used to orchestrate/manage all of these individual components. It is used primarily to setup experimental scenarios and to provide feedback so that various apects of the LR-PON protocol can be tested and demonstrated.

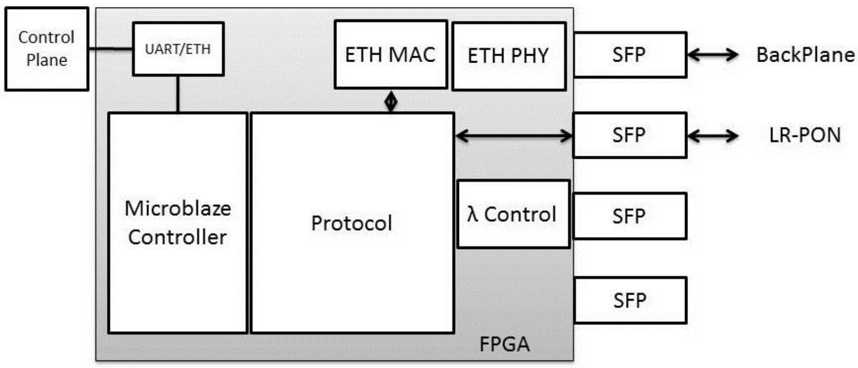

Figure 27. FPGA framework for LR-PON protocol hardware

4.1 LR-PON Protocol

The LR-PON protocol is based on the XG-PON standard [1]. The XG-PON standard has a number of advantages over the G-PON standard. Firstly it allows for 10G symmetric data channels. Secondly XG-PON addressed a number of limitations in the G-PON standard that slowed down the activation process. The XGPON standard allows for multiple PLOAM messages per frame in the downstream direction and this greatly improves the activation time when two or more ONUs require activation at the same time [36]. The major difference between LR-PON and XG-PON is that the LR-PON protocol's TC layer must work over a longer maximum fiber distance (125km in LR-PON as opposed to 60km in XG-PON1) and across a higher split ratio. XG-PON is designed to be deployed to 128-512 customer premises whereas LR-PON would be shared between up to 1023 customers to help reduce the overall network installation costs.

The LR-PON protocol hardware includes both an OLT implementation and ONU implementation. The design is logically broken into three distinct layers as described in the XG-PON standard. These layers are the Physical Adaptation layer, the Framing Sublayer and the Service Adaptation Layer. Each layer contains multiple components responsible for various aspects of the LR-PON functionality. Figure 28 is a block diagram of the LR-PON protocol hardware setup for the OLT and ONU.

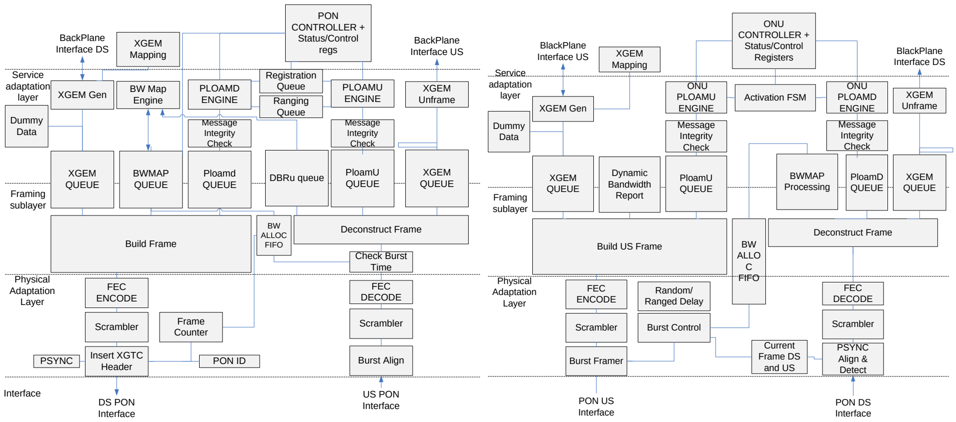

Figure 28. Block Diagram of OLT and ONU hardware implemented on FPGA

The physical adaptation layer of the PON hardware is responsible for ensuring the PON data is reliably sent and received between the OLT and ONU. In the downstream direction it creates the GTC frame structure and in the upstream direction it controls the burst frames structure. This layer places a sychronisation word at the beginning of each frame to ensure data alignment on the PON. In the downstream direction it also adds a PON ID tag and a frame counter which allows the ONUs to identify the connected OLT and ensures the ONUs are synchronized downstream respectively. In the upstream direction it ensures that data bursts from the ONU meet the requirements of the PON's burst profile message received at activation. The PON data is also scrambled to aid clock recovery and FEC is applied to the data to ensure reliable transmission. In this implementation we have omitted the HEC signing of the frame counter and PON_ID. These are included in the XG-PON standard to ensure this data is recieved correctly. However, as they have no effect on the LR-PON timing and little effect on the overall operation of the PON we have chosen to omit HEC from the LR-PON FPGA implemenation. In the upstream direction the physical adaptation layer is also responsible for generating the burst envelope for the ONU upstream transmissions.

The framing sublayer is responsible for muxing and demuxing the various components of the data frames, these are the bandwidth map, the PLOAM messages and the XGEM data in both the upstream and downstream directions. The bandwidth map contains precise instructions as to when each ONU can send data bursts upstream. This ensures that only one ONU uses the upstream channel at any time thus avoiding contention issues. PLOAM messages are management messages sent between the OLT and ONU to pass vital operational information about the PON. The XGEM data is the user data being transported on the PON.

The Service adaptation layer is responsible for translating data from the backplane network data structures (Ethernet frames) to data structures used on the PON or vice-versa. Data being transported on the PON needs to be translated and encapsulated into PON data structures called XGEM frames. To do this the ethernet frame headers and preambles are removed. All VLAN and MPLS tags are removed. The data in these tags together with the destination address is used to address the XGEM frame to a specific XGEM Port within a specific ONU on the PON. The protocol has been designed to allow for 1023 ONU-IDs to be registered on the PON. Furthermore, it allows up to 16,384 separate XGEM ports/T-CONTs to be addressed. For simplicity we have used a one-to-one mapping between XGEM ports and T-CONTs. This allows us to demonstrate different levels of service without overly complicating the FPGA hardware implementation. Furthermore, in order to simplify the FPGA implementation and to ensure space on the FPGA for DBA implementations and DWA implementations we have opted to limit the number of XGEM ports in each ONU to 8 and in the OLT to 16. Increasing this number could be achieved by using offboard memory however for simplicity of implementation for the LR-PON protocol prototype we have opted to use onboard memory.

The PLOAM engine is also in the service adaptation layer in this implementation. The PLOAM engine is responsible for creating and interpreting the PLOAM management messages on the PON. PLOAM messages are generally used by the OLT to setup and maintain the ONUs on the PON. Currently the PLOAM engine can send and interpret all messages needed for activation, ranging and we have added a new PLOAM message to the protocol for DWA which will be discussed in Section 4.3.

The service adaptation layer also contains the Activation finite state machine (FSM) in the ONU unit. This state machine ensures that the ONU goes through full activation before becoming active on the PON. To get to the operational state the ONU must first synchronize to the downstream data. The ONU must then wait until it receives a burst profile PLOAM which is periodically sent by the OLT. This PLOAM message contains details of how the OLT expects upstream transmissions to be formatted on the PON. Once the burst profile has been received the ONU must wait for the OLT to initiate an activation cycle. Since the OLT does not know when a new ONU might come online it periodcially creates a break in upstream transmission and invites new ONUs to send their serial numbers in a PLOAM message. It does this by sending a broadcast bandwidth map entry. All new unregistered ONUs reply to this message and so collisions can occur. To reduce probability of collisions all new ONUs wait a random time before sending a burst upstream containing their serial number. The OLT responds to all successful serial number PLOAMs by sending directed registration PLOAMs that register the ONU on the PON and give it an ONU-ID. The OLT then ranges the ONU to ensure that it is synchronized with all other ONUs on the PON. The ONU is now in the operation state and is ready to receive traffic.

In the event of a failure of the OLT or of the fiber on the PON the ONU does not return to startup straight away. Instead it enters a temporary loss of synchronisation state where it waits for 100ms or until downstream synchronisation is restored. It is during this time that the backup OLT can take control of the PON without needing to register and range all the ONUs again.

The DBA engine responsible for creating and interpreting the Bandwidth Map also resides in the service adaptation layer in the implementation. This block will be discussed in Section 4.2.

4.2 DBA

The current FPGA implementation does not include a fully functional DBA engine, however, a version of the DBA is planned for implementation before the end of the project. The current LR-PON protocol hardware does create bandwidth maps in each frame and all ONUs attached to the PON adhere to the bandwidth map for upstream bandwidth. The bandwidth map is not influenced by the real time needs of the ONU. Instead, the control plane can set the bandwidth allocation for any given ONU and this bandwidth allocation will be served to the ONU in every upstream frame. This equates to a variable fixed bandwidth implementation and has been implemented to ensure that control plane features can be demonstrated over the PON.

The more realistic DBA that has not yet been implemented will allow the control plane to set the maximum assured bandwidth allocation and the ONU will report queue occupancy in the dynamic bandwidth report upstream. The OLT will then use this information to calculate the next round of bandwidth maps for the PON.

4.3 DWA

The LR-PON protocol has been designed to natively work in a DWA environment. This has been achieved by adding laser and filter control to the LR-PON protocol hardware and control mechanisms. Each LR-PON OLT/ONU unit can be dynamically switched between wavelengths using a new integrated handshaking mechanism added to the PON protocol.

At any time an OLT unit can be tuned to a given wavelength by requesting a DWA tuning over the control plane (discussed in more detail in Section 4.4). Upon seeing this command the OLT will retune its transievers to the given wavelength. Tuning the ONU is a little more difficult as it does not have a direct connection to the control plane. The correct OLT must relay the message to the ONU. To achieve this we extended the LR-PON protocol by adding a DWA PLOAM message to the OLT. If the control plane requests that a given ONU migrate to a different wavelength the OLT passes this information in the form of a PLOAM message over the PON. The message contains the time that this wavelength switch should take place. This time must be far enough in the future to allow the message to traverse the PON and for the ONU to acknowledge the message. Once the ONU see the DWA PLOAM message it acknowledges the message via a new upstream PLOAM message. At the agreed time the ONU switches wavelength and waits for an activation cycle on the new wavelength to begin. The orginating OLT then removes the ONU from its active ONU list and informs the Control Plane. If the ONU cannot activate on the new wavelength before a customisable timeout it returns to the original wavelength and reactivates on the original PON. Figure 29 shows the order of this message passing over the PON.

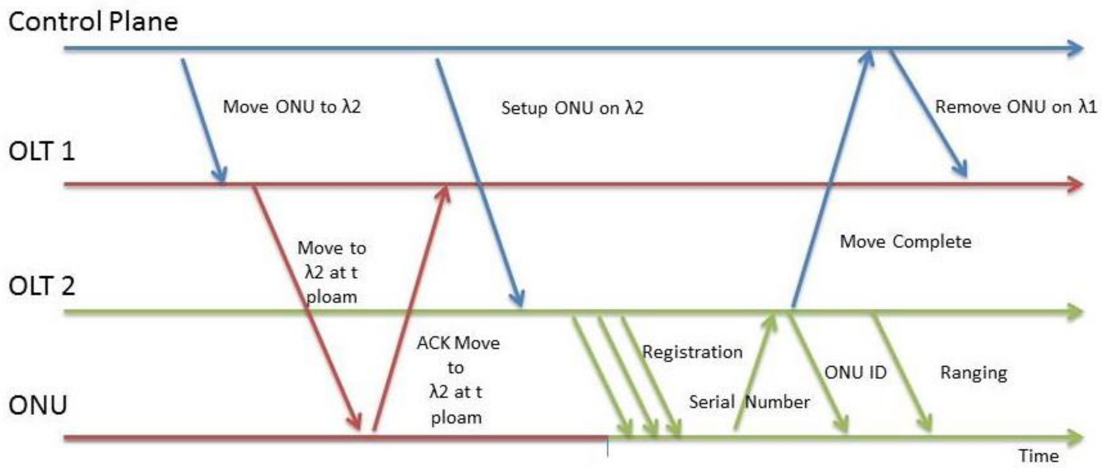

Figure 29. DWA handshaking mechanism in the LR-PON hardware implementation on FPGA

4.4 Control Plane

As described in DISCUS deliverable D6.3, the FPGA LR-PON implementation includes an access control plane interface to demonstrate various service scenarios of interest to the DISCUS consortium. The Access Network controller uses openflow to manage the various network components in the access network, such as the optical switch, access switch and PON components. To allow the FPGA hardware to be controlled using openflow commands we have developed an openflow wrapper for the OLT. This interprets the openflow commands coming from the Access Network controller and communicates various changes to the PON network via a UART control link in the FPGA hardware. The OLT and connected ONUs can be controlled via the access network controller like any other network components. Table 5 shows a list of control functions that can be carried out over the control plane interface.

Function	**Description**
Customer Registration	New ONU serial numbers can be added to the registered users table in the OLT
Alloc ID registration	A customer can be assigned a new alloc ID
Alloc ID mapping	Gives the OLT information on how to match PW-MAC information from incoming packets to active Alloc-Ids on the PON and vice-versa
Alloc ID Assured Upstream bandwidth allocation	Each alloc id can be assigned a maximum upstream bandwidth as per their service level agreement. This is used in DBA described in section 4.2 above.
OLT wavelength	The laser wavelength of the DS transmissions

OLT Enable	Enable or disable the entire OLT
OLT reset	The OLT can be reset
OLT simulate failure	The OLT can simulate a failure in the feeder fibre. This is used for testing protection mechanisms)
ONU Remove	Remove an active ONU from the PON
ONU wavelength	Any active ONU can be migrated to a different wavelength by using the DWA method outlined in section 4.3

Table 5. Access control plane functions in LR-PON protocol hardware on FPGA

5 Conclusion

In the DISCUS LR-PON, the long logical reach (125 km), large logical split (1023) and large potential number of user Alloc-IDs (16,368), could be very challenging for dynamic bandwidth assignment (DBA) algorithms, to meet the specific delay (Assured Bandwidth Restoration Time and DBA Convergence Time) and bandwidth fairness recommendations of G.987.3. This has been tested on two distinct types of DBA scheduling algorithm. These are the GIANT algorithm from G-PON, which is pointer and timer based, and a Bandwidth Update algorithm from B-PON, which pre-calculates bandwidth assignments for the duration of a bandwidth update interval (DBA cycle).

The maximum balanced loads that each algorithm can support have been theoretically calculated, together with their bandwidth overheads, before Alloc-ID queues build up and packets begin to be lost. Because the Non-Assured bandwidth pointers in the GIANT algorithm become de-correlated from the frames in which Assured bandwidth grants are made, resulting in additional ONU bursts for Non-Assured bandwidth grants, the Bandwidth Update algorithm always provides greater maximum balanced loads for the same service interval. But, when the worst delays possible under each algorithm must satisfy any given Assured Bandwidth Restoration Time requirement, the GIANT algorithm provides higher maximum balanced load for all required Assured Bandwidth Restoration Time values. This is despite having de-correlated pointers and more ONU bursts than GIANT.

Nevertheless, only the Bandwidth Update algorithm is expected to satisfy the DBA Convergence Time recommendation at very high loads, with acceptable delays a) from a traffic change event to the 1st grant of the last Alloc-ID receiving a new bandwidth allocation, and b) between successive Non-Assured or Best Effort bandwidth grants. DISCUS therefore proposes the Bandwidth Update algorithm, whenever delays a) and b) would be excessive for the Alloc-ID numbers used and their supported traffic. Otherwise, the GIANT algorithm is slightly preferable.

DBA simulations have been implemented to date on the GIANT algorithm, at 10 Gbit/sec in the NS3 simulation package, using the XG-PON protocol. The total bandwidth overhead, including PHY, XGTC and XGEM overheads, is 29% at Load = 0.71, compared with the 29.5% bandwidth overhead at Load = 0.705 calculated from the Maximum Balanced Load theory. Theory and simulations are therefore in very good agreement.

The DWA studies in this report provide an understanding of the full range of options for ONU start-up, tuning, power levelling and normal operation, taking into consideration relationships between services, ownership, co-operation, bandwidth assignment protocols and laser tuning precisions, as well as physical layer performance and impairments and their mitigation protocols.

The worst three wavelength referencing, calibration and start-up options, not preferred by DISCUS, apply when laser tuning precision is poor, e.g. to +/-100 GHz, so ONUs may start up in the wrong wavelength channel. These include synchronous quiet windows, a single isolated wavelength channel under the control of a single network operator, and multiple low power/bandwidth AMCC channels each occupying a wide optical spectrum, e.g. 150 GHz, also under the control of a single network operator. Studies of interferometric and linear crosstalk, in conjunction with a proposed mitigation protocol, in which ONUs randomly choose time slots and wavelength channels in which to transmit serial number acquisition bursts, show that it is possible for ONUs to start up at a low US AMCC transmission speed (e.g. 1.6 bit/sec) that avoids the need for photon counting. But this requires potentially very long protocol run times. Experimental measurements of interferometric crosstalk between AMCC channel and working channel, using an optical amplifier, confirm the proposed theoretical, statistical analysis. For all three options, tuning to the desired channel wavelength can be performed at only slightly higher US transmission speed (e.g. 160 bit/sec).

DISCUS' fall-back option assumes that lasers are calibrated at just one power level per wavelength, in manufacture, to reduce calibration costs, with good tuning precision, e.g. to +/-10-15 GHz, to ensure that ONUs start up in the correct wavelength channel. Fine tuning is achieved by feedback control from the OLT. Although a modest increase in US AMCC transmission speed to 275 bit/sec during start-up could be obtained using Time Gaps, these require very high laser ON/OFF ratios, which may be impractical. Far greater increases are achieved by adapting the interferometric crosstalk mitigation protocol to operate with quiet windows. ONUs randomly choose a particular time slot, within a particular quiet window, within a predetermined set of quiet windows. An AMCC rate of 25 Mbit/sec is possible. This reduces start-up protocol run times enormously.

During start-up attempts, the calibration in manufacture at one power level must be transferred to higher power levels, by re-tuning the laser locally within the ONU. This is done by firstly transferring the tuning precision to the Tx tunable filter, by centring it on the calibrated laser wavelength, holding the filter stable, then transferring precision back to the laser by tuning this back to the centre of the filter passband at the higher power level. During this local re-calibration, the laser output power to line must be attenuated, to prevent interferometric crosstalk. It is possible for fine tuning to be performed at full working US LR-PON transmission speed. But if laser tuning precision worsens during the fine tuning procedure, perhaps because the power level has to be changed, then fine tuning could be performed at a lower power, but not necessarily as low as with poor tuning precision. Future work is needed to define precise procedures for fine tuning and possibly for fine power levelling under feedback control from the OLT.

The theoretical calculations of amplifier noise, Rx performance and speeds for working channels and AMCC channels (low power/low bandwidth), and the resulting start-up and fine tuning protocol run times, are all initial estimates. For example, only the first upstream amplifier at the splitter node is considered, and some additional noise is expected from the OLT amplifier. Further studies, simulations and experimental work would be needed to refine these estimates. Furthermore, physical and protocol parameters will depend on the precise LR-PON component values, such as adjacent channel crosstalk isolation in wavelength demultiplexers, agreed upon by vendors and operators in future recommendations.

The wavelength referencing, calibration and start-up option, preferred overall in DISCUS for its protocol simplicity, uses interleaved US and DS wavelength channels, enabling wavelength referencing to be performed locally at the ONU, and removing the need for the OLT to provide monitoring equipment and tuning feedback control to the ONU.

Full details of the design and implementation of FPGA-based LR-PON OLT and ONU prototypes are described. for demonstrating key features of the LR-PON protocol, including proof-of-concept aspects of DBA and DWA, and interactions with the control plane. Currently the PLOAM engine can send and interpret all messages needed for activation and ranging, and a new PLOAM message for DWA has been added.

The current FPGA implementation does not include a fully functional DBA engine, however, a version of the DBA is planned for implementation before the end of the project. In the meantime, the control plane can set the bandwidth allocation for any given ONU, and this bandwidth allocation will be served to the ONU in every upstream frame. This equates to a variable fixed bandwidth implementation, and has been implemented to ensure that control plane features can be demonstrated over the PON. The more realistic DBA yet to be implemented will allow the control plane to set the maximum assured bandwidth allocation, and the ONU will report queue occupancy in the dynamic bandwidth report upstream. The OLT will then use this information to calculate the next round of bandwidth maps for the PON.

The LR-PON protocol has been designed to work natively in a DWA environment. This has been achieved by adding laser and filter control to the LR-PON protocol hardware and control mechanisms. Each LR-PON OLT/ONU unit can be dynamically switched between wavelengths using a new integrated handshaking mechanism added to the PON protocol.

The FPGA LR-PON implementation includes an access control plane interface to demonstrate various service scenarios of interest in DISCUS. This allows the Access Network controller to use openflow commands to manage the PON OLT and ONU components. An openflow wrapper has been developed for the OLT. This interprets the openflow commands coming from the Access Network controller and communicates various changes to the PON network via a UART control link in the FPGA hardware. The OLT and connected ONUs can be controlled via the Access Network controller like any other network components.

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7 Abbreviations

A	Assured
ABsur	Surplus Assured Bandwidth Grant
ABmin	Minimum Assured Bandwidth Grant
ABRT	Assured Bandwidth Restoration Time
Alloc-ID	Allocation Identifier
AMCC	Auxiliary Management and Control Channel
APD	Avalanche Photo-Diode
ASE	Amplified Spontaneous Emission
AWG	Arrayed Waveguide Grating
BE	Best Effort
BER	Bit Error Rate
BMRx	Burst Mode Receiver
B-PON	Broadband Passive Optical Network
BPSK	Binary Phase Shift Keying
BU-ER	Burst Extinction Ratio
BW	Bandwidth
BWmap	Bandwidth Map
CAC	Connection Admission Control
C-band	Band in the wavelength range 1530–1565 nm
CIR	Committed Information Rate
CoS	Class of Service
DBA	Dynamic Bandwidth Assignment
DBACT	Dynamic Bandwidth Assignment Convergence Time
DBRu	Upstream Dynamic Bandwidth Report
DC	Direct Current
DISCUS	The DIStributed Core for unlimited bandwidth supply for all Users and Services
DML	Directly Modulated Laser
DR	Dynamic Range
DS	Downstream
DTWA	Dynamic Time and Wavelength Assignment
DWA	Dynamic Wavelength Assignment

DWDM	Dense Wavelength Division multiplexer
EAM	Electro-Absorption Modulator
EDC	Electronic Dispersion Compensation
EDFA	Erbium Doped Fibre Amplifier
EML	Externally Modulated Laser
ER	Extinction Ratio
ESA	Electrical Spectrum Analyser
F	Noise Factor
FEC	Forward Error Correcting
FP	Fabry Perot
FPGA	Field Programmable Gate Array
FSAN	Full Service Access Network
FSR	Free Spectral Range
GIANT	GigaPON Access Network
G-PON	Gigabit-capable Passive Optical Network
GPS	Global Positioning System
GTC	G-PON Transmission Convergence (protocol layer)
IP	Internet Protocol
IPTD	IP Transfer Delay
Int	Interferometric
ITU	International Telecommunications Union
ITU-T	ITU's Telecommunication Standardization Sector
λ	Wavelength
LAN	Local Area Network
L-band	Band in the wavelength range 1565–1625 nm
LE	Local Exchange
LR-PON	Long Reach Passive Optical Network
MAC	Media Access Control
M/C	Metro/Core
MPLS	Multi-Protocol Label Switching
NA	Non-Assured
NB	Nota Bene (take note)
NF	Noise Figure

ODN	Optical Distribution Network
OLT	Optical Line Termination
OMCC	ONU Management and Control Channel
ONU	Optical Network Unit
OOC	Out Of Channel (optical power)
OOK	On-off keying
Opt	Optical
OSNR	Optical Signal-to-Noise Ratio
PD	Photo-Diode
PHY	Physical
PIR	Peak Information Rate
PLR	Packet Loss Ratio
PLOAM	Physical Layer Operations, Administration and Maintenance
PON	Passive Optical Network
Port-ID	Port Identifier
PRBS	Pseudo-Random Binary Sequence
PtP	Point-to-Point
PTP	Precision Time Protocol
RR	Ring Resonator
RTD	Round Trip Delay
RTT	Round Trip Time
Rx	Receiver
SDN	Software Defined Network
SFP	Small Form Factor Pluggable
SI	Service Interval
sig	Signal
sig-spon	Signal-Spontaneous
SImin	Minimum Service Interval
SIR	Signal-to-power-Interference Ratio
SMSR	Side Mode Suppression Ratio
SN	Serial Number
SNI	Service Node Interface
SOA	Semiconductor Optical Amplifier

SOI	Silicon on Insulator
SP	Service Provider
spon-spon	Spontaneous-Spontaneous
TC	Transmission Convergence
T-CONT	Transmission Container
TDM	Time Division Multiplexing
TDMA	Time Division Multiple Access
TF	Tuneable Filter
ToD	Time of Day
TWDM	Time and Wavelength Division Multiplexing
Tx	Transmitter
UART	Universal Asynchronous Reception and Transmission
UNI	User Network Interface
US	Upstream
VLAN	Virtual Local Area Network
WDM	Wavelength Division Multiplexing
WDM-PON	Wavelength Division Multiplexed Passive Optical Network
WM	Wavelength Demultiplexer
WNE	When Not Enabled
WP	Work Package
WRR	Weighted Round Robin
X	Crosstalk Isolation
XFP	10 Gigabit Small Form Factor Pluggable
XGEM	XG-PON Encapsulation Method
XG-PON	10-Gigabit-capable Passive Optical Network
XGTC	XG-PON Transmission Convergence (protocol layer)
Xtalk	Crosstalk

8 Appendix I. Maximum Balanced Load Theory

The maximum balanced load is obtained when the available PON capacity, excluding bandwidth overheads, just equals the traffic level arriving. Arriving and departing packets are in equilibrium, no packets are lost, and the T-CONT queues do not build up with time. In this analysis, all Alloc-IDs (T-CONTs) support both Assured Bandwidth and Non-Assured Bandwidth types.

The following overhead byte parameters are defined:

ONUburst = guard time + preamble + delimiter

XGTC = XGTC header + trailer

DBRu = dynamic bandwidth report

XGEM = XGEM frame header

Other defined parameters are:

SI = service interval in number of XGTC frames

F = number of bytes per frame (e.g. 155,520 at 10 Gbit/sec)

B = SI.F = number of bytes per service interval

Alloc = number of Alloc-IDs (T-CONTs)

ONU = number of ONUs

ABmin = Assured Bandwidth bytes

ABsur = Non-Assured bandwidth bytes

Packet = mean packet size

$N = N_{GIANT}$, N_{Update} = mean number of packets arriving & departing per service interval

Let the mean number of packets arriving per service interval SI and forwarded per service interval be N. It is expected that there may be some delays involved, because a small build-up of packets is expected due to DBA delays, as well as randomness of arrivals. But there is no long-term queue build-up.

GIANT DBA Algorithm

The GIANT DBA algorithm operates frame-by-frame. Assured bandwidths do not employ pointers, so Assured bandwidth grants are always given in the same frame within the service interval (DBA cycle). Non-Assured bandwidth grants are assigned and allocated within the current frame, and the use of pointers allows any Non-Assured T-CONT to be served in any frame within the service interval. So Assured and Non-Assured bandwidth grants to the same T-CONT can become decorrelated, i.e. unsynchronised. They are assumed to do so here, such that Non-Assured bandwidth grants to a T-CONT are made in different frames to Assured bandwidth grants. Furthermore, in GIANT, each T-CONT's payload is served in one frame only; grants are not continued into the next XGTC frame.

In each service interval (SI), every ONU transmits an ONU burst containing XGTC header and trailer, and DBRu reports from all T-CONTs in the ONU. Across all ONU bursts, a number N_{GIANT} of Assured bandwidth payloads each has an XGEM header. Therefore the total Assured Bandwidth overhead bytes per SI are

$$ABWoverhead = ONU.\left(ONU_{burst} + XGTC + \frac{Alloc.DBRu}{ONU}\right) + N_{GIANT}.XGEM$$

...(A1.1).

and Assured bandwidth payload bytes per SI

$$ABWpayload = N_{GIANT}.AB_{\min}$$ ...(A1.2).

Therefore, the number of bytes available for Non-Assured payload + overhead per SI is

$$P_{available} = B - ABWoverhead - ABWpayload$$
$$= B - ONU(ONU_{burst} + XGTC) - Alloc.DBRu - N_{GIANT}.XGEM - N_{GIANT}.AB_{\min}$$

...(A1.3).

For Non-Assured bandwidth grants, it is assumed that within each XGTC frame, more than one packet is waiting in the same ONU, but in a different T-CONT queue. So multiple packets share the same ONU burst overheads. On average, the number of packets waiting in each ONU when being granted Non-Assured bandwidth in a frame is

$$\frac{N_{GIANT}}{ONU}$$ packets per ONU ...(A1.4).

So the total overhead and payload bytes per ONU burst are

$$ONU_{burst} + XGTC + \frac{N_{GIANT}}{ONU}(XGEM + Packet)$$ bytes/ONU burst ...(A1.5).

and the number of ONUs served Non-Assured bandwidth per frame is

$$\frac{P_{available}}{SI\left[ONU_{burst} + XGTC + \frac{N_{GIANT}}{ONU}(XGEM + Packet)\right]}$$ ONUs per frame ...(A1.6).

Hence the number of Non-Assured packets served per frame is (4)x(6), i.e.

$$\left(\frac{N_{GIANT}}{ONU}\right).\frac{P_{available}}{SI\left[ONU_{burst} + XGTC + \frac{N_{GIANT}}{ONU}(XGEM + Packet)\right]}$$ packets per frame

...(A1.7).

and the number of Non-Assured bandwidth payload bytes served per SI is

$$NABWpayload = \left(\frac{N_{GIANT}}{ONU}\right) \cdot \frac{P_{available} \cdot Packet}{\left[ONU_{burst} + XGTC + \frac{N_{GIANT}}{ONU}\left(XGEM + Packet\right)\right]}$$

...(A1.8).

Now, because we assume that over the SI, the number of arriving packets equals the number of granted packets (transmitted/forwarded from the T-CONTs), i.e. no queue build-up overall, we can say that the number of bytes of payload per packet equals the average packet size. Therefore, the number of Assured + Non-Assured payload bytes arriving and transmitted per SI is

$$N_{GIANT} . Packet = ABWpayload + NABWpayload \qquad \text{...(A1.9).}$$

Equations (A1.2), (A1.8) and (A1.9) can be solved for number of packets per SI, N_{GIANT}, such that

$$N_{GIANT} = \frac{B - 2.ONU.\left(ONU_{burst} + XGTC\right) - Alloc.DBRu + ONU.\left(ONU_{burst} + XGTC\right).\frac{AB_{\min}}{Packet}}{Packet + 2XGEM - XGEM.\frac{AB_{\min}}{Packet}}.$$

...(A1.10).

Since the load is $Load_{GIANT} = \frac{N_{GIANT} .Packet}{SI.F}$ ...(A1.11).

we get maximum balanced load

$$Load_{GIANT} =$$

$$\frac{Packet.\left[SI.F - 2.ONU.\left(ONU_{burst} + XGTC\right) - Alloc.DBRu + ONU.\left(ONU_{burst} + XGTC\right).\frac{AB_{\min}}{Packet}\right]}{SI.F.\left[Packet + 2XGEM - XGEM.\frac{AB_{\min}}{Packet}\right]}.$$

...(A1.12).

Bandwidth Update DBA Algorithm

In the bandwidth update algorithm, the Assured bandwidth overhead bytes are functionally the same as in GIANT, because Assured bandwidth payloads and overheads are always within the same XGTC frame.

$$\therefore ABWoverhead = ONU.\left(ONU_{burst} + XGTC + \frac{Alloc.DBRu}{ONU}\right) + N_{Update} . XGEM$$

...(A1.13).

However, the Non-Assured bandwidth overhead bytes are quite different. This is because the Bandwidth Update algorithm makes sure that all Non-Assured grants are allocated in the same ONU bursts as the Assured bandwidth grants, so the Assured and Non-Assured payloads use the same ONU burst overheads and the same XGEM header. Furthermore, unlike the GIANT algorithm, at worst Non-

Assured bandwidth grants could run into the next XGTC frame. These represent the only additional Non-Assured bandwidth overhead bytes per SI:

$$NABWoverhead = SI.(ONU_{burst} + XGTC + XGEM) \quad ...(A1.14).$$

Therefore, the number of available payload bytes per SI is

$$P_{Update} = B - (ONU + SI).(ONU_{burst} + XGTC) - Alloc.DBRu - (N_{Update} + SI).XGEM \quad ...(A1.15).$$

Since the number of packets arriving and transmitted per SI is

$$N_{Update} = \left(\frac{P_{Update}}{Packet}\right) \quad ...(A1.16).$$

We have

$$N_{Update} = \frac{B - (ONU + SI).(ONU_{burst} + XGTC) - Alloc.DBRu - SI.XGEM}{Packet + XGEM} \quad ...(A1.17).$$

and $P_{Update} = \dfrac{Packet.[B - (ONU + SI).(ONU_{burst} + XGTC) - Alloc.DBRu - SI.XGEM]}{Packet + XGEM}$

...(A1.18).

Since the load is $Load_{Update} = \dfrac{P_{Update}}{B} = \dfrac{P_{Update}}{SI.F}$ ...(A1.19).

we get maximum balanced load

$$Load_{Update} = \frac{Packet.[SI.F - (ONU + SI).(ONU_{burst} + XGTC) - Alloc.DBRu - SI.XGEM]}{SI.F.(Packet + XGEM)} \quad ...(A1.20).$$

For a mean packet size Packet = 432 bytes, and XGEM header overhead of just 8 bytes,

$$Load_{Update} \cong 1 - \frac{[(ONU + SI).(ONU_{burst} + XGTC) - Alloc.DBRu - SI.XGEM]}{SI.F} \quad ...(A1.21).$$

9 Appendix II. Interferometric Xtalk Into Wrong Channel

9.1 Worst-Case Eye Closure Analysis

As an example of interferometric crosstalk, consider 3 ONU lasers 1,2,3 interfering with the signal channel S, the photodiode current is proportional to the sum of the complex amplitudes mutliplied by the sum of the complex conjugates, i.e.

$$
\begin{aligned}
&(a_S + a_1 + a_2 + a_3).(a_S{}^* + a_1{}^* + a_2{}^* + a_3{}^*) \\
&= a_S{}^2 + a_1{}^2 + a_2{}^2 + a_3{}^2 + 2a_S a_1 \cos\phi_{S,1} + 2a_S a_2 \cos\phi_{S,2} + 2a_S a_3 \cos\phi_{S,3} \\
&+ 2a_1 a_2 \cos\phi_{1,2} + 2a_1 a_3 \cos\phi_{1,3} + 2a_2 a_3 \cos\phi_{2,3} \\
&= P_S + P_1 + P_2 + P_3 + 2\sqrt{(P_S P_1)}\cos\phi_{S,1} + 2\sqrt{(P_S P_2)}\cos\phi_{S,2} + 2\sqrt{(P_S P_3)}\cos\phi_{S,3} \\
&+ 2\sqrt{(P_1 P_2)}\cos\phi_{1,2} + 2\sqrt{(P_1 P_3)}\cos\phi_{1,3} + 2\sqrt{(P_2 P_3)}\cos\phi_{2,3}
\end{aligned}
$$

...(A2.1).

P_S is the power in the signal channel, and P_1, P_2 and P_3 are the powers in the 3 interfering channels. The smallest eye opening occurs between the lowest current when the signal P_S is in the 1 state (P_S=1), and the highest current when the signal P_S is in the 0 state (P_S=0). See Figure 30. In the 0 state, the signal power is αP_S due to extinction ratio α, and the highest current occurs when the signal is in phase with each of the 3 interferers a_1, a_2, and a_3, and a_1, a_2, and a_3 are all in phase with each other, i.e.

in 0 state, highest current = $$\begin{aligned}&\alpha P_S + P_1 + P_2 + P_3 + 2\sqrt{(\alpha P_S P_1)} + 2\sqrt{(\alpha P_S P_2)} \\ &+ 2\sqrt{(\alpha P_S P_3)} + 2\sqrt{(P_1 P_2)} + 2\sqrt{(P_1 P_3)} + 2\sqrt{(P_2 P_3)}\end{aligned}$$

...(A2.2).

When the signal power P_S is in the 1 state, the lowest current occurs when the signal is 180º out of phase with each of the 3 interferers a_1, a_2, and a_3, and a_1, a_2, and a_3 are all in phase with each other, i.e.

in 1 state, lowest current = $$\begin{aligned}&P_S + P_1 + P_2 + P_3 - 2\sqrt{(P_S P_1)} - 2\sqrt{(P_S P_2)} - 2\sqrt{(P_S P_3)} \\ &+ 2\sqrt{(P_1 P_2)} + 2\sqrt{(P_1 P_3)} + 2\sqrt{(P_2 P_3)}\end{aligned}$$

...(A2.3).

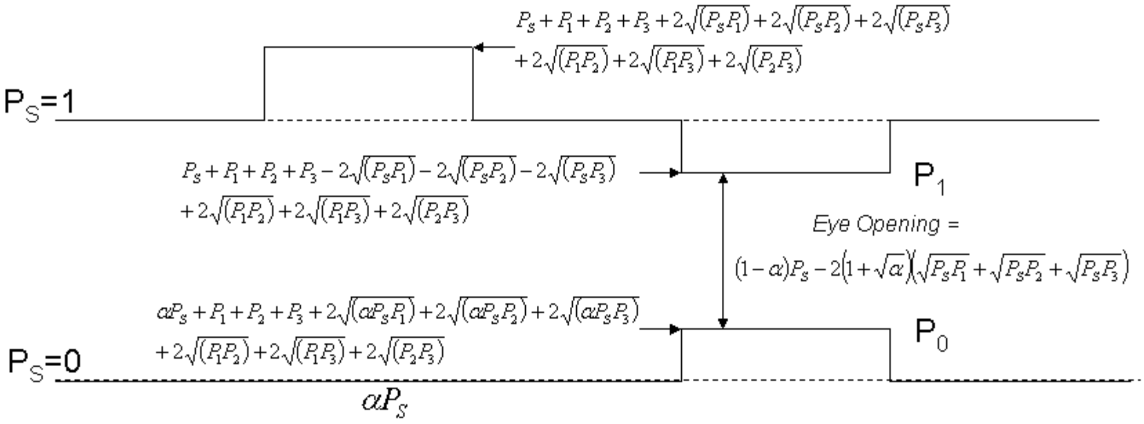
The resulting eye opening is given by (A2.2)-A(2.3), i.e.

Eye Opening = $(1-\alpha)P_S - 2\left(1+\sqrt{\alpha}\right)\left(\sqrt{(P_S P_1)} + 2\sqrt{(P_S P_2)} + 2\sqrt{(P_S P_3)}\right)$ ...(A2.4).

This can be generalised for k interferers of equal power P to:

Eye Opening = $(1-\alpha)P_S - 2k\left(1+\sqrt{\alpha}\right)\sqrt{(P_S P)}$ ...(A2.5).

3 Interferers:



k Interferers with equal powers P:

$$P_0 = \alpha P_S + k^2 P + 2k\sqrt{\alpha P_S P} \qquad P_1 = P_S + k^2 P - 2k\sqrt{P_S P}$$

$$EyeOpening = (1-\alpha)P_S - 2k\left(1+\sqrt{\alpha}\right)\sqrt{P_S P}$$

Figure 30. Worst-case eye opening with 3 and k interferers.

9.2 Statistical (Variance) Analysis

The corresponding parameters for a statistical analysis are as shown in Figure 31.

3 Interferers:

$$I_1 = P_S + P_1 + P_2 + P_3 + 2\sqrt{(P_S P_1)}\cos(\phi_1-\phi_s) + 2\sqrt{(P_S P_2)}\cos(\phi_2-\phi_s) + 2\sqrt{(P_S P_3)}\cos(\phi_3-\phi_s)$$
$$+ 2\sqrt{(P_1 P_2)}\cos(\phi_2-\phi_1) + 2\sqrt{(P_1 P_3)}\cos(\phi_3-\phi_1) + 2\sqrt{(P_2 P_3)}\cos(\phi_3-\phi_2)$$

k Interferers:

$$I_1 = P_S + \sum_1^k P_i + 2\sum_1^k \sqrt{(P_S P_i)}\cos(\phi_i-\phi_s) + 2\sum_{(i,j),i\neq j} \sqrt{(P_1 P_2)}\cos(\phi_j-\phi_i)$$

$$\therefore \overline{I_1} = P_S + \sum_1^k P_i = P_S + kP, forequal P_i$$

$$and \overline{I_0} = \alpha P_S + \sum_1^k P_i = \alpha P_S + kP$$

$$\sigma^2{}_{XT,1} = E\left[\left(I_1-\overline{I_1}\right)^2\right] = 2kP_S P + 2\left(k^2-k\right)P^2$$
$$\sigma^2{}_{XT,0} = E\left[\left(I_0-\overline{I_0}\right)^2\right] = 2k\alpha P_S P + 2\left(k^2-k\right)P^2$$

Figure 31. Statistical phase relationships of interferometric crosstalk into the wrong channel, with 3 and k interferers.

10 Appendix III. Interferometric + Linear Xtalk Into Adjacent Channel

This is a statistical analysis, modified from that in Appendix II.

3 Interferers:

$$I_1 = P_S + \frac{P_1}{X} + \frac{P_2}{X} + \frac{P_3}{X} + \frac{2\sqrt{(P_1P_2)}}{X}\cos(\phi_2 - \phi_1) + \frac{2\sqrt{(P_1P_3)}}{X}\cos(\phi_3 - \phi_1) + \frac{2\sqrt{(P_2P_3)}}{X}\cos(\phi_3 - \phi_2)$$

k Interferers:

$$I = P_S + \sum_1^k \frac{P_i}{X} + 2\sum_{(i,j),i\neq j} \frac{\sqrt{(P_iP_j)}}{X}\cos(\phi_j - \phi_i)$$

$$\therefore \overline{I_1} = P_S + \sum_1^k \frac{P_i}{X} = P_S + k\frac{P}{X}, forequalP_i$$

$$and\overline{I_0} = \alpha P_S + \sum_1^k \frac{P_i}{X} = \alpha P_S + k\frac{P}{X}$$

$$\sigma^2{}_{XT,1} = E\left[\left(I_1 - \overline{I_1}\right)^2\right] = 2\left(k^2 - k\right)\frac{P^2}{X^2}$$

$$\sigma^2{}_{XT,0} = E\left[\left(I_0 - \overline{I_0}\right)^2\right] = 2\left(k^2 - k\right)\frac{P^2}{X^2}$$

Figure 32. Statistical phase relationships of interferometric + linear crosstalk into the adjacent channel, with 3 and k interferers.

The mixing terms between P_S and the interferers P_i are removed. Interferometric mixing occurs only between the interferers. The linear Xtalk ratio X is due to the wavelength demultiplexer spectral shape. The equations are given in Figure 32.

11 Document versions

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[1] Last row represents the current document version