

SARDANA: AN ALL-OPTICAL ACCESS-METRO WDM/TDM-PON

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Keywords: access networks, Fiber-To-The-Home (FTTH), next generation Passive Optical Network (ngPON), Wavelength Division Multiplexing (WDM).

Abstract: A new optical access network, named “Scalable Advanced Ring-based passive Dense Access Network Architecture” (SARDANA), is presented. It transparently integrates WDM metro and TDM PON access technologies, implementing ring protection, 100 km reach and up to 1024 users served at 10 Gb/s, with passive highly-shared infrastructure. The introduced innovations are hybrid ring/tree WDM/TDM Passive Optical Network (PON) architecture; a resilient remote node (RN), which is distantly pumped from the Optical Line Terminal (OLT); and a reflective ONU (Optical Network Unit); as well as an enhanced Medium Access Control (MAC) protocol.

1. INTRODUCTION

Fiber-To-The-Home (FTTH) technologies and new network architectures have to enable universal communication with one order of magnitude increase in terms of connected users, capacity and distance reach, as well as incorporate enhanced security, scalability, service integration and other key functionalities. These are the goals of the FP7 European research project “Scalable Advanced Ring-based passive Dense Access Network Architecture” (SARDANA), undertaken by seven partners in 2008-2010 [1], towards the construction of a future-proof access-metro optically converged network that also minimizes the infrastructure and maintenance requirements while keeping compatibility and integration with existing standards. Since operators face a high degree of uncertainty at this level (take rates, user demands, extension branches, etc.) and the necessity of deferring the investments, incremental scalability is a major objective.

SARDANA aims at serving more than 1000 users spread along distances up to 100 km, at 10Gbit/s, with 100M-10Gbit/s per user in a flexible way, transparently combining new OLT/ONU equipment with WDM metro network transmission

and protection schemes in a next generation Passive Optical Network (ngPON).

2. SARDANA NETWORK ARCHITECTURE

In search of high scalability and trunk protection, SARDANA implements an alternative architecture of the conventional tree WDM/TDM-PON, organizing the Optical Distribution Network (ODN) as a WDM bidirectional ring and TDM access trees, interconnected by means of cascable optical passive add&drop Remote Nodes (RNs), as is depicted in Fig. 1.

The ring+tree topology can be considered as a natural evolution, from the conventional situation where metro and access networks are connected by heterogeneous mixed optical-electro-optical (O/E/O) equipment at the interfaces between the FTTH OLTs and the metro network nodes, towards an integrated metro-access network. In this case, covering similar geographical area, users and services; but concentrating electronic equipment at a unique Central Office (CO), and implementing an all-optical passive alternative, operating as a resilient TDM over WDM overlay. Depending on the scenario, the ring+tree mixed topology optimizes the

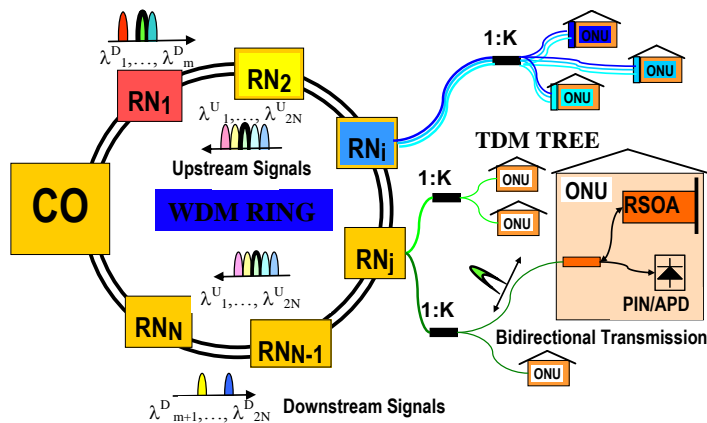


Figure 1: SARDANA network architecture with bidirectional metro WDM ring and TDM access tree.

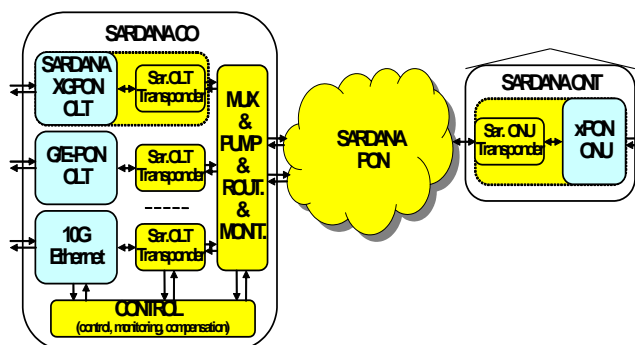


Figure 2: General network model, transparent to xPON standards.

usage of the fiber infrastructure in the ODN, and also offers enhanced scalability and flexible distribution, as new RNs can be installed.

The project mainly focuses on the physical layer, specifically on the optical and electro-optical (E/O) subsystems, being highly transparent to the protocol, coding and bit rates of existing xPON standards. The optical parameters are changed (e.g. the wavelengths band), but the chipset is kept compatible with ngPON, for a smooth migration and interoperability. The ITU-T Gigabit-capable Passive Optical Networks (GPON) standard [2] is taken as the reference and adapted to a new transparent optical layer, with WDM and active E/O devices using the existing metro/access optical passive infrastructure, as illustrated in Fig. 2.

For the full network demonstration, a down/up 10G/2.5G MAC protocol, based on FPGA, compatible with the GPON Transmission Convergence (GTC) layer has been developed in the project, and advanced new broadband multimedia services will be exhibited in the field trial.

3. KEY PHYSICAL SUBSYSTEMS

The implementation of the network subsystems: passive Remote Node (RN), colorless Optical Network Unit (ONU) and the Optical Line Terminal (OLT) at the CO, encompasses a number of technical challenges. Although several solutions have been investigated, the selected implementation for network demonstration is made on the basis of cost and robustness, leaving more complex advanced solutions for parallel research (Figs. 1 and 3).

3.1 Remote Node

The RN is a key element of the SARDANA network, and many of the performances and functionalities of the network depend on its design, like protection and routing. It implements cascadable 4-to-1 fiber optical add&drop function, by means of athermal fixed filters, splitters that perform spatial diversity for protection and distribute different wavelengths to each of the access trees, and remote

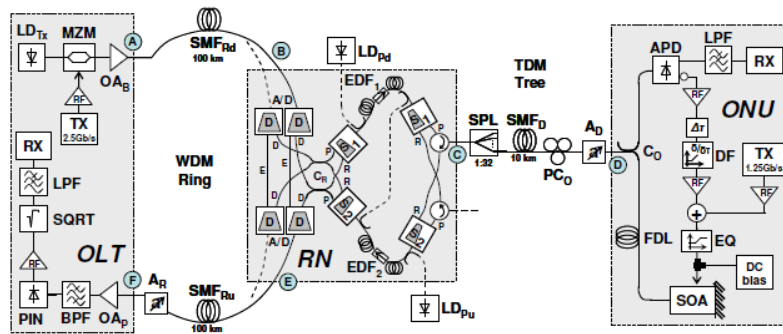


Figure 3: OLT, RN and reflective-ONU demonstration test-bed.

amplification, introduced at the RN by means of Erbium Doped Fibers (EDFs) to compensate add&drop losses. Optical pump for the remote amplification is obtained by pump lasers located at the CO, also providing extra Raman gain along the ring.

This new network element, passive but with dynamic behavior, incorporated in the new PON, is not present in current standards, but it inherits concepts from the following existing standards:

- ITU-T G.984.6 on PON Extender Box;
- ITU-T G.973 on remotely pumped amplifier (ROPA) for submarine systems;
- ITU-T G.983 PON protection;
- ITU-T G.808 Generic protection switching.

The RN encompasses some key challenges, like passiveness in the sense of not using electrical supply, efficient 1480 nm pump use, and burst mode amplification generating gain transients. The inset in Fig. 3 shows a RN with 2 drop wavelengths (2 trees) and bidirectional remote amplification in the drop. Wavelength extraction is done by means of two athermal thin-film Optical Add Drop Multiplexers (OADMs) at alternated 100 GHz or 50 GHz ITU-T grid channels. The natural gain transients due to the amplification of dynamic burst-modes of the PON upstream are cancelled in this RN thanks to the crossed wavelength direction design and co-amplification of higher power continuous downstream, also avoiding Rayleigh backscattering of the ROPA. The implemented RN presents 1 dB insertion loss in by-pass, 6 dB in drop/add, and >30 dB rejection. The losses are largely compensated by about 14 dB gain of the EDF. In [3] this is compared to other types of Extender Boxes for PONs, in terms of reachable trunk&access power budget. We specify up to 16 RNs; thus, employing 32 wavelength channels, with a splitting ratio between 1 and 32 each, services up to 1024 ONUs.

Lately, a reconfigurable RN has been also assembled, operated with optical power by means of particular power converting/harvesting modules, controlling latched optical switches or tunable power splitters, that enter into play at network protection and balancing [4].

3.2 Optical Network Unit

A key requirement of the ONU is to be colorless and to reuse the down wavelength, in full-duplex operation compatible with xPON electronics. A reflective-ONU optical transceiver based on Reflective Semiconductor Optical Amplifier (RSOA) has been taken as preferred option because it is the cheapest available choice for the WDM-PON, although it can rise up serious impairments operating in full-duplex with wavelength reuse. To overcome the bandwidth, noise and crosstalk limitations, a complete study of the possible optical modulation formats has been done and several compensating techniques have been developed:

- reduced Extinction Ratio (ER) downstream with feed-forward cancellation at ONU [5];
- wavelength dithering to reduce Rayleigh backscattering and reflections [6];
- upstream chirped-managed RSOA with offset-filtering, reaching 10G operation [7];
- adaptive electronic equalization, using MLSE and DFE/FFE at 10G [7,8];
- integrated colorless optical FSK demodulation with a SOA/REAM [9];
- wavelength shifting at ONU for reduction of Rayleigh scattering [10];
- other modulation formats tested like SCM, SSB and homodyne PSK are kept as longer term research.

For example, Fig. 3 shows the WDM/TDM PON system scheme implemented with downstream cancellation based on feed-forward injection and square root equalization, employing intensity modulation and wavelength reuse over 100 km reach and high split. An optimum downstream ER of about 3 dB was deduced for the given budget and receiver sensitivities. For the FEC threshold, the ER can be increased, maintaining down- and upstream. With an ER of 4 dB, the upstream penalty is 2.9 dB while the downstream benefits from 1.2 dB over an ER of 3 dB (Fig. 4).

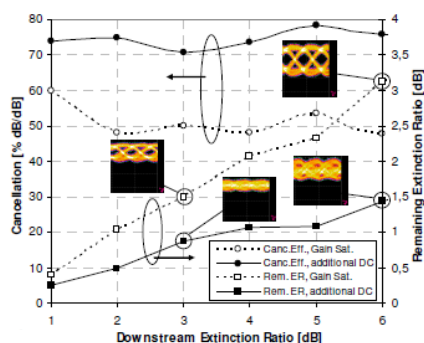


Figure 4: Downstream Extinction Ratio cancellation measurements.

3.3 Central Office

The CO furnishes the light generation for the whole network and its control. Optics at the OLT includes: WDM multiplexers, optical pre/post-amplifiers, equalizers, and protection switches and monitors.

4. NETWORK TESTS

First tests of the SARDANA network have been performed, in different configurations. Fig. 5 shows the scheme and results in a 105 km ring between Rome and Pomezia cities, at 10G down- and 2.5G upstream, with 2 RNs and 3 channels; the pump power was below 1.2 watts at 1480 nm. Sensitivities are -33 and -36 dBm respectively. Protection against fiber cut was validated, with less than 1 dB penalty at rerouting, in down- and upstream directions.

With the burst mode upstream operation, any gain transients at CO or RNs EDFs can be mitigated by means of pre-distortion carving of data packets at the ONU, allowing a strong reduction, to 30%, of the packet overshoot [11]. On the other hand, and because of the highly variant optical traffic at the ring, it is useful to develop an automatic method

based on a genetic algorithm to assess and minimize the impact of nonlinear crosstalk in WDM ring channels; by optimizing channel frequencies and powers, the budget is improved in 3-5 dBs [12].

5. PROPOSED MAC PROTOCOL

Considering the increased bandwidth, number of users and distances, as well as the interactive services that SARDANA plans to demonstrate, the design of an advanced new MAC protocol plays an important role. GPON [2] is the access standard being deployed by many operators and is taken as reference in SARDANA, but the Dynamic Bandwidth Allocation (DBA) algorithm for multi-service Quality of Service (QoS) is not specified and its implementation is open; hence, to provide QoS, a fair DBA adapted to bursty traffic is proposed. The DBA is validated by traffic simulations.

5.1 GPON Frames and MAC with QoS

GPON provides various transmission rates in both downstream and upstream directions. In downstream the bit rate can be either 2.5 Gb/s or 1.25 Gb/s, whereas in upstream the rate can be selected from 622 Mb/s, 1.25 Gb/s or 2.5 Gb/s. Rates up to 10 Gb/s are under consideration in the 10G GPON study by FSAN consortium [13]. The GPON frame duration is 125 μ s for both down and up-transmission rates, supported over the GPON GTC layer [2]; as shown in Fig. 6.

GPON transports Ethernet or IP frames using the GPON Encapsulation Method (GEM). This enables fragmentation, encapsulation and extraction of variable client frames with different traffic types to support diverse QoS requirements, allowing efficient transport in GEM packets (GEMs). The GEM contains the GEM header, with information to address the ONU, and a payload up to 4095 bytes. The GEMs are allocated in the GTC payload. Downstream Header includes the BWmap fields, which specify the granted data queues of the ONUs, identified by the Allocation Identifier (Alloc-ID).

In response to the BWmap granted allocations, upstream GTC is composed of a number of transmissions bursts coming from the ONUs. Each upstream burst contains a Physical Layer Overhead (PLOu) and one or more bandwidth allocation intervals, associated with individual Alloc-IDs, which contain a Dynamic Bandwidth Report upstream (DBRu), specifying the amount of data buffered in the ONU corresponding to this Alloc-ID,

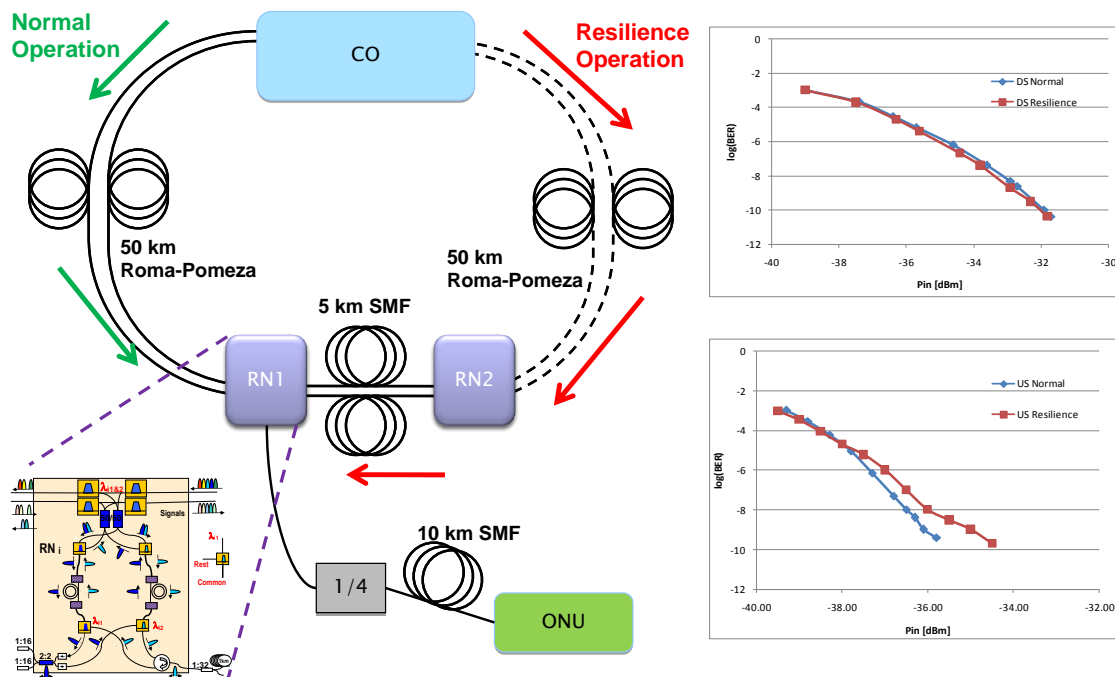


Figure 5: Network test configuration with 105 km ring, RN scheme (inset) and down- (above) / upstream (below) transmission BER measurements.

and the payload where the GEMs are allocated. The traffic arrived at the OLT and at each ONU is classified in separated QoS classes of service (CoS) and placed in corresponding queues Traffic Containers (T-CONTs), so that it can be treated in a different manner by MAC protocol run at the OLT. According to G.983.4, traffic is classified in the T-CONT CoS types 1, 2, 3 and 4:

- T-CONT type 1. Fixed bandwidth is supported, like emulation of leased line services and Constant Bit Rate (CBR) applications. Corresponds to the SARDANA Premium Class, using a permanent portion of bandwidth matching its Committed Information Rate (CIR).
- T-CONT type 2. Supports assured bandwidth for Variable Bit Rate (VBR) traffic, with both delay and throughput requirements, such as voice and video. Corresponds to the SARDANA Silver Class, but there having an assured CIR bandwidth plus an extra Excess Information Rate (EIR) assigned in DBA manner.
- T-CONT type 3. Better than best-effort services offering a guaranteed minimum rate. Corresponds to the SARDANA Bronze Class, with guaranteed rate up to its CIR and surplus EIR bandwidth granted by DBA.

- T-CONT type 4. Best-effort services, such as browsing and FTP, up to a maximum rate R_{max} and receiving bandwidth as the higher priority types do not use it. Corresponds to the SARDANA Standard Class using any bandwidth left.

The scheduling discipline applied in downstream is very simple: a Strict Priority (SP) data burst queuing discipline is employed, serving the data bursts in order of their priority and considering also the particular Service Level Agreement (SLA). Bursts with higher priority are attended first and bursts with lower priority wait to be served until there are no bursts with higher priority to be considered.

In upstream the polling Status Reporting (SR) technique [2] is used in order that the OLT knows the T-CONT bursts generated and stored in the ONUs, and subsequently the OLT will create the proper grants to the ONUs, which will send its authorized data bursts in the upstream frame (Fig. 6). The SR, informing the burst length of existing T-CONT bursts in the ONU in a nonlinear code, is furnished every Scheduling Interval (SI), which is the number of GPON frames of the ONU polling cycle. The SI is a critical parameter and must be adjusted to the traffic and propagation conditions, so that the OLT achieves global and current

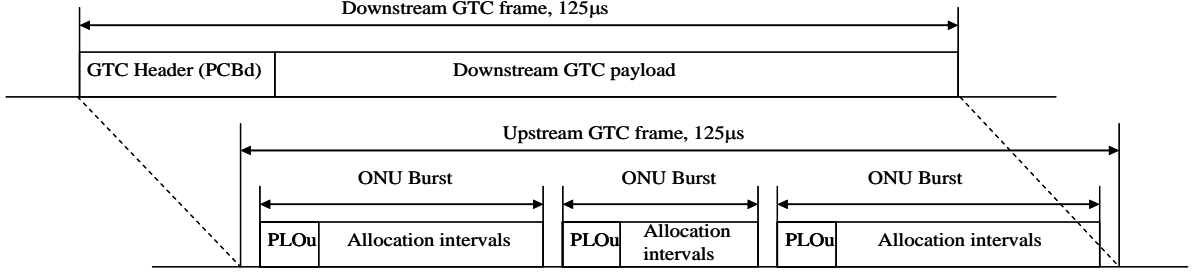


Figure 6: Downstream and upstream GPON Transmission Convergence (GTC) layer frame formats.

information on time about the T-CONT bursts generated in each of the ONUs. Once the OLT gets knowledge of the ONUs traffic needs, it will distribute the available bandwidth, applying the SP discipline (with a round-robin in case of several bursts in queue of the same CoS) plus particular SLA, between the requests [14]. Grants are generated and inserted in the BWmap fields in the downstream frames. Moreover, when an upstream T-CONT burst is sent, additional piggybacked information about new bursts generated from the same T-CONT is also added beside the up-burst in the DBRu field, informing if a new burst of the same CoS is originated in the ONU, and the OLT reaches an updated awareness of the T-CONT bursts generation status.

The upstream operation is collision-free because all ONUs are timed by using a ranging procedure during activation and registration; thus, an extra delay may be forced at the ONU side and the Round Trip Time (RTT), which is two times the propagation time OLT-ONU, is seen as fixed and common for all OLT-ONUs pair.

5.2 Traffic Performance Evaluation

We model each k CoS data source with a VBR traffic flow, with $k = 2, 3, 4$. The DBA will consider the data bursts to allocate once they are generated in each T-CONT in the Optical Burst Switching (OBS) manner: a burst will be scheduled when a time edge t_{edge} is reached, with a maximum burst size B allowed [15]. The VBR data has a mean rate b_{in} ; hence, the average burst length is $L_{burstk} = t_{edgek} b_{in}$. The output optical burst bit rate is b_{opt} , with $b_{opt} > b_{in}$, and the ratio $A = b_{opt} / b_{in}$ is the rate gain. The Wavelength Holding Time t_{WHTk} used for data burst transmission is

$$t_{WHTk} = t_{idle} + t_{tk} = t_{idle} + t_{edgek} / A \cong t_{edgek} / A \quad (1)$$

where $t_{tk} = L_{burstk} / b_{opt}$ is the transmission time of the data burst, and t_{idle} is a time where the reserved wavelength is idle or used by headers, being $t_{idle} \ll t_{tk}$. The optical load per active user L_{ou} in Erlangs, having every input flow the same b_{in} , does not depend on the aggregation time t_{edge} ; thus, it is independent of the CoS:

$$L_{ou} = t_{WHTk} / t_{edgek} \cong 1/A \ll 1 \quad (2)$$

With N_u active T-CONTs, the data burst optical load is then $A_d = N_u L_{ou} \cong N_u / A$. The optical rate b_{opt} for downstream and upstream is taken to be 2.48832 Gb/s; thus, a rate gain $A = 100$ provides a mean data source b_{in} of 25 Mb/s for both down and up. In downstream the DBA is executed on real time, because the OLT is aware of all arrived data bursts. In upstream the DBA is executed every frame considering the polling and piggybacked SRs received at the OLT. The processing delays $OLT_p = ONU_p = 35 \mu s$ and the number of ONUs $N = 32$, located 20 km far from the OLT. Different traffic loads are accomplished by gradually increasing the user bit rate b_{in} .

We suppose Short Range Dependence (SRD) traffic exhibition, so we generate down and up-bursts in Poisson arrivals with arrival mean t_{edge} per burst and time of service exponentially distributed (M/exp) with mean service time t_{WHT} . In a more practical self-similar scenario, we consider Long Range Dependence (LRD) burstiness behavior, which we emulate with the M/Pareto model [15]: again, the bursts are generated randomly in a Poisson distribution, but with Pareto time of service distribution with mean service time t_{WHT} . The Hurst parameter H is chosen to be 0.7, not very high because burst assembly reduces slightly the self-similarity. We consider four CoS, with traffic load distribution in 10% for the first fixed type Alloc-ID and 30% for the rest of the CoS assigned in DBA manner. The aggregation time t_{edge} is set to 10 ms for CoS types 2 to 4; then, e.g. a bit rate gain ratio $A = 100$ provides a mean time of service $t_{WHT} = 0.1$ ms.

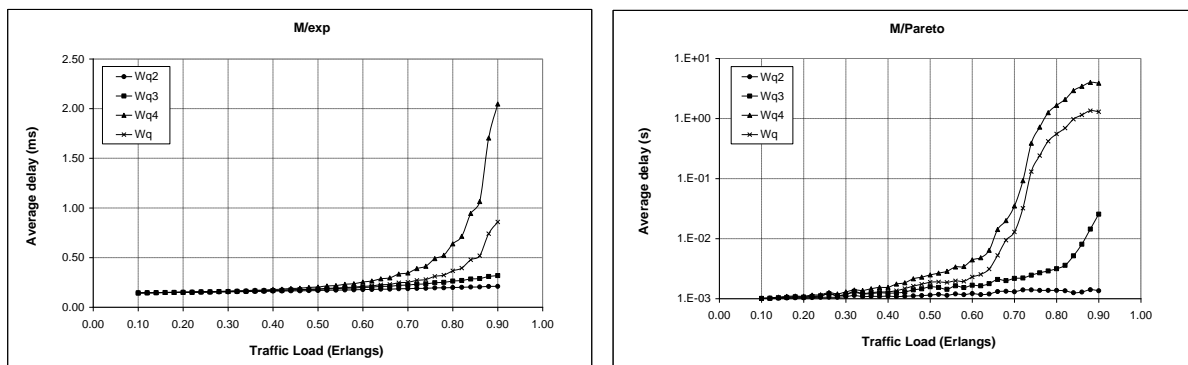


Figure 7. Downstream total average delay W_q and W_{qk} for each CoS, with Strict Priority discipline. On the left under SRD traffic, on the right under LRD traffic.

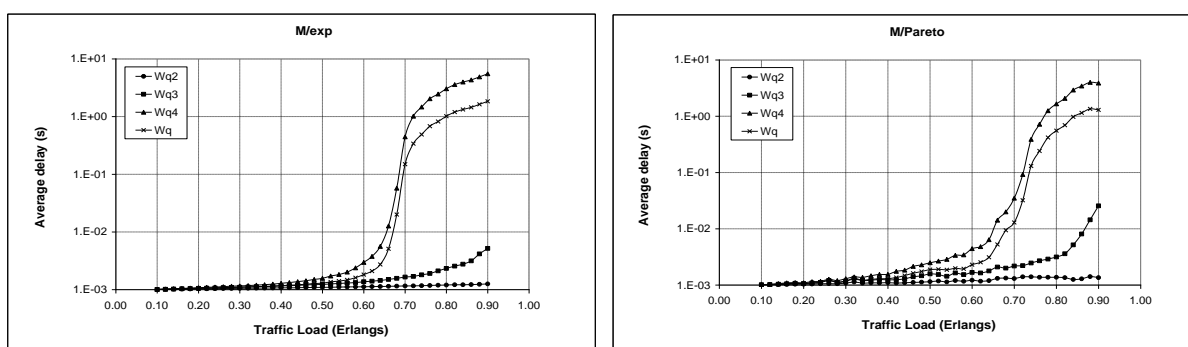


Figure 8. Upstream total average delay W_q and W_{qk} for each CoS, with Strict Priority discipline. $SI = 6$ frames. On the left under SRD traffic, on the right under LRD traffic.

Fig. 7 depicts the downstream average delay simulation results, which include the OLT-ONU propagation time.

The average delays obtained in downstream under SRD traffic are very low, bounded to 0.2 ms for all CoS types up to a 0.5 traffic load, confirming the correct choice of data burst aggregation time t_{edge} . The results for LRD traffic differ very much from SRD because of the self-similarity, which furnishes long data bursts when transmitted; nevertheless, up to a 0.5 traffic load, the average delays are limited to 1 ms for all CoS and the latencies for CoS types 2 and 3 are kept in the order of 0.5 ms.

In upstream, to get a very good ONUs traffic knowledge on real time, the SI must be in the order of $t_{edge}/10 = 1$ ms (8 frames). For a 20 km OLT-ONU distance, the minimum polling SI_r is 0.27 ms (RTT + processing, 2.16 frames), which is rounded to 3 frames. The data upstream is accomplished in $2SI_r$ (traffic knowledge, BWmap report and upstream transmission); therefore, 6 frames are used for the SI . Simulations for both SRD and LRD behaviours provide minimum delays with $SI = 6$

frames. Fig. 8 shows the upstream average delay simulation results.

The resulting average delays in upstream under SRD traffic are bounded to 1.5 ms for all CoS types up to a traffic load of 0.5, and limited to 2.5 ms under LRD traffic and up to the same traffic load. The results for LRD traffic do not differ very much from SRD because of the data segmentation in the BWmap allocation, which provides fair assignment among all data bursts to be served despite of its length. The DBA module can be improved using a bursty traffic prediction to enhance the transmission efficiency in the Long Reach approach [14].

6. CONCLUSIONS

The SARDANA project for new FTTH deployment proposes a future metro-access network, involving the development of novel techniques at different levels and layers. The targeted scenario, the main new functionalities and the critical elements have been identified and the chosen solutions are tracked and experimentally validated. SARDANA network

furnishes a solution for the ngPON integrating access and metro technologies, thus reaching a superior performance in security, scalability, capacity and service integration while keeping compatibility with the existing standards.

ACKNOWLEDGEMENTS

This work was supported by the European FP7 SARDANA project and the Spanish MICINN project TEC2008-01887.

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