# Exploiting PONs for Mobile backhaul

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**Abstract**

The growing popularity of mobile data services necessitates a rapid rise in network capacity not only on the air interface to the end user but also in the backhaul network. The latter is quite important in the mobile operator business model affecting capital investment, operational expenses, service deployment and customer experience. Fiber infrastructure is inevitably the only long-term solution and the deployment of Passive Optical Networks (PONs) presents an opportunity for a cost-effective, scalable and future proof solution. In this paper we investigate the use of PONs for mobile backhaul and propose a resource allocation framework building on the efficiency of PONs to share resources, dynamically allocate bandwidth in real-time and enhance efficiency by improved statistical multiplexing. The main objective of this work is to exploit existing standardized technologies and provide design and deployment guidelines regarding the PON MAC operation enabling a gradual and future-safe infrastructure upgrade of mobile backhaul systems.

## 1. Introduction

Mushrooming mobile traffic driven by 3/4G systems and novel mobile data applications are saturating the current microwave-based backhaul networks. However, present solutions have limited upgrade potential, while the recent traffic trends will make the eventual need to connect the stations to some form of fiber inevitable sooner than later. Given that the situation is not static but rapidly changing, the introduction of fiber backhaul has to follow a careful migration path compatible with revenue generation since a large initial cash outlay does not seem a viable approach for even the more affluent operators. In this light, PONs offer the significant advantage of cost-effective port and traffic consolidation particularly in their TDMA variant. Apart from the lower cost compared with dedicated fibers for the initial deployment, PONs retain the extra comfort of a secure, gradual and future-proof evolution path. This can lead to any desired bandwidth in the form of upgrades to 10GPON and later WDM PON which can even provide dedicated wavelengths, without retrenching and cabling whenever this ever becomes necessary. However, even more important is the fact that PONs are already available in most areas, deployed for the fixed telecom needs, and can easily serve as wireless backhaul with little extra effort and cost enhancing revenue to both operators.

A mixed use of PON for both fixed access / wireless backhaul offers obvious synergy bringing forward the economic brake-even point for both mobile and fixed line operators/providers while benefiting the end-user at the same time. This serendipity provides a strong edge to PON selection over competing technologies, particularly for the introductory phase, when costs will be critical and traffic not high enough to justify the full PON capacity for neither the residential market nor the mobile backhaul.

In the mixed use and as traffic picks up, the obvious simple initial approach of over-provisioning exhausts its usefulness and the role of the TDMA part of the PON and the MAC protocol become prominent for a good utilization and hence profitability. The purpose of this paper is to investigate the critical worst-case delay and latency issues arising in this environment, assess the traffic handling capabilities of TDMA PONs under such a mixed initial traffic scenario and provide design and deployment guidelines to both manufacturers and operators as to the fine tuning of the PON MAC parameters.

To this end typical initial deployment architectures are presented in section 2, then guidelines for traffic handling in section 3 and computer simulation is used in section 4 to assess the traffic performance under typical and worst-case service scenarios that such a TDMA PON can provide. In addition suggestions for PON MAC fine-tuning are presented.

## 2. Architectural set-up

A typical set-up under the presented introductory scenario of a PON used for mixed residential and mobile backhaul (MBH) is depicted in Figure 1 where some Optical Networking Units (ONUs) support residential or professional users and small businesses while one or two serve mobile Base Stations (commonly called BTS or eNodeB depending on the technology; we keep the broader term BTS hereafter) and are interconnected through the PON fiber tree to the Optical Line Termination (OLT). The effect is that PONs allow deeper fiber penetration at a lower cost and simplify integration with optical metro and core networks.

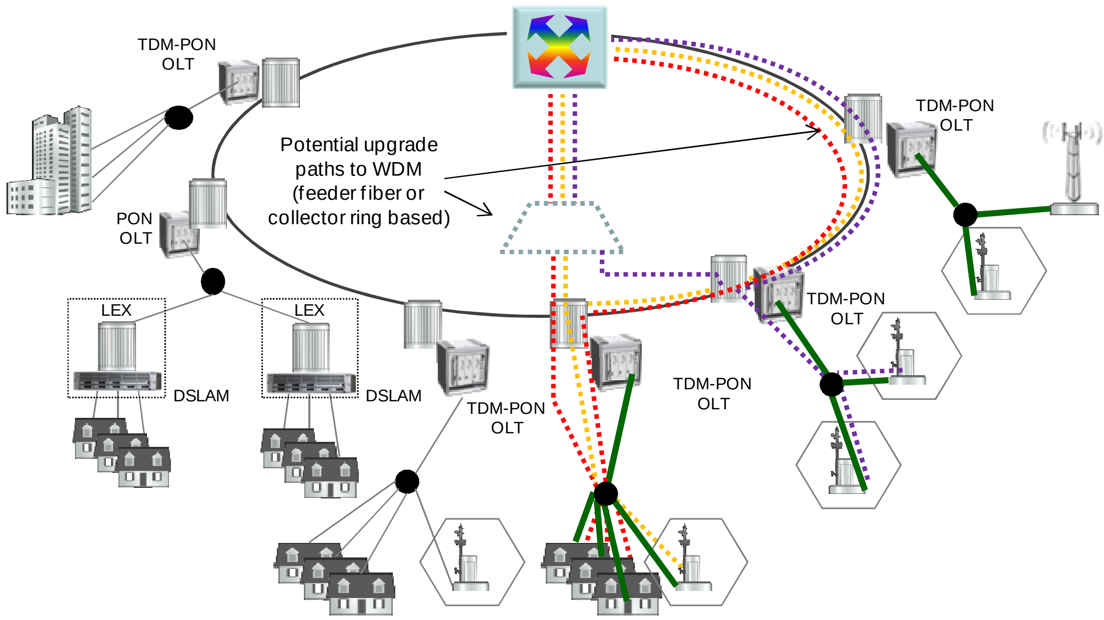


Figure 1: Typical architecture and potential WDM evolution paths (dotted lines)

No cost or technical advantage would make the PON a viable proposition for MBH as initial or interim solution, if it could not offer an obvious, easy, cost-effective, well-defined, and safe evolution path to any desired bandwidth in the future without tearing up the infrastructure and retrenching. Upgrades to faster data rates (e.g. 10 Gb/s) are the obvious first step but also at a later time more technological alternatives may mature and find their way into standard systems exploiting subcarrier multiplexing (e.g. OFDMA-PONs), Radio-over-Fiber (RoF) and ultimately WDM [1]. In the latter case a dedicated PON wavelength may become feasible and justified for wireless systems –as well as other network segments with stringent service level agreements (SLAs)- but a lot of income must have been generated before this can be viable and this dedicated link can still be provided via a later WDM PON enhancement creating a win-win situation. The replacement of the TDMA element with WDM links can be gradual, starting with the reduction of the splitting ratio by overlaying new PONs at different wavelengths as shown in Figure 1 reducing reliance on TDMA mode to eventual elimination.

## 3. Traffic handling in TDMA PONs

Mobile operators have been using static links (whether leased lines or microwave-based or even optical) to connect the traffic of BTSs. Compared to such links, TDMA PONs are quite a different affair. Their passive multiplexing that underpins their cost-effectiveness in a mixed residential-mobile BH deployment requires a much more complex traffic management. A thorough understanding and a refinement of the Dynamic Bandwidth Allocation (DBA) aspects of the TDMA PON are essential to achieve efficient utilization of network resources while respecting quality of service (QoS) parameters and SLAs. A significant cost-advantage of the PON comes from the cheap and effective way that traffic multiplexing into a single port is realised by a low-cost passive combiner. Packets are marshaled one behind the other in perfect and gapless succession as a by-product of the MAC operation.

When referring to the TDM PON, there are two dominant standards that can be used for the mixed backhaul network: GPON [2], [3] and EPON [4]. Both foresee the support of different QoS levels embedded in TDMA PONs for a successful performance, but operators must be well aware of the idiosyncrasies of priorities and MAC functions particularly since the differences between EPONs and GPONs in this respect are not trivial, though based on the same general principles. There is no space herewith to dwell on the way the PON MAC operates and the reader can find relevant information in [2] for the GPON and [4]-[7] for EPON. However, it is important to outline below the available MAC mechanisms so that the fine-tuning of allocation policy and the impact on performance in the MBH case can be established. The MAC operation is not explicitly part of either standard but the provisions make clear what mechanisms must be used without restricting the freedom of the implementor.

A crucial parameter when deploying a TDMA PON as a MBH, is delay introduced by the shared nature of the fiber medium on which packets are multiplexed under MAC guidance. The problem that leads to increased delay is that the MAC controller resides away from the queuing and may not be aware of the distributed queue activity as fast as a centralised multiplexer. In the PON case, a packet arriving in an empty queue can only seek service by means of receiving a periodic polling MAC signal. Obviously the polling period is the lowest possible latency. To reduce this by frequent polling results in waste because most polling responses will be empty. Since the quantitative assessment of this delay and ways to reduce it is the central theme of this work, we will investigate this PON peculiarity in the rest of this section preparing for the simulation study in the next section.

The access delay imposed by a TDMA PON backhaul particularly as the worst case latency adds a significant burden against the requirements imposed by the evolving standards for wireless and mobile networking which are quite stringent. For example [8] requests lower latency bounds for user plane (unload condition), control plane transitions and real-time games of 5 ms, 50ms and 75ms respectively. A particularly demanding situation in terms of latency (when a packet arrives in a previously empty queue which has therefore no pending request) arises in the handling of the string of hard handover messages ([9], [10]) from a base station situated in one ONU, to another station supported by a different ONU or a different PON. The performance of such a worst-case scenario will be investigated in the next section as it is of particular importance before feeling confident that a PON-added delay is no problem. It is also of interest to compare EPONs and GPONs in the handling of this, and investigate ways to alleviate the problem.

It is important in the context of this work to clarify the way PON DBA works and why latency is inevitable, how it can be controlled and what are the performance-utilization trade-offs. The DBA scheme has been well studied in GPONs and EPONs [2]-[7]. As seen in Figure 2 DBA relies on a continuous exchange of requests followed by grants a while later. DBA works by first having the ONUs request service indicating their queue length in a report field, and then the OLT allocates upstream transmission grants enough to allow them to relieve the full content of their queues. Hence, at least a minimum portion of bandwidth should be statically reserved in any case in order to guarantee transmission opportunities for requests as well as traffic with low-latency requirements that cannot afford the delay of the request-grant cycles. The requests are piggy-backed inside the transmissions departing from an ONU and packets arriving into an already empty queue would never get a chance to declare their presence if it was not for the unsolicited grants (UG) arriving for the purpose of polling. Thus, polling involves granting a transmission interval to an ONU on the basis of time passed and not on known queued traffic. It is like a chain smoker who needs no fire to light one cigarette after the other, but will need new light (polling) once he breaks the chain and extinguishes the last one. In the PON the new light comes from UGs. Frequent polling results in wasted bandwidth, large polling intervals, on the other hand, increase latency (i.e. the time waiting for the first grant when arriving into an empty queue, since non-empty queues can always transmit requests). The importance of UG frequency is also illustrated in Figure 2 where two scenarios with different UG rates are shown resulting in reduced packet delays (e.g. $Td_1$, $Td_2$) in the scenario (b) with the higher UG rate. This feature will be exploited in our proposals in section 4 below.

The situation with XG-PON and 10G-EPON is somehow improved for high priority traffic because the high rate allows faster polling while delay will not change significantly for DBA-based traffic since this is dominated by the round trip delay of the request/grant cycle.

Another important observation is that strict isolation between elastic and real time traffic is required to provide performance guarantees and this is achieved by strict prioritisation into 4 CoS classes in GPONs. In contrast, EPONs support 8 priority levels following the 802.1P approach and a somewhat restrictive native Ethernet support (i.e. Ethernet frames must be supported as a whole [4], while GPONs allow breaking up in smaller parts encapsulated in special frames [2], [4]. This allows GPONs to offer very lower levels of latency and delay than is possible in EPONs for the same level of efficiency, as will become clear in the simulation results of the next section. In GPON terms, the 4 traffic classes are called TCONTs (Traffic Containers), i.e. TCONT1 (higher priority) to TCONT4 (Best effort). TCONT1 traffic is intended for services with very strict delay and delay variation tolerance and is serviced at affixed rate by periodic unsolicited grants (UG) thus dispensing with the request/grant round trip delay, i.e. it does not participate in DBA as do the other three. There is also a TCONT5 which is a special tool combining of two or more of the other four TCONTs and is of particular interest in this work as will be explained in the next section.

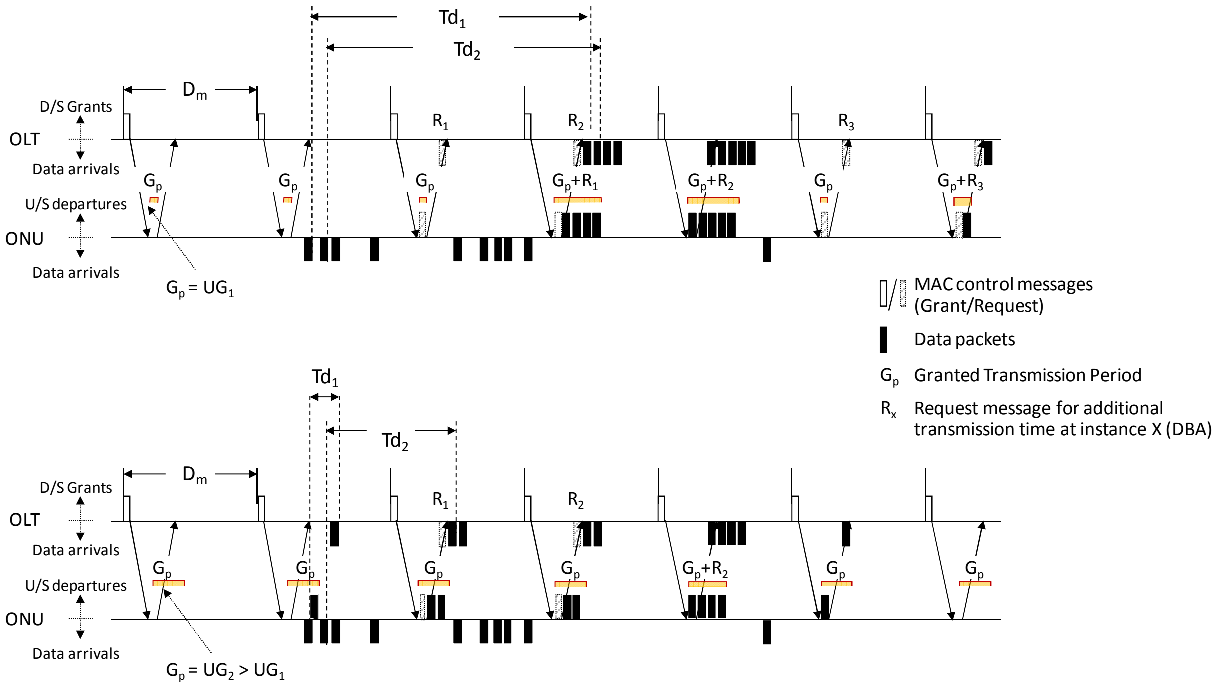


Figure 2 Principle of operation of DBA in a TDMA PON

Obviously the PON MAC controller has to periodically visit all active ONU queues and this leads to the concept of the mean scheduling period $D_m$. The $D_m$ parameter must be kept low enough in order to keep latency and delay variations low as well. In GPON the scheduling period can be quite small (integral multiples of 125μs enabling even the support of TDM services) and together with the low protocol overhead and the fragmentation of frames easily achieves low latency and delay variation, while in the EPON this can only be achieved by selecting a low $D_m$ at the expense of efficiency. This has been shown in several studies [5], [6]. The same methodology as in [5] will be followed here and the reader is referred to that paper for a thorough presentation of the comparison.

Consequently, the MAC protocol serves the top priority class CoS1 (TCONT1 in GPON), periodically, allocating an adequate number of unsolicited grants in every scheduling cycle $Dm$, to cover any eventuality. This is the only way the operator can actually guarantee service to a contracted peak rate $R_{p1}$ and a strict delay bound, which can be derived as a function of $Dm$. The scheduling period $Dm$ is used to calculate the bytes to be allocated to each queue to achieve the desired service rate. Hence, considering the case where unsolicited grants cover the sustainable rate $R_{s2}$ of the second class CoS2 (TCONT2), the total number of unsolicited grants for the $i$ th ONU (UG$i$) in bytes is expressed as follows: UG$i$ $=(R_{p1i} + R_{s2i}) * Dm$ (rates expressed in bytes/s). The remaining unallocated part of each scheduling period $Dm$ is distributed dynamically in a weighted manner and a service weight $w_i$ can be used [7] to enforce proportional sharing of the upstream transmission window among

ONUs to guarantee the portion reserved for CoS3 queues (TCONT3). Finally, CoS4 is served as best effort, i.e. whenever unallocated slots exist.
It follows from the above outline of the PON MAC operation that in the simulation studies of the next section, when we assess the performance for the handover signalling exchange of messages, that the relevant packets are assigned to the CoS1 (TCONT1) queue and the operator must have foreseen an adequate number of unsolicited grants (resulting in a minimum guaranteed bandwidth) in every scheduling cycle $D_m$ to satisfy the worst case latency. A typical hard handover scenario in GSM [9] and UMTS [10] consists of a sequence of 4 or 5 upstream single packet messages and the whole exchange must be completed well within the service interruption time allowed by the mobile standards. The specification for IMT [8] gives a maximum service interruption in a handover of 40ms while [10] specifies 50ms. This includes all causes of delay (protocol processing, air interface and propagation) but the new aspect of PON MAC protocol delay, due to the queuing involved until a grant becomes available, is of course completely unaccounted for in the standard. It is reasonable to assume that only a small portion of this delay budget can consumed by the TDMA PON. While some authors suggest a value of 2ms, [11], in no case it would be acceptable to allow a value above 10ms and a safer margin might be warranted. (Obviously soft handover presents no strict latency needs and is not considered here).

## 4 Performance Assessment by Simulation

In this section computer simulation results are presented to investigate the impact on delay of replacing a fixed backhaul link with a TDMA PON and the increased probability of violating service specific delay bounds especially for the most critical case of the hard handover. As a next step, best practices for operators in allocating bandwidth to the ONU supporting the BTS and fine-tuning the unsolicited grants (UG) will be presented and evaluated. The available margins and trade-offs between latency and utilization will also be presented and evaluated.
For the hard handover delay, we investigated by computer simulation the time it takes to complete the signalling chain of messages under different loading conditions and polling distance programmed by the PON operator to check safety margins and by how much utilisation must be sacrificed to ascertain safe service. The simulation set-up employs 16 ONUs one of which serves exclusively a mobile BTS while the others carry residential traffic. Three classes of service (CoS) are simulated of which the highest priority, COS1, is served in GPON by TCONT1 and by the top priority in EPON, while the other two by TCONT2 and 3 respectively. The 4$^{th}$ class (best effort) is not represented here as its study offers no useful conclusions. The traffic mix characteristics per ONU type are shown in Table 1. For all ONUs CoS1 traffic is considered to account for 20% of its total offered load and is modelled either as constant bit rate (CBR) voice traffic or control message traffic in the case of the wireless BTS, or data traffic modelled following an on-off model with a low burst factor $BF=(T_{on}+T_{off})/T_{on}$ in the case of residential users. All other traffic sources (CoS2 and CoS3 traffic) are considered as highly bursty data sources following an on-off model.

| | CoS1 (TCONT1) | | CoS2 (TCONT2) | | CoS3 (TCONT3) | |
|---|---|---|---|---|---|---|
| | ONU load (%) | Profile | ONU load (%) | Profile | ONU load (%) | Profile |
| Residential ONUs | 20 | on-off, BF=3 | 25 | on-off, BF=5 | 55 | on-off, BF=5 |
| BTS ONU | 10<br>10 | CBR<br>signalling | 25 | on-off, BF=5 | 55 | on-off, BF=5 |

Table 1: Simulated traffic load profiles per ONU

First the total delay for the typical signalling exchange of a handover scenario was measured and the pdf of this delay is depicted in Figure 3 for a total load of 40% (no significant difference is observed at higher loads because of the highest priority as will become clear below with Figure 4). The signalling exchange consisted of 5 upstream single packets modelling the two way handover protocol message exchange, which had to endure the access delay of the PON backhaul and an additional processing delay before a response message is generated (random processing delay following a Poisson distribution was assumed with a mean of 1ms). Values near or above 10ms would risk unacceptable service interruption. As it can be seen in Figure 3, the impact of the $D_m$ parameter is dominant as expected from previous studies of TDMA PON delay. In reality only the value of $D_m$=0.75ms provides a small enough tail to give confidence in the mixed architecture studied in this paper. This $D_m$ value is 6 times the frame size of GPON and can also be easily programmed in the EPON but at the penalty of some inefficiency. This is due to the way EPON is designed to carry whole Ethernet frames leaving an unused space remainder (USR) at the end of each upstream allocation. Lowering $D_m$ decreases the mean upstream transmission length, thus increasing this waste. There is no need to repeat the interesting investigation of this EPON idiosyncrasy, which has been extensively studied (e.g., [5], [11]), however to give a quantitative indication of this effect here, we provide for comparison in the inlet of the same figure the values of $U_{loss}$, (i.e. of the throughput lost in EPON as a percentage of that of a GPON) for each $D_m$ value and the same loading. It is worth noting that the GPON can still improve on the latency by using an even lower $D_m$=0.5 without noticeable inefficiency.

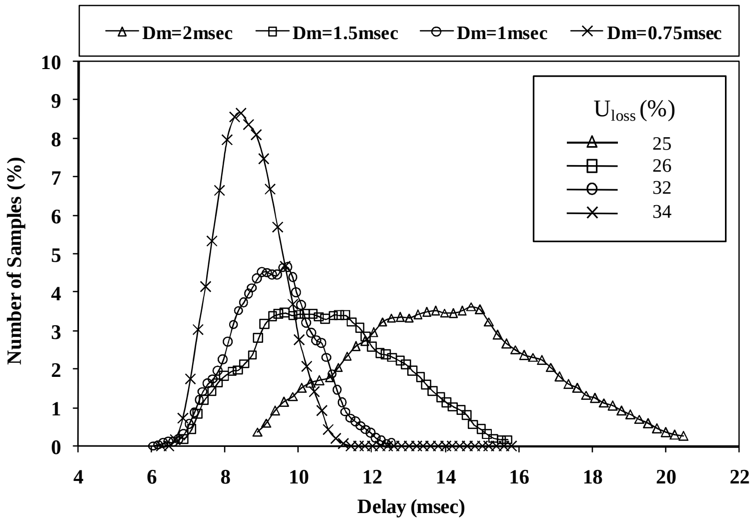


Figure 3: PDF of signaling delay (load 40%) and throughput loss (EPON v. GPON)

Next, attention in this simulation study was directed to fine-tuning strategies on bandwidth allocation investigating alternative policies more suited to MBH traffic and the consequent performance trade-offs. The core idea is to demonstrate the performance benefits arising from allowing more leeway in queue management to the ONU attached to the BTS than is the practice with the other ONUs. The reason is that this ONU carries traffic from an operator and this differs in two major ways from the rest: first it already has multiplexed traffic from many users, and second, the mobile operator can understand more complex SLAs enabling better local handling of the queuing process than is possible with the other users. For this reason we propose to aggregate all traffic as one MAC entity belonging to T-CONT 5 (this allows a mix of priority levels in grant allocations). The characteristic is that no target TCONT queue is specified (only ONU) and it is now left to the ONU to choose which queue to service (also called intra-ONU scheduling in [6], [7]). The use of this approach, is left by the standards [3] to the system designer and its activation (when implemented) is left to the operator. Once such tools are available, it is possible to use the arriving grants locally for higher CoS traffic (whenever such traffic is queued) under the control of the local ONU. In this case requests refer to the aggregate sustainable rate and the ONU decides which specific queue to serve using local queuing information which is more current and more responsive to sensitive traffic. This approach often called "colourless" grant policy is in contrast to the alternative where grants are targeting specific queues (and at specific CoS class) already decided by the far away MAC controller at the OLT. The latter (which is by far the most common practice in today's PONs) is called "coloured" since the grants are intended for specific target queues (colours) in the ONU and is quite appropriate whenever all customers are plain residential or small businesses with no complex SLA needs. The advantage of the colourless policy in the MBH case is that by leaving the allocation to be decided locally in the ONU, lower latency and better utilisation can be achieved (e.g. it and can serve packets which were not even present when the grant was sent).

In addition to colour or not, two polling policies are also investigated. In the first one, the polling rate (by means of UG) is set to just that required for the expected signalling rate of the first priority (while the rest used requests made possible by these UGs). This policy is indicated as $R_{s,sign}$ in the result figures below. In the other, UGs are issued at a rate equal to the sum of signalling plus the sustainable rate contracted by the SLA and is indicated as $R_{s,sign}+R_{s,data}$. This of course refers to the top priority incurring no waste by providing UG, since they will be used anyway by a packet of any class and will also provide the opportunity to send requests for the lower classes provoking corresponding grants at a second round since T-CONT 5 works as aggregate of many classes of traffic.

In combination, these policies create four alternatives which were investigated in the simulations. For each one, the queuing delay per individual packet (in addition to the signalling scenario) is measured against increasing total PON load. The results are shown in Figure 4(a)-(d), the first for the signalling exchange and then one for each class of service (CoS). A mean $D_m$ of 0.75ms was used. As expected, the first two classes have an almost steady delay across all loads since they do not feel any competition from the lower priorities and therefore they enjoy an always lightly loaded medium. The temporal bursts, when the total offered load temporarily exceeds the available bandwidth, are borne by the lower classes, which, as expected, become unstable before reaching 100% total offered load, but at what load strongly depends on the specific MAC policy.

The first observation is that increasing the polling rate with UG equal to both the expected maximum signalling traffic plus the sustainable rate improves delay performance but this comes at the expense of utilisation. This is to be expected as the resulting denser polling reduces latency but a lot of these UG grants go unused thus wasting bandwidth. Clearly a trade-off is needed but there is no straightforward solution, so it is worth elaborating further on the UG rate choice.

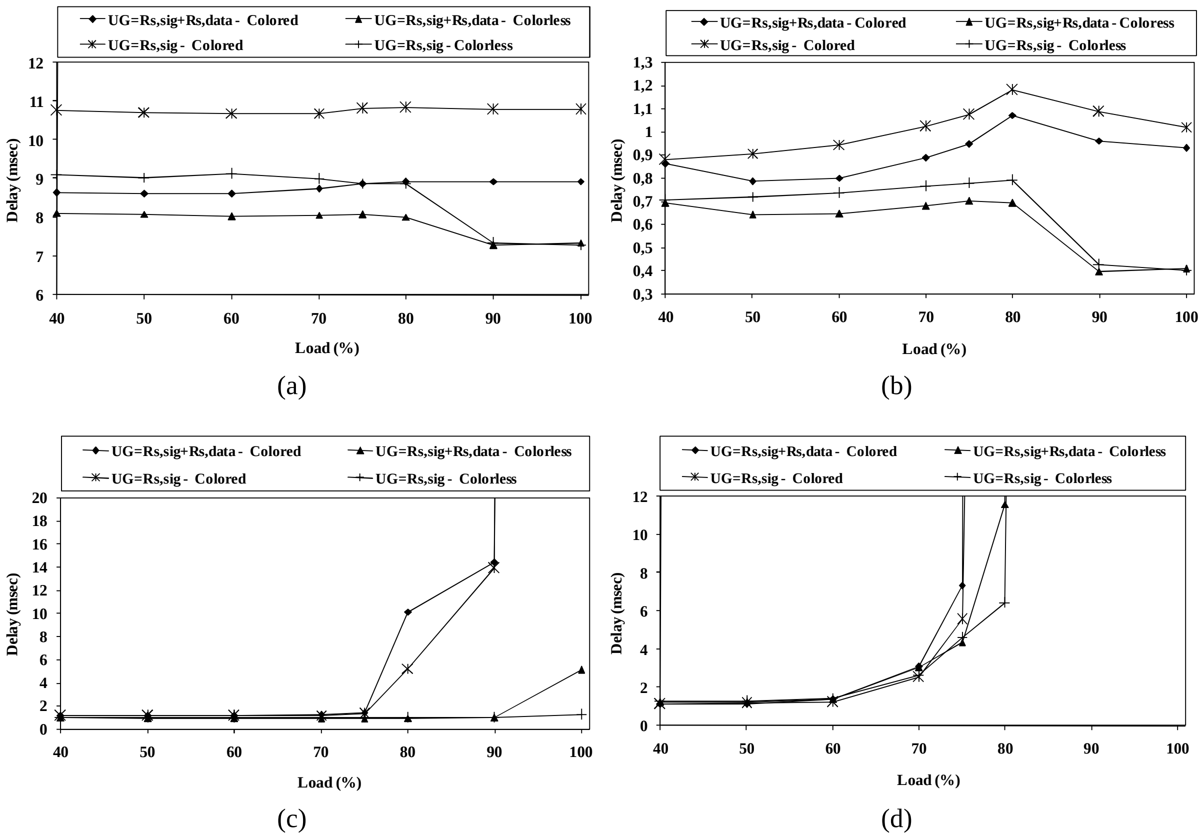


Figure 4: Average packet delay vs. load, service policy and traffic type a) handover message exchange, b) CoS1 (BTS voice and residential high priority), c) CoS2, d) CoS3

To understand the incentive for an elaborate UG policy, one must approach the issue from the operator's perspective. What is really needed is a way for the operator to predict the volume of signalling traffic in order to pre-allocate enough bandwidth via polling to guarantee a lower than the maximum tolerable latency. Since in real life, the generation of signaling traffic is unpredictable, it is natural to consider over-provisioning thus allocating the UG rate equal to the expected worst-case peak rate of the signaling traffic. However, in that case, the available bandwidth is underutilized during periods of low signaling load. It then follows naturally that an improvement can be reached by multiplexing signaling and no signaling high priority traffic into the same queue. In that case, the unused bandwidth of signaling traffic is allocated to data traffic, resulting in better efficiency, without at all compromising on the critical latency and delay of the signaling traffic, neither that of first priority traffic, since the weak point of the PON lies in initiating transmissions from an initially empty queue and not for continuing service on a queue (which takes place by the chain of requests). Exploiting this idiosyncrasy of the TDMA PON we propose this strategy (i.e. $R_{s,sign}+R_{s,data}$) by pre-allocating bandwidth equal to the sustainable rate of signaling traffic plus the sustainable rate of high priority traffic. As can be seen from Figure 4(a)-(d), this policy outperforms the mode ($R_{s,sign}$) in terms of signaling delay both under low and high loads. On the other hand, as seen from Figure 4, using ($R_{s,sign}+R_{s,data}$), in case of high loads, drives the CoS2 and CoS3 classes into high delay values at high load. The solution to this problem is the use of *colorless mode* instead of *colored mode*.

As seen from the same Figure 4(a)-(d), the colourless policy gives consistently better results in all cases and its adoption is recommended. This is to be expected since the OLT has limited knowledge of the local situation in comparison with a centralised multiplexer which instantly knows all queue lengths. Unable to have this knowledge one should at least delegate the remote multiplexing enacted by the PON MAC protocol controller to the local ONU, (unfortunately with the limited scope of the local queues) thus improving performance. This is particularly useful among the different priority queues of the ONU resulting in the obviously useful effect of high priority queues “stealing” grants directed to lower priority forcing the latter to report the same packet again in their request suffering no real harm since they are delay-tolerant.

This warrants a more careful look into the colorless mode and this is provided in the next Figure 5 which depicts the pdf of signaling delay at a high total offered load of 90% and a *Dm* of 0.75ms.

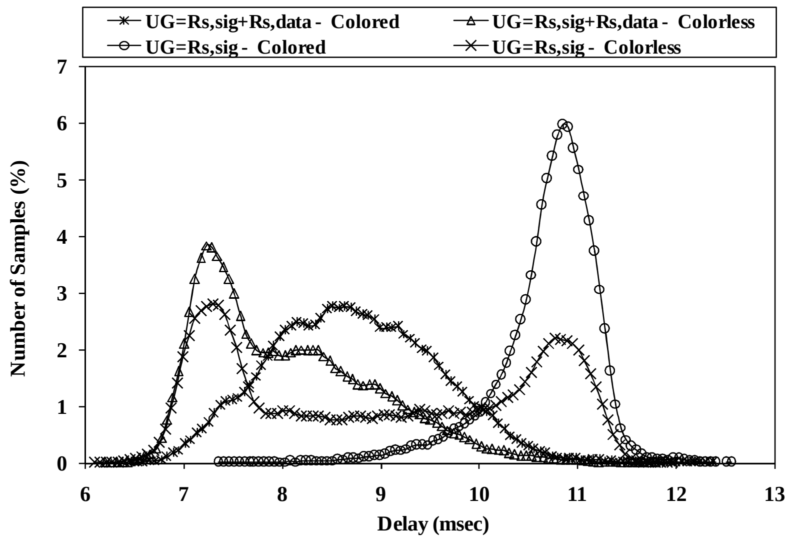


Figure 5 Comparison of coloured v. colourless mode

The superior delay performance of the colourless policy is clear in both relevant curves in Figure 5. Further improvement is reached by a higher UG rate (i.e., $R_{s,sign}+R_{s,data}$) compared with the simple $R_{s,sign}$ UG rate. A concentration of values around two peaks shows the importance of the polling rate (which in this case coincides with the *Dm*). On average each packet waits ½ of *Dm* for the grant and an additional 1ms for processing, (thus totaling about 7ms for 5 packets). This is of course not fixed but a distribution around this value which corresponds to the first peak. Now some packets miss the first round and need another *Dm* to get the grant on the next round, giving a second concentration of values around 11ms.

## 5. Conclusions

The widespread deployment of PON systems for fixed communications covering first mile access for residential and small business customers provides a serendipity for MBH that can not be missed as it offers a smooth migration path both in technical as well as financial terms. Although the TDMA technique will exhaust itself at some point, PONs still constitute a future-proof solution because of their ability to accommodate WDM extensions without further fiber laying or other costly operations. However, the TDMA aspect presents certain peculiarities and a careful traffic management by the operator is needed. As demonstrated in this paper, the added access delay jeopardizes specified limits for sensitive services. Also quantitative assessment showed that this can be improved by delegating more multiplexing decisions to the local ONU of the mobile BTS, while aggregating traffic for several flows relying on T-CONT 5. This policy carries distinct advantages in terms of latency and delay bounding for sensitive traffic without sacrificing efficiency under high load. This is particularly useful in the EPON case since it does not possess the better frame fill level afforded by GPON because of its tighter encapsulation thanks to frame fragmentation.

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