Remote Nodes topologies for hybrid WDM-ring TDM-tree passive optical networks

A. Baptista, M. Ferreira, A. Quintas, M. Lima, A. Teixeira

Abstract: In this paper is presented a WDM-ring TDM-tree passive optical network able to provide more than 1024 users spread over 100km with a symmetrical bandwidth of 100Mbps. A set of optically fed passive remote nodes are also presented able to provide increased efficiency and resili90ency.

I. INTRODUCTION

While already standardized Time Division Multiplexing (TDM) optical networks are currently under deployment, recent research is focused on the next generation access networks [1]. Next generation access networks are aiming at offering higher user density, extended reach, scalability, flexibility and resiliency while keeping the network simple and economically feasible [2]. The figure 1 presents the evolution of the optical networks towards new generation passive optical networks (NG-PON).

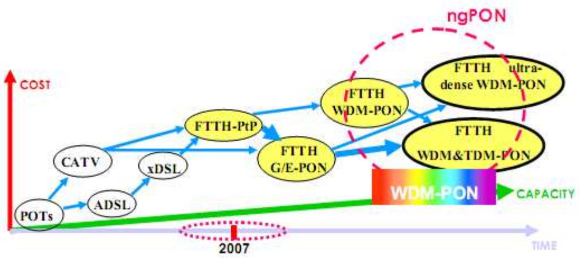


Figure 1. Evolution of access technologies [3].

Research activities are focusing on possible extensions of current GPON and EPON since these systems may suffer bandwidth limitations in the future, and they do not make full use of the optical bandwidth. The major goal is to reduce the overall access network cost while assuring a remarkable symmetrical bandwidth per user and establishing an optical passive transparent infrastructure over a dense extended range area, capable of supporting unknown future demands [3].

Scalable Advanced Ring Based Passive Dense Access Network Architecture (SARDANA) is an effort to demonstrate how to exploit the NG-PON in a cost effective and reliable way [4]. It is a Framework Project Seven project and is the main objective of this document. It consists on a Metro-Access convergence network pretending to supply at least 100Mbps per 1024 users spread over more than 100km [5].

SARDANA Topology

This novel PON topology is based on a main ring and secondary trees connected by means of special nodes, the remote node (RN) [6]. There were proposed two different topologies to SARDANA, the first consists on a single fiber ring [7] and the second a double fiber ring [8]. When the main ring is implemented with double fiber, one fiber carries the Downstream (DS) signal and the other the Upstream (US) signals in order to reduce the total degradation imposed majority by Rayleigh Backscattering (RB) distortions, optimize the total used spectrum and providing the ONU with a colorless RSOA keeping it simple. For a ring implemented with single fiber, the DS and US signals require to be in different wavelengths to avoid RB distortions so the ONU cannot be implemented with a simple reflective component [8].

In order to achieve the highest efficiency from implemented fibers, the main ring operates in wavelength division multiplexing (WDM) and each tree shares a wavelength from the WDM ring in a TDM basis, allocating a temporal slot to each of the users. Operating at TDM basis in the tree allows the migration from the currently deployed infrastructures overlaying E-PON and G-PON into this novel topology. Different services can be accommodated on different wavelengths to serve different users with different transmissions requirements, offering a flexible network [9].

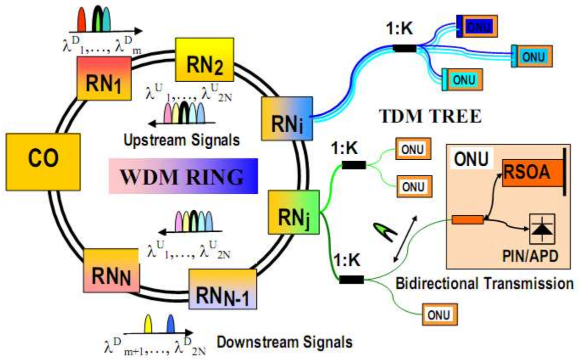


Figure 2. SARDANA network architecture [3].

Robustness is achieved by the passive ring and the use of monitoring techniques and electronic compensation strategies, intelligently supervising and managing the impairments of the PON. The network scalability is guaranteed by inserting supplementary RN to the ring that is wavelength transparent is a simple task. Due to the implementation of the main ring, the network is able to provide traffic balance through the shorter path and resiliency in case of fiber, splice, connector or component failure, being the signals redirected for the other path. All the light generation and control is centralized in the central office (CO) keeping the outside plant completely passive. The SARDANA network is presented in figure 2.

II. REMOTE NODE

The overlay between the WDM ring and the TDM trees is made by the passive RN. It implements cascadable 2 to 1 fiber optical Add&Drop functions distributing different wavelengths to each of the access trees. Two trees are connected to each RN with a splitting ratio of 1:K providing a flexible number of users. The RN with reduced footprint, do not require any environmentally controlled location. The RNs are completely transparent in the ring and compatible with the already deployed fiber structures being no modification required as the network grows. The introduction of a new RN in the ring is a simple task requiring just transmitting 2 more wavelengths from the CO. The RN Add&Drop signals independent of the direction of the signals in the ring. A basic diagram of the main blocks present in the RN is demonstrated in figure 3.

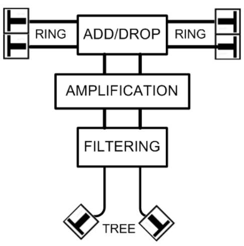


Figure 3. Remote Node main structure [10].

To compensate distance, dropping and filtering losses in the outside plant, amplification is convenient [8]. It allows significant improvement in the scalability of the network, geographical flexibility and average bandwidth per user but decreasing the OSNR [9]. Amplification is provided by means of EDFs present on the RN remotely pumped from the CO by means of two 1480nm pumping lasers, one for each ring direction, balancing the total power in the ring and providing resiliency in case of fiber failure [7]. The pump power is provided through the US fiber in order to produce extra Raman gain. The pump power present on the US fiber is previously demultiplexed from the fiber and led to the EDFs for amplification.

As described , it is very important to understand the referenced topologies [8], [5] and the evolution of the proposed topologies in order to reduce the total amount of pump power produced by the CO, reduce the Insertion Loss (IL) and allow higher scalability, resiliency, increase the number of users per network and bandwidth per user. The optimization of the RNs can be divided into two categories: the signal path related to the reduction of the signal attenuation and degradation through the RN and the pump path related to the optimization of the pump distribution through the network and requirements from each RN.

III. PUMP PATH ARCHITECTURES

An important part of the topology to optimize is related to the pump power demanded per RN and forward required from the CO. The first and easier pump configuration is present in figure 4.a). It consist on simply drop the pump power at 1480nm from the US fiber and direct it to the EDF being the remaining pump power supplied to the other(s) EDF(s). It requires less optical components to implement but it is not efficient.

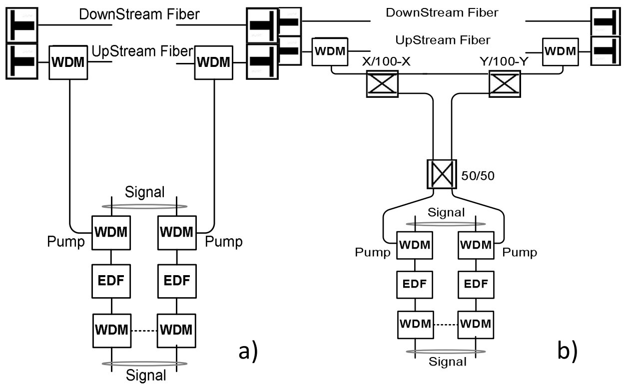


Figure 4.a) Simple Remote node pump topology and b) double power splitter pump topology [10].

As demonstrated in [10], increasing the pump power supplied to the EDF leads to the saturation of the amplification while keep increasing the consumption of that pump power decreasing drastically the efficiency of the network, leading to impossibility to supply all the RNs with pump power.

A better approach is to provide the EDFs with a fraction of the total pump power available in the network. For that the RN pump topology is proposed in figure 4.b). It consists in three power couplers being two of them inserted in the pump ring path with coupling factors (X / 100-X and Y / 100-Y) and the other a 50/50 for resiliency and power balancing mode. The two power couplers inserted in the pump ring path have different ratios due to the fact that the pump can arrive from the both sides of the ring. This approach increases the efficiency compared to the previous approach since it just supply the EDFs with a fraction of the power, although extra IL is inserted in the ring pump path due to the two power couplers and for the adjustments of the ratios for the better approach, pump power is wasted in the couplers [10].

A third approach consists on a single power coupler with a ratio adjusted to be the most efficient for scalable and resilience purpose. This new configuration is presented in figure 5.a). With this configuration no pump power is wasted in the pump power coupler and the total insertion loss in the pump ring path is reduced reducing the number of power couplers from two to one leading to a fairer pump distribution and higher network pump efficiency. A problem arise now that consists on the appropriate ratio for the power coupler having in consideration the number of RNs, the number of users per tree, the scalability of the network and the resilient operation. It is impossible to select that value being the most efficient for all the situations individually but a value can optimize it considering all [11].

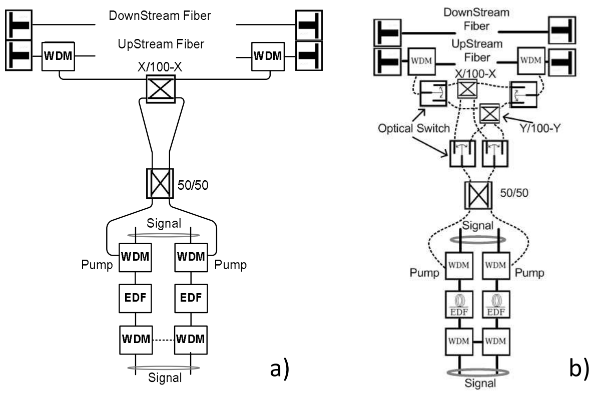


Figure 5.a) Single power coupler pump topology and b) optical switching [10].

A pumping configuration proposed that considers all power splitters ratios equal to 90/10 provide resilient and scalable network and a second approach able to provide each RN with a different splitting ratio as 10, 13, 17, 20, 25, 30, 40, and 50 can be seen in figure 6. A third approach is to provide each RN with a different splitting ratio as 13, 14, 17, 20, 25, 33, 50, and 100.

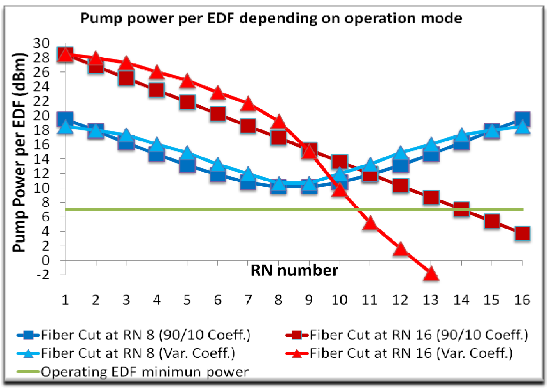


Figure 6. Comparison of variable and 90/10 power couplers for different states of the network [11].

The first approach is the simplest to implement and the one that provides better resilience and scalability compared to the others but for normal operation mode, it requires higher pump power from the CO than the other approaches. The second approach is not scalable as the previous one, is not the best option for the normal operation mode (the intermediate approach) but it provides some resilience in case of fiber cut. The second and third approach require power coupler ratios not available commercially. The third approach is the best one for normal operation mode as it requires less pump power demand from the CO. By the other hand it is not resilient, since in case of fiber cut no pump power pass at the central RN to the reminiscent RNs and the scalability is not guaranteed since an introduction of more RNs require all the pump power ratios from all RNs require to be readjusted [12].

The selection of the appropriate power coupler ratio should depend of the normal and resilient operation mode, so, an average power coupler ratio must be chosen, although, it is difficult to achieve. An alternative propose for the previous configuration is to select between the best option for normal operation and the best option for extreme resilient mode, fiber cut at RN 16 by means of optical switching as presented in figure 5.5.

For the normal operation the ratios would be 13, 14, 17, 20, 25, 33, 50, and 100 and for extreme resilient mode all ratios equal to 90/10. This approach is still not scalable since an introduction of RNs in the ring requires the readjustment of the normal operation power coupler ratios. Other impairment with this solution is the extra insertion loss introduced in the pump path ring, that increases significantly the total insertion losses degrading the efficiency of the network [11].

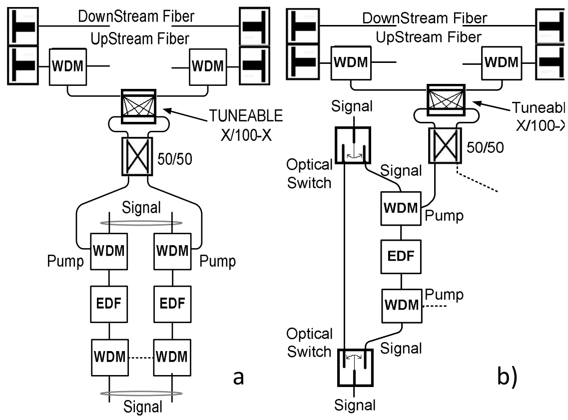


Figure 7.a) Tunable Power Splitter pump topology and b) reconfigurable modules pump topology [12].

A better approach is the introduction of a tunable power splitter instead of the optical switches as presented in figure 7.a). With this approach the RN can adjust the ratio factor to the most appropriate ratio eliminating the extra pump power dropped to the RN and providing completely scalability, resiliency and higher efficiency reducing the total pump power supplied from the CO [11].

Despite of the apparently simple implementation of this configuration it increases the Ring IL in the pump path compared to the main topology in figure 5.a). Even more, it is difficult to implement a passive optical tunable power splitter controlled precisely and consumed very low optical converter energy, being also very expensive to implement.

Other approach to the pump power topology has in consideration the distance from the RNs to the CO. EDFs supplied with signals to be amplified with high power, will not be able to provide gain although it will attenuate and degrade the signals [10]. Also, the pump power consumption will increase being required higher pump power for that RN decreasing the efficiency of the network. With these characteristics, RNs close to the CO where the signals have enough power to reach the ONU do not provide gain to the signals. A simple solution would be to omit the tunable power coupler and the EDFs in the RN, reducing the components and the cost of the network and reducing the total pump power demanded by the CO. Although, it must be considered the scalability and the resilience of the network, where the RN that is the closer to the CO can be the farthest in case of network grow or fiber cut and resiliency. For those cases amplification must be provided is some situations. The proposed RN implements two distinct modules, one of them providing gain to the signal and the other establishing just a direct connection without amplification as presented in figure 7.b). The selection between those two modules can be achieved by means of optical switching. This approach is the most efficient in terms of pump consumption, being the best pump topology [10].

IV. SIGNAL TOPOLOGY

The first and simpler RN signal architecture with a single fiber ring is presented in figure 8. Each RN provides Add&Drop functions by means of three optical couplers. The first two, introduced in the ring, are designed depending on the number of RNs to minimize the pass through losses. The third coupler, 50/50, is responsible for traffic balance and resilience operation since it provides the signals to be Add&Drop from both sides of the ring. Since the couplers in the ring drop from the network a fraction of the entire spectrum filtering is required.

Two thin film filters select the specific downstream and upstream wavelengths for the PON trees that are connected to the RN. In order to compensate the distance, drop and filtering losses, amplification to the signals is required. With this design, the ONU just require some change from the commercially available EPON/GPON ONU. That is the substitution of the 1310nm upstream transmission laser by a laser to transmit on the wavelength assigned to that specific PON segment remaining the rest of the equipment and logical control invariant. Important design parameters to make the network compatible with the EPON/GPON standards are related to PB restrictions [10]. This kind of topology based on a single fiber ring is appropriate for non reflective ONU since DS and US signals require different frequencies.

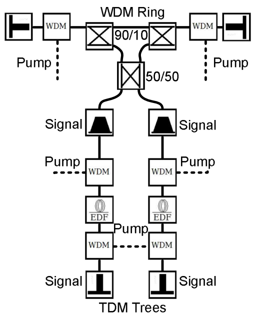


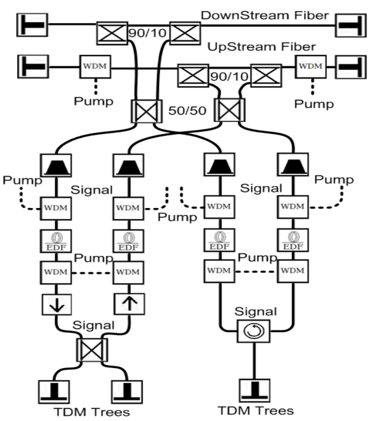
Figure 8. Simple Remote Node signal topology proposed in [10].

The network capacity depends on the splitting ratio K in the trees. Experimental results demonstrate that for a K= 16, 32 and 64 the data rate per user is 125, 62.5 and 32.25Mbps respectively in a GPON at 2.5Gbps for this previous topology.

Despite the simplicity of the implementation of this RN topology, it requires US and DS signals to have different wavelengths to avoid RB distortions not utilizing the spectrum in a efficient way [7].

To avoid the previous impairments of efficient optical spectrum handling and use of non reflective ONU a new topology was proposed in figure 9. In this new configuration the main WDM ring is implemented with 2 fibers instead of 1. One of the fibers is implemented for DS signals and the other for US signals. The US signals follow a similar path with the DS but they pass through different EDFs and different fiber rings. With this topology no more requirements related to RB distortions in the ring and efficiency utilization of the spectrum is required, although, those distortions still remains in the TDM access tree. The pump power to the EDFs is present in the US fiber producing extra Raman gain to the signals with lower power, the US signals. With this RN architecture, the transition from double fiber ring to single fiber tree section is provided by means of a 2:2 optical coupler and two isolators as a more cost effective solution than a circulator. Then the TDM trees are implemented with two 1:16 power splitters per tree.

Figure 9: Double ring fiber Remote Node simple topology proposed in [10]



Four EDFs are implemented in the RN, two for US and two for DS for each tree, increasing the total pump consumption compared with the previous architecture where just two EDFs were implemented. After the remote amplification a second filter avoids adding ASE noise to other signal channels decreasing the OSNR. Finally, for a much more convenient network implementation with identical ONUs, a wavelength agnostic transmission device is implemented. RSOAs are suitable devices due to their capabilities for re-modulation and amplification, as well as their wavelength independence. An ONU has been implemented with a power splitter, an RSOA and a receiver similar to the one user in the CO. This topology allows up to 80 C-band 50Ghz ITU channels at the WDM ring, leading to a maximum network size of 40RNs and 2560 users [10].

It has been experimental proved for 512 ONUs and 50kms ring, 512 ONUs and 100kms ring and 1024 ONUs and 50kms ring with guaranteed downstream bandwidths of 155Mbps per user [8].

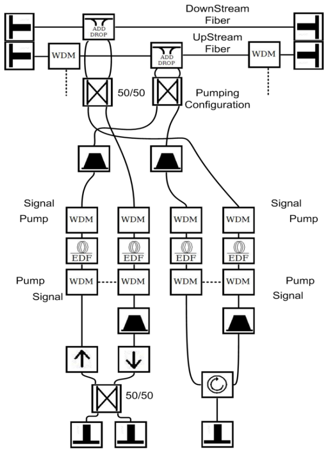
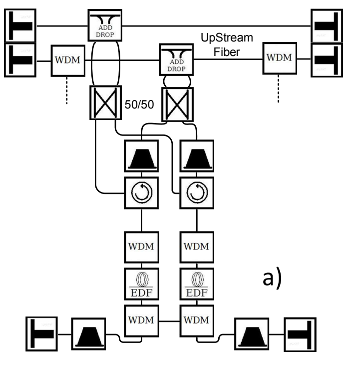


Figure 10: Remote Node topology based on OADM thin filters [10].

With the proposed RN architecture in figure 9, the Add&Drop function is still made recurring to couplers 90/10. Utilizing those couplers, the network is easily scalable and simple to implement but there are important limitations related to the RN insertion loss in the ring. To solve this limitation a topology is presented in figure 10. In here the Add&Drop function is made by means of thin-film filters that is a very mature technology able to provide very good performances at low cost.

The advantage of this RN configuration is the completely transparency for the WDM channels present on the ring being the RN just dropping the assigned wavelengths and not dropping 10% of the total power as the previous and reducing the drop attenuation from 10,2dB to only 0,8dB and the pass IL from 1,4dB to 0,8dB. Each DS EDF amplifies both the DS signals and other thin-film filter is used forward to limit the ASE noise and select the appropriate wavelength for the corresponding tree. Experimental results had demonstrated that with this RN implementation is possible to achieve 1024ONUs by means of 16RN spread over a ring with 100Km [5].



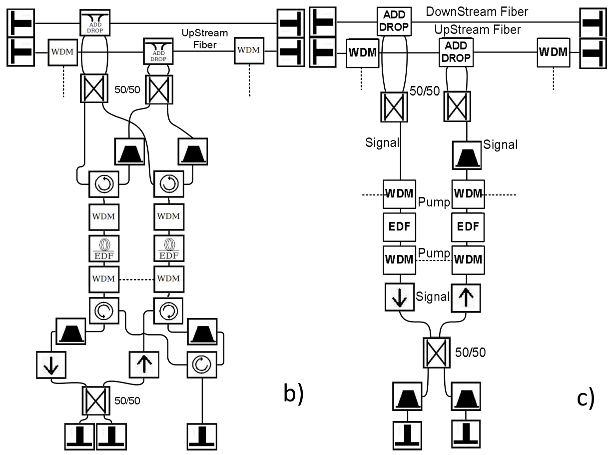


Figure 11: RN topology based on 2 EDFs. a) tunable tree gain, b) multi wavelength with no tunable gain and c) DS and US tunable gain [10].

Despite of the best topology for pumping, improvements can be done in terms of signal topology in the RN. The RN topology proposed previously were implemented with 4 EDFs requiring higher pump power and not using one of the properties of the amplifiers based on EDFs that is the multichannel amplification. To solve that limitation several RNs approaches are proposed based on 2 EDFs RNs [10].

The first solution is presented in figure 11.a). This architecture provides independent gain to each tree of the RN. It can be adjusted depending on the distance of the ONUs from the RN and the number of ONUs per tree. By means of optical circulators, each EDF is supplied with the US and the DS signals of each tree, this means, with the same wavelength. Therefore, the RB distortion in the EDF becomes an important limitation for this RN configuration by causing significant signals degradation [11].

A second proposed architecture with 2 EDFs is presented in figure 11.b). Each EDF is supplied with the DS signal of one tree and the US signal of the other tree, transmitting the two signals at different wavelengths, reducing the RB distortions. This architecture also provides a better stabilization of the transient burst gain. The mains disadvantage of this configuration is that the gain of each signal cannot be adjusted independently [11].

A third alternative to the previous architectures is presented in figure 11.c). An EDF is supplied with the DS signals and the other with the US signals. Since the signals are at different wavelengths, RB distortions are not a limitation. It can also provide independent gain for DS and US signals. This configuration is the adopted as the most appropriated to implement optical switching to select between amplification and non amplification modules since it can operate differently for fiber failure in the US and DS domain [11].

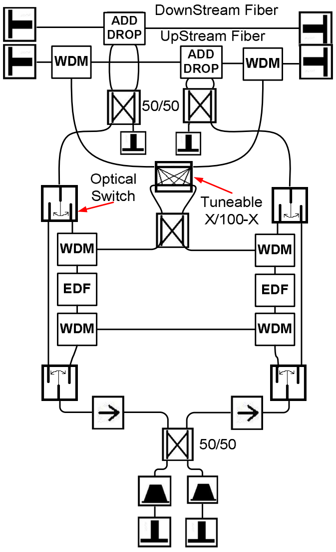


Figure 12: Remote Node topology considering the better pump and signal topologies providing full reconfigurability of the network [10].

The final topology of RN version implemented in laboratory is presented in figure 12. It is able to select a amplifying and non amplifying module and adjust the necessary pump power for operation, reducing the total amount of pump power required per RN, increasing the total efficiency of the network.

EDF analysis

An important component of the RN to understand and optimize is the EDF since it determined the total amount of pump power required per RN. In order to optimize the EDF length and pump power supplied to each EDF experimental tests were made in laboratory. It consists in varying the pump power at 1480nm supplied to the EDF for different lengths as 7.5, 10, 12.5 and 15m and measuring the gain of a signal with -20dBm at 1550.12nm. The figure 13 presents the results of the tests. It can be seen that for achieving gains of 7 the better EDF length is 7,5m supplied with 7dBm; for 11 and 15dB of gain the better EDF length is 10m supplied with 8 and 10dBm respectively. The reminiscent pump power is 3, 3 and 7dBm respectively for 7, 11 and 15dB of gain.

From these results, it can be seen that the reminiscent pump power from the 7 and 11dB of gain is not enough to supply a second EDF, although the reminiscent pump power from the 15dB gain is able to be redirected to a second EDF. This is an important factor developing the amplifiers configuration since it can lead to an optimal low pump requirement multiple amplifiers.

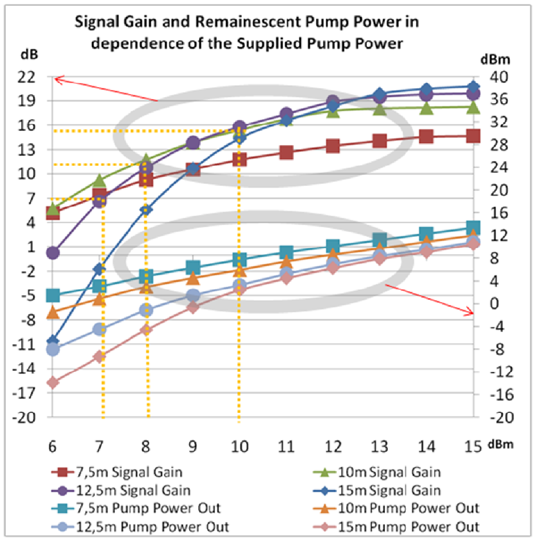
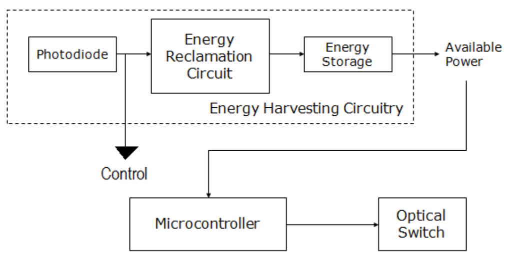


Figure 13: Signal Gain and pump reminiscent in function of the input pump power and EDF length.

VI. RECONFIGURABILITY

The most important component in the re configurability of the network is the power converter, control and harvesting module [13-14].

The figure 14 represents a block diagram of the equipment in the module and the states of operation. An optical signal is supplied to the photodiode present on the module. Part of the converted electrical signal is lead to a control unit by means of an RF component and the mainly part of the energy is supplied to an Energy Reclamation Circuit that will be stored (battery or capacitor). By the other hand, the control module is listening tones codified in the signal until it recognizes a pre allocated pattern and turn on the microcontroller that is in sleep mode. After the pattern an operation is communicated and the microcontroller will control external components, in this case optical switches, with the power stored in the battery/capacitor going back to sleep mode after. Different topologies are being considered in order to increase the efficiency of the module and allow harvesting with lower input powers.



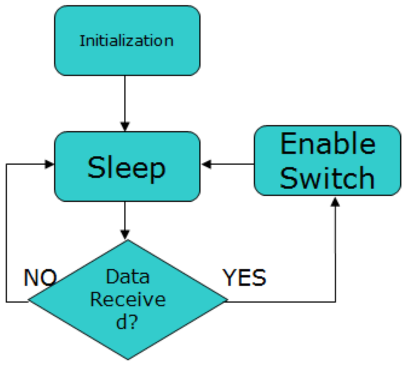


Figure 14. Schematic of the harvesting and control module and the micro controller states.

VI. RN COMPARISON

In order to compare between all the RN topologies the SARDANA network was simulated recurring to the high efficiency operation points of the EDF. The ring is implemented with 20, 40 and 60km with 16RNs each with 2 trees and 32 users per tree 2km distant from the RN, for a total of 1024 users. The comparison is done between the Non Optical Switching (NOS) architecture with a pump topology presented in figure 5.a) and a signal topology presented in figure 10, the Optical Switching (OS) with pump topology presented in figure 5.b), the Tunable Drop (TD) with pump topology presented in figure 7.a) and the Reconfigurable RN (REC) presented in figure 12.

In the figure 15 there is present a comparison of the RNs. In order to compare the different efficiencies of each RN topology is simulated a fiber cut for the RN 8, 12 and 16 and analysis are made to calculate the total requirements of the network in terms of pump power and the number of RNs that are not supplied with enough pumping power to provide the necessary amplification. It should be noticed that the maximum pump power allowed to be produced by the CO is 44dBm. Despite of being extremely high power, it was the limit operation studied in previous analysis.

It can be seen in the figure 15 that the OS topology requires higher pump power than all the others topologies since the IL is higher being this not an efficient alternative. For the implementation of TD topology the required pump power for fiber cut RN8 is the same than for NOS, although for fiber cut at RN16 a reduction of 5,3 and 2 RNs without enough pump power to provide amplification is achieved for 20, 40 and 60Km of ring length respectively. The REC topology provides the higher efficiency of all the four RNs topologies. For fiber cut at RN8 the total pump power required decreases in 5, 3 and 4 dB respectively for 20, 40 and 60Km and for the extreme case, fiber cut at RN16 the number of RNs that do not have enough pump power decreases at 6, 4 and 3 respectively for 20, 40 and 60Km.

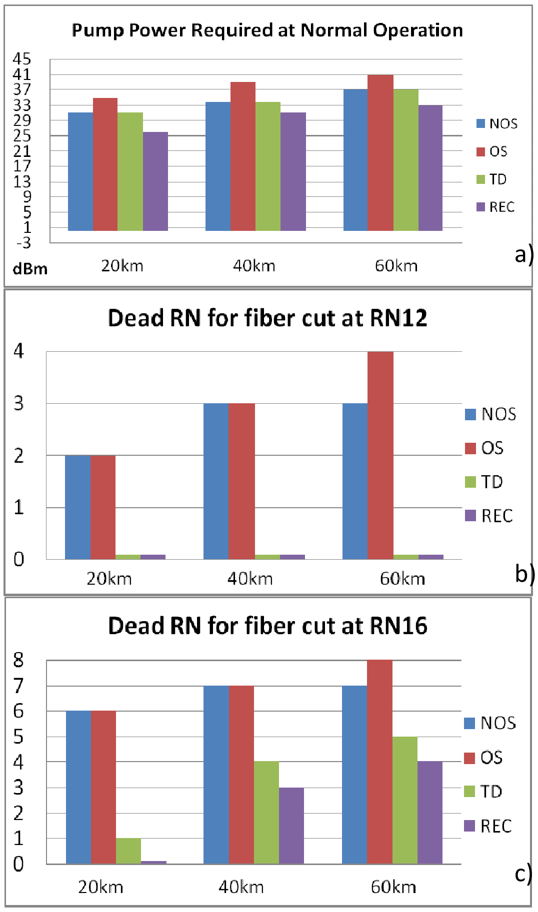


Figure 15. Results of the SARDANA network simulation for 20, 40 60km of ring length. a) Pump power required to the CO, b) number of dead RNs (RN not supplied with enough pump power) for fiber cut at RN12, c) number of dead RNs for fiber cut at RN16.

VII. CONCLUSIONS

The demonstrated SARDANA network provides flexibility, scalability, resiliency, higher user density and bandwidth, robustness and extended reach that are important features for next generation dense FTTH networks also called NG-PONs. It operates in a WDM ring TDM tree topology. Two different main topologies can be applied, one consists on a single fiber ring and the other and more efficient consists on a double fiber ring. To provide simplicity all the light generation and control is placed in the CO and the ONU are based on reflective devices such as RSOAs. The RN as the main theme of this document is presented in several topologies, some of them referenced as state of art and others proposed. There are two distinct evolutions in the RNs, the signal and the pump path.

An analysis to different EDFs with different parameters has been demonstrated. Some important conclusion that had been utilized at the RN architecture development was the use of low doped erbium concentration (5dB/m of peak absorption) as the most efficient solution. For input signal powers higher than -20dBm, the amplifier saturates leading to a reduction of efficiency. In order to provide 7, 11 and 15dB of gain is required 7, 8 and 10 dBm of pump power, for a reminiscent pump power of 3, 3 and 7 respectively.

The control of the tunable power splitter and the module selection switches is done by means of a power converter, harvesting and control module. That module is briefly introduced and presented. Further improvements are required to increase the efficiency of power conversion.

The introduction of tunable pump power splitters and optical switching, introduce significant improvements on the total pump power produced by the CO, diminishing 5, 3 and 4dB for 20, 40 and 60km respectively, at normal operation mode (fiber cut at RN 8). At extreme resilience mode (fiber cut at RN 16), for the same pump power supplied by the CO, the number of RNs with no pump power available (dead RN) decreases 6, 4 and 3 unities for 20, 40 and 60km, respectively.

REFERENCES

[1] R. Davey et al, ECOC 2005, We2.1.3, 2005.

[2] R. Sananes et al, “Techno-economical comparison of optical access networks,” ICTON 2005, Th.A1.8, pp. 201–207, 2005.

[3] Josep Prat, SARDANA, STREP, FP7, 2007.

[4] J.A. Lázaro, paper OTHL2, OFC/NFOEC 2008, 2008.

[5] J.A.Lázaro, “Power budget improvement for passive outside plant long reach high density access network using high bit rate RSOA-ONUs”, ECOC 2007, 2007.

[6] C. Bock, JLT, vol.25, no.6, 2007

[7] C. Bock, “Extended resilient single fiber ring access network featuring EPON/GPON service overlay”, ECOC 2006, 2006.

[8] J.A. Lázaro, “Remotely amplified SARDANA: Single fiber tree advanced ring based dense access network architecture”, ECOC 2006, 2006.

[9] C. Bock, “High density optical burst switched access network combining WDM and TDM over passive optical infrastructure”, OFC 2006, 2006.

[10] A. Baptista, “Hybrid WDM dual fiber ring with TDM single fiber trees passive optical network”, CLME 2008, 2008.

[11] A. Baptista, “Improved remote node configuration for passive ring tree architectures”, ECOC 2008, 2008.

[12] A. Baptista, “Reconfigurable remote node for hybrid WDM dual fiber ring with TDM single fiber trees passive optical network”, ICTON 2008, 2008.

[13] H. Ramanitra, “Scalable and Multi-service Passive Optical AccessvInfrastructure Using Variable Optical Splitters”, OFC 2006, 2006.

[14] H. Ramanitra, “Optical access network using a self-latching variable splitter remotely powered through an optical fiber link”, JOE 2007, 2007.