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DYNAMIC BANDWIDTH AND WAVELENGTH ALLOCATION STRATEGIES FOR LONG REACH WDM/TDM PASSIVE OPTICAL NETWORK

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Abstract

Dynamic Bandwidth Allocation is a major open research challenge in the migration of Passive Optical Network (PON) systems towards Long Reach PON, especially when hybrid WDM/TDM is used (Long Reach WDM/TDM PON). New and efficient solutions for Dynamic Bandwidth and Wavelength Assignment are sought to address two main critical issues of such PON system: how to schedule the transmissions over multiple wavelengths and how to efficiently exploit the bandwidth in presence of long propagation delays that characterize long reach scenarios. While several DBAs have been proposed for long-reach single-wavelength PON systems or for WDM/TDM hybrid PONs (with no regard to the long reach aspect), only few DBAs have been investigated in the case of combined LR WDM/TDM PON scenario. In this work we propose and evaluate a number of Dynamic Bandwidth and Wavelength Allocation schemes with the aim of utilizing the available bandwidth efficiently while reducing as much as possible the average packet delay within a LR WDM/TDM PON. In particular, the algorithms proposed in this thesis are QoS-unaware, which means that QoS requirement of different ONUs are not taken into account. However, the proposed schemes do guarantee a bandwidth to each user.

Sommario

Durante la migrazione dai sistemi d'accesso ottici passivi (PON) verso reti d'accesso a lungo raggio (LR-PON), uno dei campi di ricerca che si apre è quello relativo ai metodi di allocazione dinamici della banda. Questo tema è ancora più importante se si considerano sistemi d'accesso che utilizzano come tecniche di multiplazione sia il TDM che il WDM (LR WDM/TDM PON). In questi sistemi, il design di nuovi sistemi di allocazione dinamica della banda deve essere rivolto, in particolare, alla soluzione di due problemi principali: la ricerca di metodi per assegnare gli slot di trasmissione su reti con più lunghezze d'onda e la ricerca di metodi che siano in grado di sfruttare efficientemente la banda disponibile in presenza di scenari a lunga e lunghissima distanza (fino a 100 km). Molte soluzioni di allocazione della banda sono già state proposte in sistemi LR-PON a singola lunghezza d'onda (LR TDM PON) e in reti ibride WDM/TDM passive, senza però tener conto dei problemi introdotti dalla lunga distanza. Per quel che riguarda gli algoritmi di allocazione dinamica della banda e della lunghezza d'onda in sistemi LR WDM/TDM PON, invece, esistono in letteratura solo poche soluzioni già proposte. Per questo motivo, e considerato l'elevato interesse da parte del mondo scientifico per questi nuovi sistemi d'accesso LR WDM/TDM PON, in questo lavoro di tesi proponiamo e valutiamo diversi schemi di allocazione dinamica della banda e della lunghezza d'onda. Gli algoritmi studiati in questo lavoro hanno come obiettivo quello di cercare di utilizzare la banda disponibile quanto più efficientemente possibile e, contemporaneamente, quello di trovare metodi per ridurre il ritardo medio in rete delle trasmissioni. Le strategie proposte sono valutate attraverso

simulazioni e confrontate con algoritmi esitenti per reti LR WDM/TDM PON. In particolare i sistemi considerati possono essere classificati QoS-unaware, cioè che non differenziano il servizio fornito agli utenti sulla base delle diverse richieste di QoS. Tuttavia, gli algoritmi proposti sono in grado di garantire una stessa capacità minima di trasmissione, in modo da assicurare la fairness tra tutti gli utenti finali.

Chapter 1

Introduction

In the near future due to the new Internet media services, such as symmetrical HD real time applications, videoconferencing, and broadcast it is expected that end users will require much more guaranteed bandwidth than is available today. Bandwidth limitation due to today's copper based and hybrid fiber access solutions will be overcome by FTTH. This technology aims at providing fiber directly to the home. If the implementation of FTTH is based on Passive Optical Network (PON) instead of a point-to-point solution, it is possible to reduce the network cost by eliminating the power supply (operational cost), through the installation of passive network elements, and by sharing a significant portion of the network cost among multiple users.

1.1 Passive Optical Network

Passive Optical Networks [1] are point-to-multipoint access network solutions based on passive components such as optical power splitters. Today's PONs typically support 32-64 subscribers minimizing fiber deployments and providing a subsequent cost reduction.

A typical PON is composed of an Optical Line Termination (OLT) located at the Central Office (CO) and several Optical Network Units (ONUs). A common feeder fiber connects the OLT to a passive optical splitter/combiner, located at the Remote Node (RN), through which the signal is conveyed to each ONU in the network. The ONUs share the upstream channel in the time domain, with Time Division Multiple Ac-

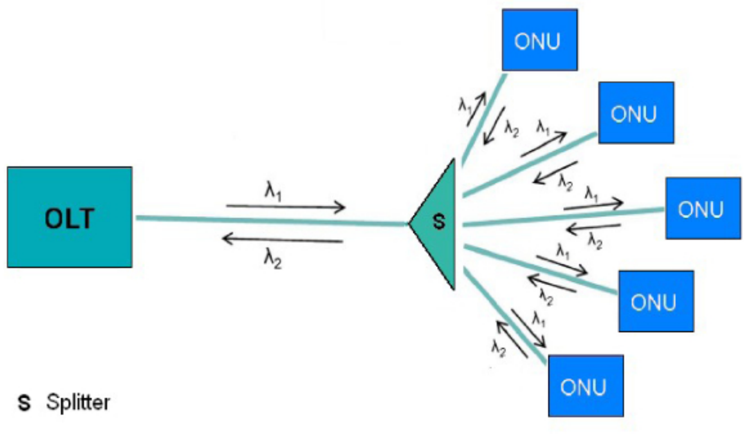

Figure 1.1: TDM PON configuration.

cess techiques (TDMA) whereas the downstream channel is broadcasted to all ONUs. This basic implementation, shown in Figure 1.1, of PON can be also referred to as TDM PON. In a TDM PON the OLT time multiplexes packets and transmit them to the ONUs. As in the downstream direction the signal is split among all ONUs through a splitter. Each ONU, which has a unique identifier, reads the destination address of each packet and selects the ones that match its address. In downstream the synchronization among transmissions for different ONUs is straightforward because is done directly by the OLT, which is the only transmitter in this direction. In the upstream direction, each ONU is assigned a time slot in which packets are transmitted to the OLT through the splitter, which now acts like a combiner, and where optical packets are passively multiplexed. Using more elaborate protocols the time slot duration can be dynamically adjusted according to the need of each ONU allowing for dynamic bandwidth allocation (DBA). DBAs can then be used to better utilize the capacity which is a limited resource.

Different PONs solutions, including Ethernet PON (EPON) [2] and Gigabit-PON (GPON) [3], have been standardized and are commercially available today. In both solutions, the equipment installed, such as optical splitters/combiners, is fully passive, with a network coverage of up to 20 km, and using a point-to-multipoint topology. Moreover, they provide a wide bandwidth to the end users allowing also video broad-

Table 1.1: Basic features of GPON and EPON standards

	GPON	EPON
Standard	ITU G.984	IEEE 802.3 ah
Capacity Downstream (DS)	1244 / 2488 Mbps	1000 Mbps
Capacity Upstream (US)	155 / 622 / 1244 / 2488 Mbps	1000 Mbps
DS/US wavelength	1490 / 1310 nm	1490 / 1310 nm
Typical split ratios	1:32 / 1:64	1:16 / 1:32
Distance range	10 - 20 km	10 - 20 km
Maximum data rate	2.5 Gbps	1 Gbps
MAC (Framing)	GEM	Ethernet

casting (digital and/or analogue). The split-ratio is variable between 32 and 64 users. What makes them different is the MAC protocol and the data encapsulation scheme. While EPON carries bursts of pure Ethernet frames, GPON encapsulates data using Generic Encapsulation Method (GEM) also redefined as GPON Encapsulation Method in [3].

In the last few years, in order to increase the split ratio, the number of network users, and the offered bandwidth, a lot of solutions using Wavelength Division Multiplexing (called WDM PON) have been introduced [4]. A simple version of WDM PON, shown in Figure 1.2, where a different pair of wavelengths, one for upstream and one for downstream transmission, is assigned to each ONU, can provide a large amount of bandwidth to each user. In WDM PONs the ONUs can be classified as: colorless or colored. In the former one, the downstream carrier can be reused or remodulated at the ONUs such that, in this network element, no light source is required [5]. These network components are called Reflective Semiconductor Optical Amplifiers (RSOAs). Another way to implement a colorless ONU is through installing a tunable laser (TL). This component can be dynamically tuned to a particular wavelength according to the needs of the ONU. A colored ONU, instead, need a transmitter/receiver which is set to a particular wavelength. Such feature can be achieved through an array of fixed tuned laser. In order to decrease the costs of operation, administration, and maintenance (OA&M) functions in a WDM PON it is highly desirable to use colorless ONU. Moreover, with these transceivers, mass production becomes possible due to the high number of these components needed into a PON. In such way

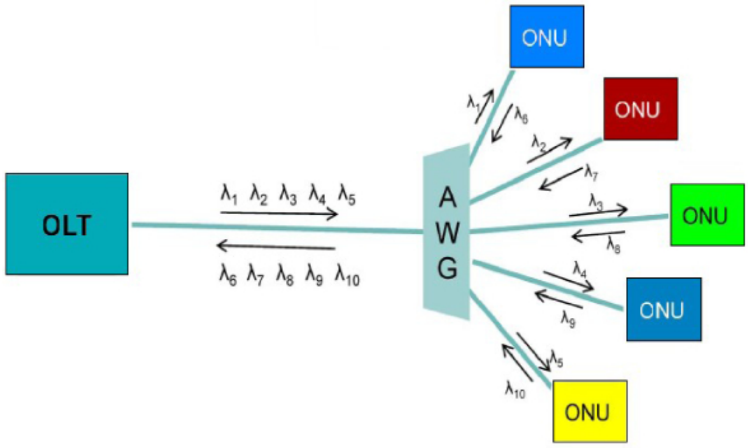

Figure 1.2: WDM PON configuration.

production costs can be reduced.

In a WDM PON, the splitter, usually used in TDM PON, is replaced by a wavelength selective filter implemented with an arrayed waveguide grating (AWG). Besides other more complex functionalities like the wavelength routing function, this component allows to multiplex or demultiplex different wavelengths.

However, the use of a pure WDM PON can lead to inefficiencies in the use of the available capacity because ONUs do not always transmit or use the entire channel capacity. For this reason it is important to combine WDM with TDM in the access system in order to increase the channel utilization by sharing multiple channel among several ONUs. Another reason for hybrid TDM/WDM architectures to be investigated is the need to have a system which is compatible with existing TDM PON architectures. Therefore, the integration of TDM and WDM can ensure the flexibility in bandwidth allocation, and a smooth transition from already placed TDM PONs to high bandwidth WDM PONs.

PON systems which combine TDM with WDM techniques are called TDM/WDM PONs. They are a compromise between the two multiplex schemes which exploit the advantages of both techniques and combine network features of both TDM and WDM PONs.

In such networks splitters and AWG components can be installed together. In this way it is possible to achieve a high split ratio since the

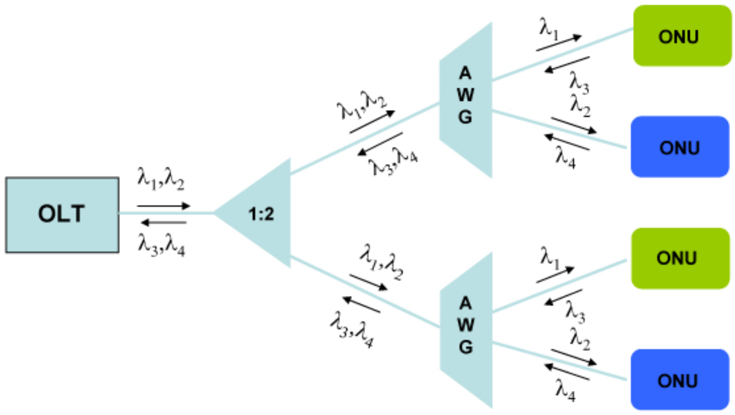

Figure 1.3: TDM/WDM PON: first AWG/SPLITTER configuration.

signal is divided both by the power splitter and by the AWG. Figure 1.3 and Figure 1.4 show two different way to combinate splitters and AWGs into a TDM/WDM PON. In these examples splitters have a split-ratio equal to 2. Moreover, this network configuration allows all the ONUs to share the physical medium in both time and wavelength domain.

Unlike in WDM PONs, where each ONU sends and receives data over a different couple of wavelengths, in hybrid TDM/WDM PONs, ONUs can transmit over different wavelengths. For this reason, ONUs must be equipped with transceivers (TL or RSOA) which allow them to switch from a wavelength to another according to the assignment produced by the OLT.

These particular PONs provide a large amount of available bandwidth, by using different wavelengths and dynamically sharing them, according to the needs of each user, using time-slot allocation. Moreover, as the bandwidth can be shared in both time and wavelength domains, the coordination among different transmissions is even more complicated for these network configurations. For this reason it is necessary to implement efficient schemes for Dynamic Bandwidth and Wavelength Allocation (DBWA).

However, the cost reduction provided by a PON might not be enough for future telecom network. In fact, as an example, research shows that the realization of this kind of fiber access, throughout the United Kingdom, would cost around £ 15 billion [6]. For this reason, an alternative

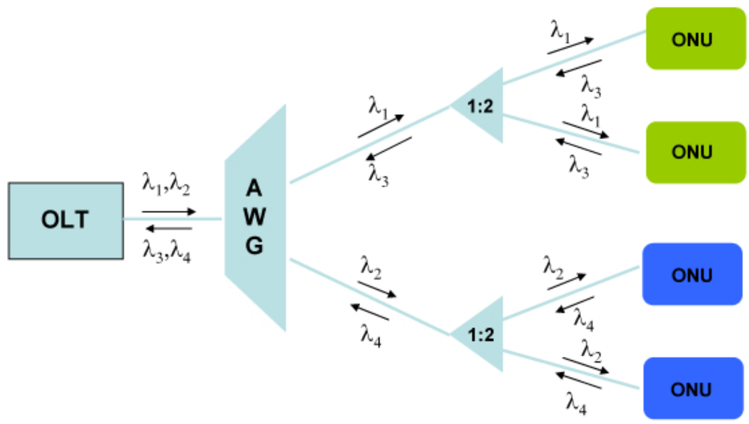

Figure 1.4: TDM/WDM PON: second AWG/SPLITTER configuration.

technology, called Long-Reach Passive Optical Network (LR-PON), was recently proposed as more cost-effective architecture for future broadband access network.

1.2 Long-Reach Passive Optical Network

LR-PON [7] is a solution based on PON architecture that extends network coverage to enable a greater cost reduction by decreasing the number of the network plants. Therefore few control units need to be installed (CapEx reduction) and managed (OpEx reduction). This solution increases the coverage span of PONs from the traditional 20 km range to 100 km and beyond extending the physical reach of the access network to the core network, integrating then the first with the metro network. A general LR-PON architecture consolidates the multiple headend devices known as Optical Line Terminals (OLTs), which were located at the Local Exchange (LE) within PONs, and the Central Office (CO). An extended shared fiber is then deployed to the LE where optical splitters connect users to the shared fiber. By providing an extended geographic coverage, LR-PON combines optical access and metro into an integrated system. In general, the LR-PON can simplify the network, reducing the number of equipment interfaces, network elements and nodes placement. In this way, access headends are closer to the backbone network. Thus,

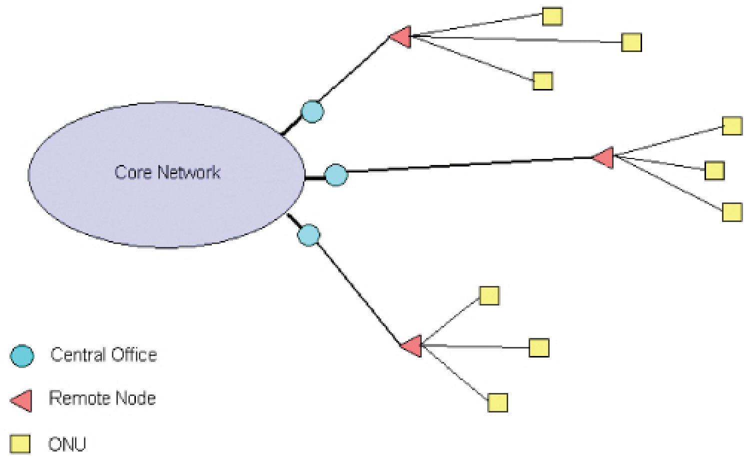

Figure 1.5: Branch and Tree architecture.

each customer no longer requires a dedicated fiber from the local exchange to the premises. LR-PON introduces also a cost per customer reduction. This allows the use of more expensive devices in the LE since the costs of these equipments are shared among a large number of users. On the contrary, it is necessary that the ONUs are as simple as possible to be cost-effective. Furthermore, removal of the metro equipment would free space in local exchange sites, possibly allowing smaller sites to be removed, providing real-estate savings.

LR-PON architectures have two main topological configurations, the branch-and-tree structure, shown in Figure 1.5, and the ring-and-spur topology, Figure 1.6. Branch-and-tree topology is composed of a feeder section, between the CO and the Remote Node (RN), and a distribution section where the optical signal is split among different users attached to the same RN. In the ring-and-spur configuration the feeder section is composed of a fiber ring where different trees networks are connected.

In summary, it is possible to make optical access networks more attractive and more feasible economically through a careful design of the network. LR-PON reduces the fiber requirements and, by increasing the split size, reduces the cost of shared devices. Using an expensive technology in the shared section of the network, such as at the OLT or at the RN, allows a cost reduction of the ONU. However LR-PONs, due to their

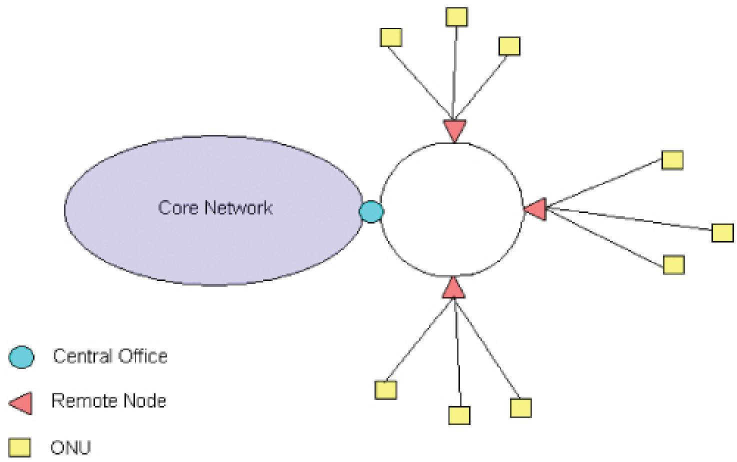

Figure 1.6: Ring and Spur architecture.

particular features and configuration, introduce new research challenges. In section 1.4, some research challenges are explained.

1.3 Long-Reach TDM/WDM Passive Optical Network

The evolution from LR TDM PON towards LR WDM/TDM PON is a quite recent research topic motivated by the need of such network architectures to support higher capacity. LR WDM/TDM PON system is an interesting high bandwidth, energy-efficient future network solution which combines the advantages of Long Reach, WDM, and TDM systems.

The development of LR WDM/TDM PON architectures [15]-[16]-[17] poses a set of new research challenges both in terms of transmission technologies and control protocols. Among the latter, a challenging problem consists in developing new and efficient Dynamic Bandwidth and Wavelength Allocation (DBWA) algorithms for LR WDM/TDM PONs. These algorithms can provide an efficient utilization of the upstream channel and should be devised with the aim of minimizing the average packet delay between the OLT and each ONU.

1.4 Research Challenges

Introducing LR-PON architectures with high distance and high splitting factor introduce a number of new research challenges [8] which need to be addressed, also because these technologies have to be cost efficient in order to be adopted as an access solution.

1.4.1 Network Components

The first of these research challenges is caused by the need to compensate the signal power due to the high attenuation introduced by high splitting factor and long reach. With this aim Optical Amplifiers (OAs) are installed in the network configuration. Unfortunately, these components introduce Amplified Spontaneous Emission (ASE), a device dependent noise, which contributes to lower SNR that is already decreased by the high splitting factor of LR-PONs. Besides, due to burst mode transmission, OAs must be able to adjust their gain fast to output packet with uniform signal amplitude.

In order to lower ONU equipments costs, it is necessary to install optical sources which are cost efficient. A first solution to reach this aim is to use uncooled transmitter which are temperature-dependent and, for this reason, can produce wavelength drift of 20 nm. Wavelength drifts can cause problems when a DWDM system is used because a precise wavelength transmission is required; therefore other solutions like Reflective ONU (R-ONU) have to be investigated. R-ONU, using Reflective SOAs (RSOAs) modulator [9], generates upstream signal from an external carrier which can be placed at the Remote Node or at the Central Office.

Due to burst mode transmission and different signal powers transmitted by ONUs placed at different distances from the OLT, burst mode-receivers [10] are needed in LR-PONs. Some implementations of a burst-mode receiver already exist for actual access technologies but, as in LR-PON the speed of links and the number of customers supported is scaled up, it is necessary to investigate new burst-mode receivers with a higher sensitivity and a wider dynamic range.

1.4.2 Dynamic Bandwidth Allocation Algorithms

Considering challenges at levels higher than physical layer, a wide research field consists of the development of new and efficient Dynamic Bandwidth Allocation (DBA) algorithms for LR-PON [11]. Already existent DBA algorithms, used in TDM PON, are not efficient if used in LR-PON due to high round trip time (RTT) introduced by the high range of this technology. Such feature of PON systems causes important delays due to the signaling procedure, affecting in this way the whole network performance. Therefore it is necessary to implement new DBA algorithms which:

- avoid performance decay due to signaling message delay;
- support different classes of services;
- be scalable in terms of the number of efficiently supported users.

Moreover, with the introduction of LR WDM/TDM PONs, it is also introduced the issue of how to efficiently assign to each ONU the time and wavelength to transmit in order to improve the channel utilization. This problem adds to the challenges of how to efficiently exploit the bandwidth in presence of the long propagation delays and of a higher number of users. Furthermore, these schemes must lead to reduce the average packet delay in order to improve performance and to allow the network to support new Internet media services like symmetrical HD real time applications. Another issue of DBWA algorithms is to fairly share the available bandwidth among all the ONUs also providing Quality of Service (QoS) to the end users. Nowadays several DBAs for LR PON have been presented together with just few DBWAs for LR WDM/TDM PON [12]. Basically, all these algorithms can be grouped in two categories: Qos-aware and QoS-unaware schemes. In particular, in this thesis, we investigate QoS-unaware DBWA methods with the objective of developing new algorithms that efficiently exploit the available bandwidth while reducing the end-to-end traffic delay.

1.4.3 Network Protection

Another high level challenge is protection of the access network. As LR-PONs utilizes the great transmission capacity of optical technology, and it is oriented to serve a large number of end users, any network failure may cause a significant loss of data. Therefore it is necessary and really important to implement efficient protection schemes in LR-PONs [13]. A basic protection system is naturally implemented in the ring-and-spur topology [14] exploiting the two different transmission directions of the ring in case of fiber or node failures. In branch-and-tree topology, instead, can be used a dual homing technique in the feeder fiber section in order to recover from fiber failures. The dual homing technique consists in connecting the same LR-PON to different CO/OLT to ensure that, in case of single node failure, at least one of these two provides connection to the network. In any case protection schemes for LR-PON need further investigation.

In chapter 2 we present different architecture solutions already proposed in literature, which try to solve these new research challenges.

1.5 Work Organization

The rest of the work is organized as follows: In chapter 2 we present a survey on LR PON architectures, from both industry and academy, including branch-and-tree and ring-and-spur topologies. We dedicate chapter 3 to introduce basic Dynamic Bandwidth Allocation scheme features such as the signalling protocol used and the evolution from DBAs designed for PONs to DBAs for LR-PONs. Then, in chapter 4, we survey Dynamic Bandwidth and Wavelength Allocation schemes for LR WDM/TDM PONs already available in literature. Chapter 5 is dedicated to the explanation of new Dynamic Bandwidth and Wavelength Allocation algorithm proposals, while in chapter 6 we report our numerical results regarding these same algorithms. Moreover, in chapter 6 we compare the results of our proposed algorithms and we evaluate their behavior according to the variations of simulation parameters, such as number of wavelengths supported and distribution of the distances between OLT and ONUs. Finally in chapter 7, we conclude this work with some significant observations on the performance of the different scheduling disciplines, and also possible future works are discussed.

Chapter 2

Survey of Long-Reach PON Architectures

In this chapter, we present a survey on the most important industry architectures for Long-Reach PON. In particular, those architectures are divided by topology: branch-and-tree and ring-and-spur. Many of the presented schemes are result of research from industry-academia consortiums or relevant demonstrators present in literature. For each case are provided a background and overview of the network architecture.

2.1 Branch-and-Tree architectures

2.1.1 Reach Extension of a DWDM GPON to 135 km

The DWDM reach extension of a GPON was proposed and tested by R.P. Davey, P. Healey, I. Hope, P. Watkinson and D.B. Payne, of British Telecom, with O. Marmur, of FlexLight Networks, and with J. Ruhmann, Y. Zuiderveld of Infinera in 2005.

Network Architecture

Network architecture [18] of this proposal is based on a 135 km branch-and-tree structure, composed by a 125 km of fiber between the Central Office and the Local Exchange and by another segment of fiber of 10 km between Local Exchange and each ONU. In the first part of

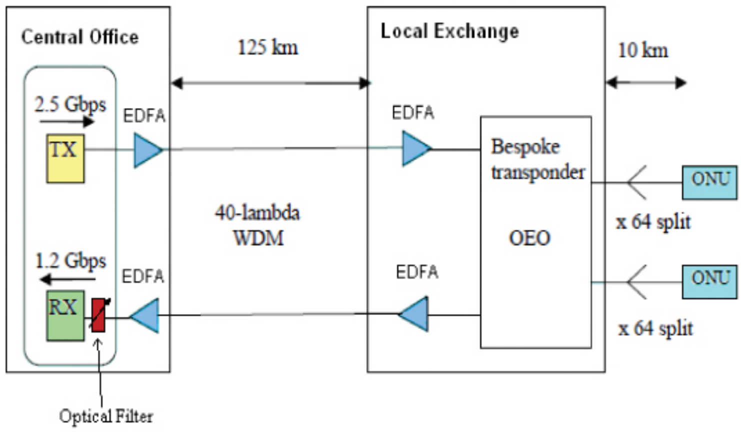

Figure 2.1: Reach Extension of a DWDM GPON to 135 km.

the network, between Central Office and Local Exchange, a DWDM system is used over dual working fibers. In the second part of the network, between Local Exchange and each ONU, a single fiber segment is installed. This architecture, shown in Figure 2.1, can support 2560 users through a DWDM system with 40 optical channels (1 per PON) and a splitting factor of 1:64 for each PON. The 40 optical channels correspond to 40 different wavelengths transmitted, for upstream and downstream, over two different optical fibers. A splitting factor of 1:64 is, instead, achieved through a cascade of two 1:8 splitters. Consistent with ITU-T G.984 GPON standard [3], transmitters and receivers of this solution, located at the Central Office, work respectively at 2.5 Gbit/s and 1.2 Gbit/s. Also the wavelength plan is compliant with the standard, then the OLT transmitter is at a wavelength in the 1490 nm region and the ONU transmitters operate at a wavelength in 1310 nm and some at the 1510 nm region. Since the feeder part uses a WDM system [19], both Central Office and Local Exchange require a wavelength conversion to go from the region compliant with the GPON standard to the WDM-compatible wavelength, and conversely. This functionality is performed at the Local Exchange by a bespoke transponder which implements an OEO conversion. To allow a long reach transmission, Optical Amplifiers are used in both Central Office and Local Exchange, while to improve the SNR an optical filter is placed before the burst-mode receiver, at the OLT side. Due to the incorporation of the optical filter, the temperature

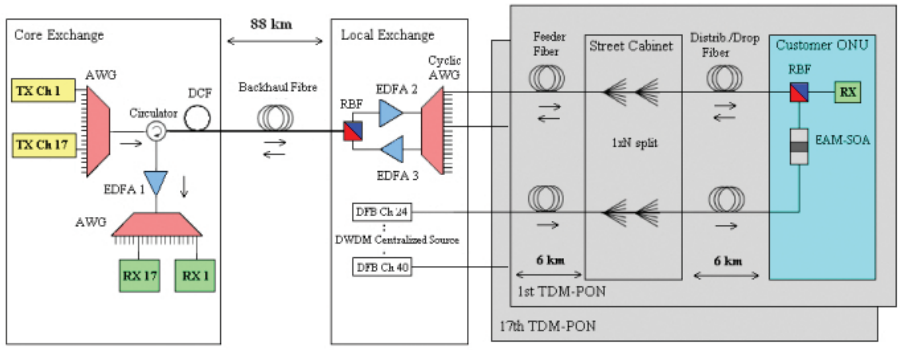

Figure 2.2: Network architecture of the hybrid DWDM/TDM proposal.

control of the system must be precise in order to prevent wavelength drift. This access network solution has a high degree of optical component integration therefore it is possible to significantly reduce the impact, on the network, of access and metro equipment. Using this architecture, the authors of this study, have demonstrated that is possible to achieve a BER better than 10^{-10} in both directions.

2.1.2 Hybrid DWDM/TDM (University College Cork)

This solution [20] was proposed by the Photonic System Group of University College Cork, Ireland in 2006.

Network Architecture

Network architecture of this solution, shown in Figure 2.2, is based on a branch-and-tree structure with a total span of 100 km. This kind of proposal is named hybrid because in the backhaul section is used a DWDM system with 40 different wavelengths, while in the distribution section the network is branched in a set of PON each of which works on a different wavelength to transmit its signal. These branches are named TDM-PON because, in each of them, is used a TDM system to multiplex and de-multiplex the signals belonging to each ONU. Practically, this network scheme, supporting 40 wavelengths, can manage 17 different optical channels, composed by a wavelength pair (one for upstream and one for downstream), and consequently there are 17 TDM-PONs. Each upstream and downstream wavelength has a transmission rate of 10

Gbit/s. The remaining 6 wavelengths are used as a guard band which has a total bandwidth of 5 nm. Each TDM-PON supports a splitting factor of 256 users. This network architecture is divided into four locations:

1. Customer ONU;
2. Street cabinet;
3. Local exchange;
4. Core exchange.

The core exchange is the edge node of the core network. The local exchange is located where the headend equipment of the current-generation PONs and copper access networks are deployed and divides the network into two parts:

- The backhaul section that starts from the core exchange to the local exchange.
- The access part connecting the local exchange to the customers.

The backhaul section fiber has a length of 88 km. Between the local exchange and the street cabinet, there is a 6 km long fiber that will be referred to as the feeder fiber while, between the street cabinet and customer ONU, there is another 6 km long fiber named distribution/drop fiber. To connect the Local Exchange and the Street Cabinet there are two fibers for each TDM-PON and another couple of fibers is deployed to link the Street Cabinet to each ONU.

2.1.3 TDMA 10 Gbit/s LR-PON (University College London and BT)

This solution [21] was proposed in 2006 by Darren P. Shea and John E. Mitchell, which are with the department of Electronic and Electrical Engineering of the University College London, and was supported in part by the EPSRC (Engineering and Physical Sciences Research Council) and BT (British Telecom).

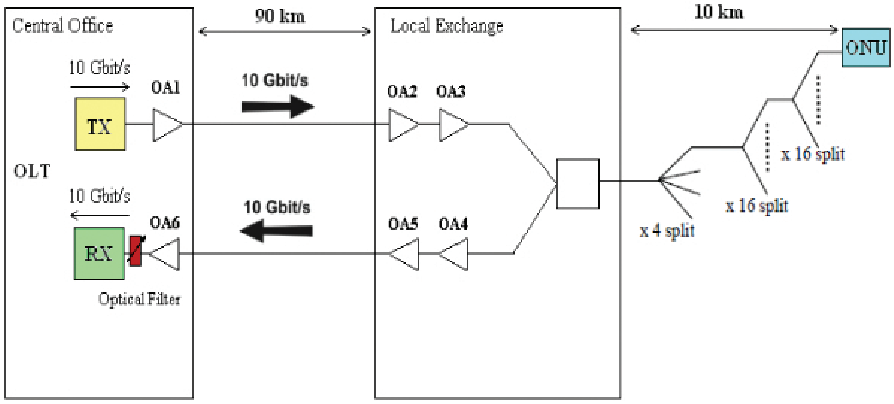

Figure 2.3: Network architecture of the TDMA 10 Gbit/s LR-PON.

Network Architecture

British Telecom Long-Reach PON is a point-to-multipoint solution, also defined as a branch-and-tree architecture, characterized by a 1024 splitting factor, an extension of 100 km and a transmission rate of 10 Gbit/s for both upstream and downstream directions. The 1024 splitting factor is composed of a cascade of two N:16 and one N:4 splitters in the drop section. This system, shown in Figure 2.3, includes a feeder section, between the OLT, located in the Central Office, and the Local Exchange, with an extension of 90 km and a drop section, between Local Exchange and ONUs, with a range of 10 km. In the feeder section, two different fibers are used to divide the upstream channel from the downstream channel. The total bandwidth of the network is shared among ONUs using a TDMA system. The increased extension of the network causes a reduction of optical power budgets; for this reason optical amplifiers are used at the central office and at the local exchange. Another technology, used to increase performance in this solution, is forward error correction (FEC) that is a coding technique through which transmission errors can be detected and corrected by encoding the data. The additional FEC overhead is calculated using a Reed-Solomon code [22] as defined in the ITU standard G.975. FEC can alleviate the system requirement by allowing a pre-FEC BER of $2.9 * 10^{-4}$ to achieve a total BER of 10^{-10}.

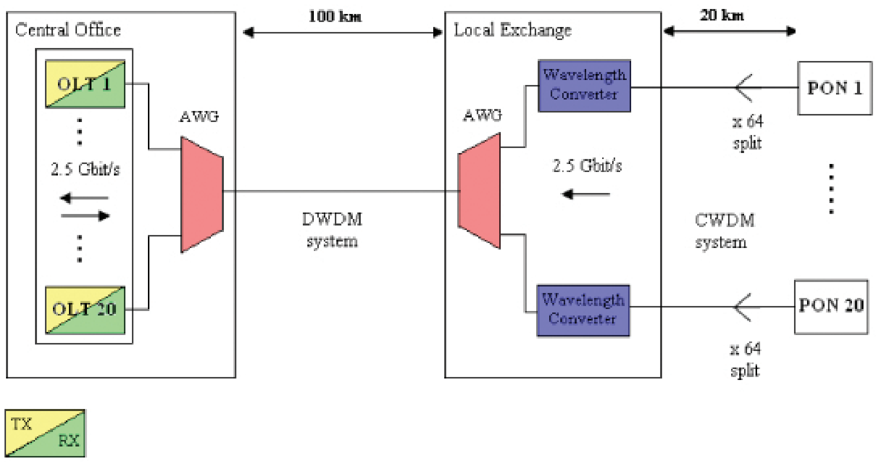

Figure 2.4: Network architecture of the Wavelength-Converting PON.

2.1.4 Wavelength-Converting PON (University College London)

Wavelength-Converting Passive Optical Network [23] is an access solution proposed and experimentally demonstrated by Darren P. Shea and John E. Mitchell from the Department of Electronic & Electrical Engineering of the University College London, in 2007.

Network Archietcture

Wavelength-Converting PON has a reach extension of 120 km composed of 100 km of backhaul fiber, which is the section between the OLT and the Local Exchange, and of 20 km of distribution section, which is a set of PON systems based on the architecture of a GPON. In particular, this access solution, shown in Figure 2.4, can support 20 optical channels, in the backhaul fiber, and then 20 PONs with a splitting factor of 64. Authors specify that it may be possible to achieve a splitting factor of 128, if a Reed-Solomon FEC is used. With a split size of 64, this access network, can support 1280 users. In this architecture, two different schemes to share the bandwidth over the fibers are implemented in the backhaul section and in the distribution section. In the distribution section, as cheap un-cooled sources with potential thermal wavelength drift are used in the ONU, a CWDM system [24] is applied to manage this possible wavelength drift. In the backhaul section, where all the chan-

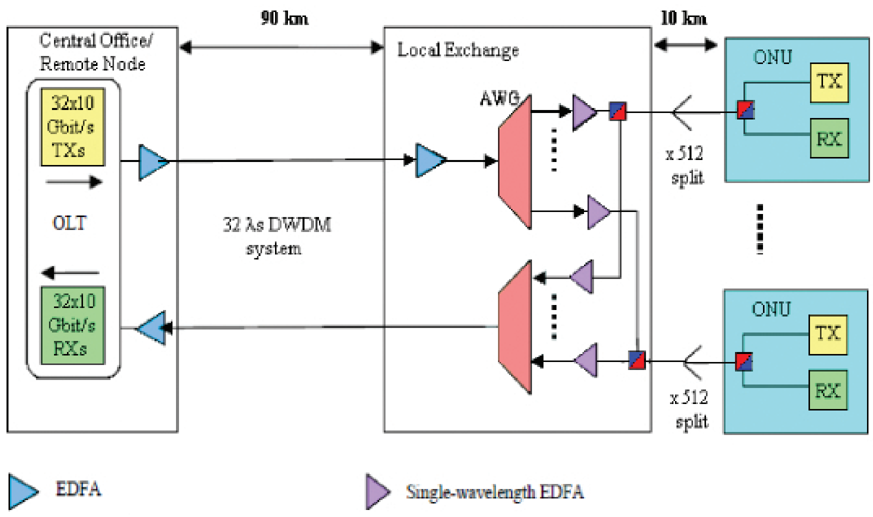

Figure 2.5: Network architecture of the PIEMAN hybrid WDM/TDMA proposal.

nels of the different PONs have to be merged together on a single fiber, a DWDM system is implemented. This network configuration, works at a transmission rate of 2.5 Gbit/s on each channel ensuring each user has a minimum of 38 Mbit/s, regardless the number of users for this architecture with a maximum split of 64 per PON.

2.1.5 Hybrid WDM/TDMA (PIEMAN Consortium)

The Photonic Integrated Extended Metro and Access Network [25] is a solution proposed in 2009 by the University College Cork (Ireland) in collaboration with British Telecom (UK), Centre of Integrated Photonic (UK), Nokia-Siemens Networks (Germany), Alcatel-Lucent (Germany) and Ghent University (Belgium). The IST project PIEMAN, belonging to FP6, has successfully developed a converged metro and access communication system using burst-mode optical components.

Network Architecture

PIEMAN architecture, shown in Figure 2.5, is based on a branch-and-tree scheme and uses a WDM/TDMA hybrid technology. This access solution works at a transmission rate of 10 Gbit/s for each optical channel. The architecture is composed by a Service Node (or Central

Office), where the OLT are located, by a Local Exchange, connected to the Service Node through two backhaul fibers and by the ONUs. The portion of the fiber connecting the Service Node to the Local Exchange has a reach of about 90 km and the fiber connecting the Local Exchange to ONUs has a length of up to 10 km, giving a total network extension of about 100 km. In each backhaul fiber, one used for the upstream and one used for the downstream, 32 wavelengths are used. Each of the 32 couples of wavelengths (one for upstream and one for downstream) is used on a different TDM-PON, each of which serves 512 customers, branched from the Local Exchange to reach ONUs. For the downstream direction the red part of the C-band (1530-1565 nm) is used, and for the upstream the blue one is used. Between the two parts of the spectrum there is a guard band of about 10 nm. This kind of architecture allows therefore to serve 16,384 users. Even in this network configuration it is necessary to amplify the signal along the fiber, due to its large extension.

Despite TDM-PONs are colored, the ONU located at the customer premises are “colorless" in order to reduce costs. In PIEMAN project both Reflective ONU and tunable ONU designs are being investigated. When a colorless device is used, the ONU contains a Reflective EAM-SOA [26], for this reason the name Reflective ONU is adopted. The SOAs are used to amplify the low-power optical carrier at the input of the ONU and to boost the upstream signal after modulation in the EAM, while the EAM is used to modulate the signal, at one specific λ, carried by the Local Exchange. Upstream wavelength for the respective ONU is determined by the OLT at the head-end of the system, either by optically delivering a wavelength-specific carrier which is then re-modulated. Using instead a tunable ONU, the transmitter is a laser which is fixed tuned at a different wavelength for each ONU.

2.1.6 Slotted-PON (National Cheng Khung University and ITRI)

Slotted-PON (SPON) [27] solution was proposed in 2009 by H.-T. Lin, Z.-H. Ho and H.-C. Cheng from the Institute of Computer and Communication Engineering of the National Cheng Kung University in Taiwan, respectively, and by W.-R. Chang from the ICT-Enabled Healtcare Program of ITRI in Taiwan.

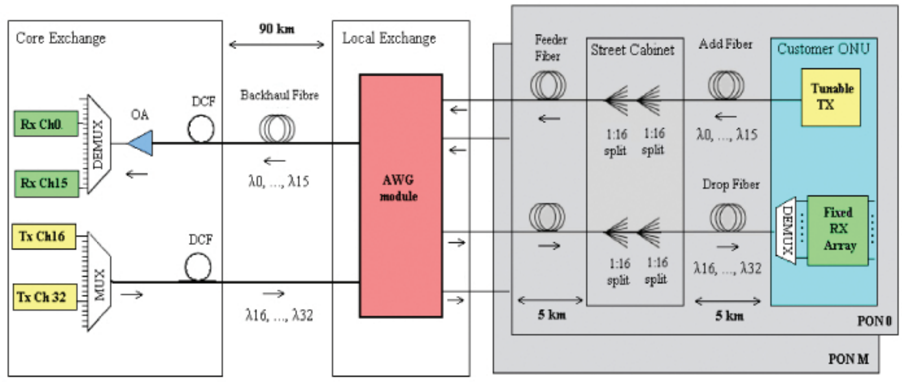

Figure 2.6: Network architecture of the Slotted-PON.

Network Architecture

SPON architecture is composed of four major components which are the Core Exchange, the Local Exchange, the Distribution Section and multiple customer ONUs. This solution is shown in Figure 2.6. The span of this network is around 100 km where 90 km are the Backhaul fiber, between the Core Exchange and the Local Exchange, 5 km are the Feeder fiber, between Local Exchange and the Distribution Section and finally 5 km are the Add/Drop fiber, located between the Distribution Section and each customer ONU. All these sections are composed of two different fibers, one used for upstream and one for downstream. The Core Exchange connects the SPON network to a WAN playing the role of an OLT. This element handles reception and transmission of packets and, for this reason, possesses an OEO conversion capability and must be powered. In this section are also performed amplification and chromatic compensation functions, in order to simplify the equipment requirements at the ONU. In the Local Exchange is performed the wavelength routing function. In particular, in this network, two different traffics are allowed and have to be managed in two different ways. The first of these two traffics is inner traffic which is composed by packets destined for other ONUs attached at the same LR-PON and is routed by the AWG located at the Local Exchange. The second kind of traffic is public traffic consisting of packets which are destined for remote end users attached to a different LR-PON or to a different access network and routed through a WAN via the OLT. Different PONs can be attached to this element through a dual fiber, increasing in this way the number of end users which can be served by a single SPON. The Distribution Section contains the optical splitters used to split the downstream signals among the ONUs and to combine the upstream signals, coming from the end users, into the same upstream fiber. In particular, this access network supports a splitting factor of 256 for each PON achieved cascading two 1:16 optical splitters. In developing the SPON architecture and its wavelength plan, it is assumed that all the ONUs attached to the same splitter/combiner form a single Internetworking Group (IG). Finally, customer ONUs contain transmitter and receivers to manage upstream and downstream signal, respectively. The high number of ONUs and the subsequently high number of different upstream transmissions, which are statistically multiplexed over the same fiber, improve the bandwidth utilization. To support the simultaneous transmission of public and inner traffic, each ONU has dedicated transmission queues for the two traffic types. In particular, a single "public queue" is used to manage public traffic and D separate "inner queues", one for each destination IG, are used for the inner traffic. In this network configuration 32 wavelengths are used to share the total bandwidth where the first 16 (λ_0 to λ_{15}) are used for the upstream transmission over the upstream fiber and the other 16 (λ_{16} to λ_{32}) are used to broadcast signals from the OLT to each ONU, over the downstream fiber. The 16 wavelengths in the upstream fiber, from λ_0 to λ_{15}, are used both for transmission from the ONUs to the OLT and for transmission between ONUs belonging to the same LR-PON. In the latter case, the upstream signal coming from a particular ONU is routed to another ONU by the AWG located at the Local Exchange, forwarding the transmission on one of the first 16 wavelengths over the downstream fiber. In addition to this 32, one single wavelength, λ_d, is used as a control channel, where all the control messages to the ONUs are transmitted in the downstream transmission.

2.1.7 Ultra-DWDM Coherent PON (Nokia-Siemens)

Coherent PON [28] was proposed by Nokia-Siemens in 2009.

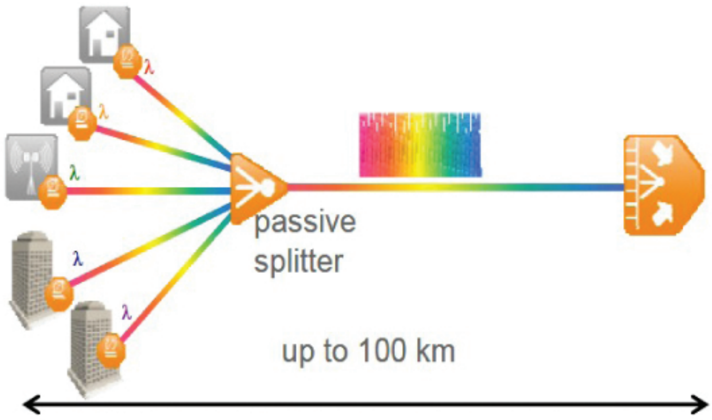

Figure 2.7: Network architecture of the Ultra-DWDM Coherent PON.

Network Architecture

Coherent PON architecture, shown in Figure 2.7, has a reach of 100 km where 80 km, between Core Exchange and Local Exchange, composes the feeder part of the network and 20 km, between Local Exchange and ONUs, composes the distribution part. This particular solution uses as a bandwidth allocation system Ultra-DWDM (UDWDM) which allows a high number of wavelengths to be multiplexed on the same fiber and then a high number of users can be served, assigning one wavelength, with a symmetric data rate of 1 Gbit/s, to each of them. To assign a wavelength to each user an equivalent band-pass filter is installed on every coherent receiver which allows a high wavelength selectivity and, together with the UDWDM, enables the increase of toward hundreds or even more than a thousand wavelengths. The equivalent band-pass filter installed on every receiver permits the elimination of the WDM filters at the splitter site which all other previously proposed solutions need. Therefore the port count is not limited by optical filter technology. Due to resilience reasons, more than a thousand users per fiber are not wanted by telecom operators, thus the number of wavelengths provided by UDWDM is enough to match operator's requirements and, for this reason, there is no need for TDM.

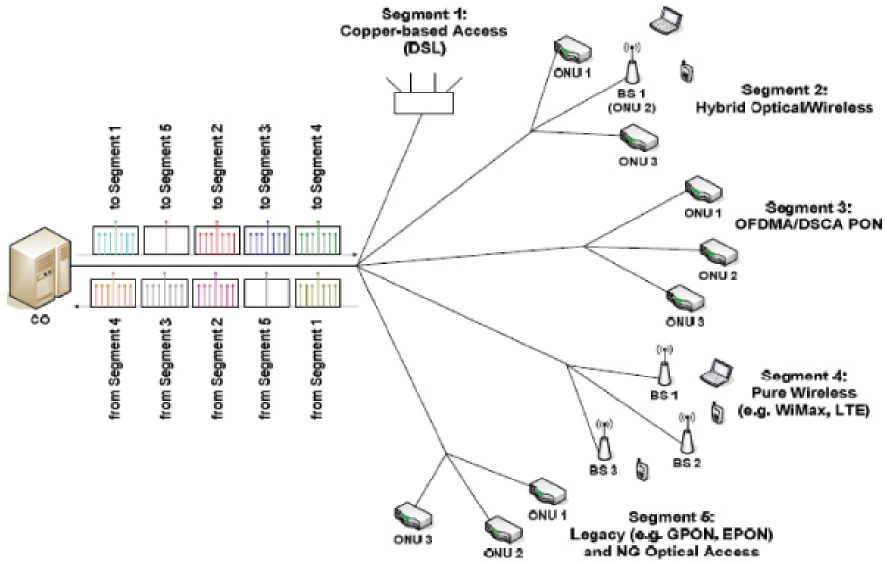

Figure 2.8: Network architecture of the ACCORDANCE Hybrid Wireless/Optical Network.

2.1.8 Hybrid Wireless/Optical Network (ACCORDANCE Consortium)

This solution [29] was proposed by M. Milosavljevic, P. Kourtessis and J. M. Senior from the Optical Networks Group, Science and Technology Research Institute (STRI), University of Hertfordshire (UK) in 2010.

Network Architecture

ACCORDANCE architecture, shown in Figure 2.8, consists of a single OLT located at the CO and different kinds of user premises as ONUs or at a wireless base station (BS) used to provide connectivity to mobile terminals. The ONUs and the BS are connected to the CO through a single feeder optical fiber which transports both upstream and downstream signals with a span that ranges from 20 km to 100 km in the simulation scenario. The downstream signal is broadcasted to all the network segments through a passive splitter. The number of ONUs which the network can support, vary from 16 to 256 depending on the number of subcarriers used in the OFDM modulation. This solution uses, as a bandwidth allocation system, OFDM modulation. In particular in each network segment is used a different FDM channel each of which is composed by a set of subcarriers to multiplex the signals coming from different ONUs. In each FDM channel there is a number of subcarriers that ranges from a few tens to hundreds. OFDM is a powerful transmission technique that, depending on the transmitter and receiver implementation, can realize up to 100 Gb/s and up to 100 Km reach, in some cases without the need of using optical amplification or/and WDM. The use of OFDM technology in the optical domain also offers the possibility to facilitate the integration between wireless and wired networks. As the two transmission systems will use the same modulation format, it is possible to allocate different bands inside the frequency spectrum for different applications. The OFDMA/dynamic subcarrier allocation (DSCA) segment represents pure OFDM where subcarriers are allocated to users dynamically depending on bandwidth demand. In this way it is possible to efficiently use the total bandwidth of the network. It is also to notice that to generate OFDM successfully the relationship between all the carriers must be carefully controlled to maintain the orthogonality between them.

2.1.9 Energy-Efficient Extended-Reach WDM/TDM PON (University of Melbourne)

This cost-effective and power-efficient extended-reach WDM/DM PON system [30] was proposed in 2011 by Hao Feng, Chang-Joon Chae and V. Tran from the University of Melbourne in Australia.

Network Architecture

The network architecture of this proposal has a reach of 120 km composed of 50-100 km of feeder fiber, between Core Exchange and Local Exchange, and of 10-20 km, between Local Exchange and ONUs, of distribution fiber. The architecture of this access solution is shown in Figure 2.9. As bandwidth allocation system includes a WDM system, supporting 16 optical channels for a total of 32 different wavelengths, and a TDM system in each PON, one for each couple of wavelengths,

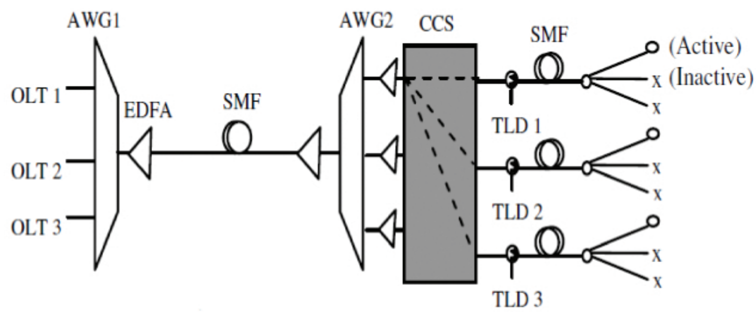

Figure 2.9: Network architecture of the Energy-Efficient Extended-Reach WDM/TDM PON.

with a splitting factor of 32, the total number of users supported by this access network is 512. The transmission rate with which the system has been tested is 10 Gbit/s. At the OLTs downstream signals are generated and then multiplexed on single mode fiber (SMF) with an AWG located at the Central Office (CO). Each OLT works at a specific wavelength. Before the long distance transmission on the SMF the signal is boosted by a bidirectional EDFA. At the Remote Node (RN) another AWG is placed, to de-multiplex different wavelengths to different TDM-PONs, with two in-line amplifiers to compensate the component and fiber losses. After these components a channel combine/split module (CCS) is used to route a particular wavelength, managed by a single OLT, on different PONs to reach different end users, as shown in Figure 2.9. In the upstream link, tunable lasers provide required wavelengths for the colorless transmitters, implement through R-SOA, at the customer sites. This procedure could be remotely and dynamically controlled with an out-of-band communication channel between DBA modules and CCS.

2.2 Ring-and-Spur architectures

2.2.1 SUCCESS Hybrid WDM/TDM PON (Stanford University, STM)

The SUCCESS Hybrid WDM/TDM PON or SUCCESS-HPON [31]-[32] is a novel optical access network architecture proposed by the Photonic and Networking Research Laboratory of the Stanford University

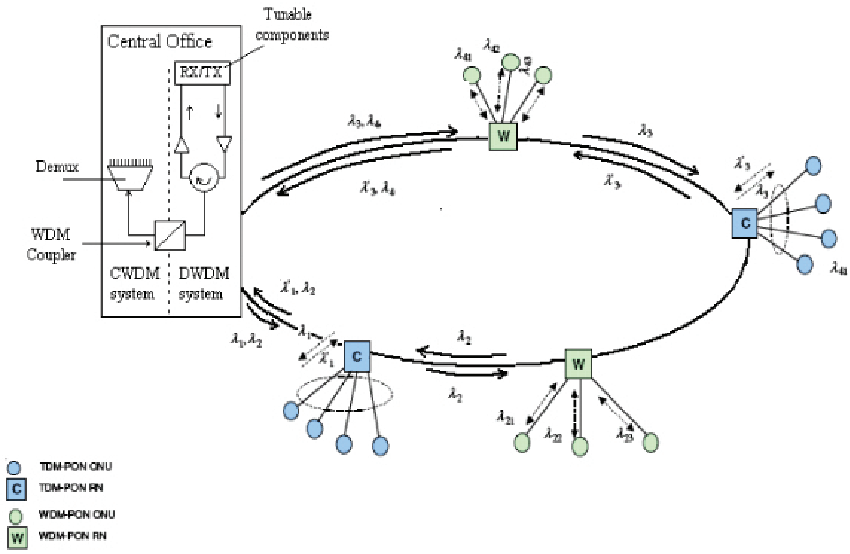

Figure 2.10: Network architecture of the SUCCESS Hybrid WDM/TDM PON.

with the collaboration of STMicroelectronics and sponsored by Stanford Network Research Center, STMicroelectronics, KDDI and Motorola. This solution was proposed for the first time in 2004 and then continued in subsequent years.

Network Architecture

SUCCESS-HPON has a ring-and-spur based architecture and is then composed of a single fiber collector ring with stars attached to it via a Remote Node (RN), which is, practically, the center of the tree sub-networks. This solution, shown in Figure 2.10, is proposed to provide a smooth migration from current TDM-PONs to higher bandwidth WDM-PONs. For this reason authors introduce an architecture where the tree sub-PONs attached to the ring, may be TDM-PONs and also WDM-PONs while, on the collector ring, a WDM system is used. In this network configuration, the ONUs attached to the RN on the west side of the ring talk and listen to the transceiver on the west side of the OLT, the same applies to the ONU attached to the RNs on the east side of the ring. At a logical level, there is a point-to-point WDM connection between the

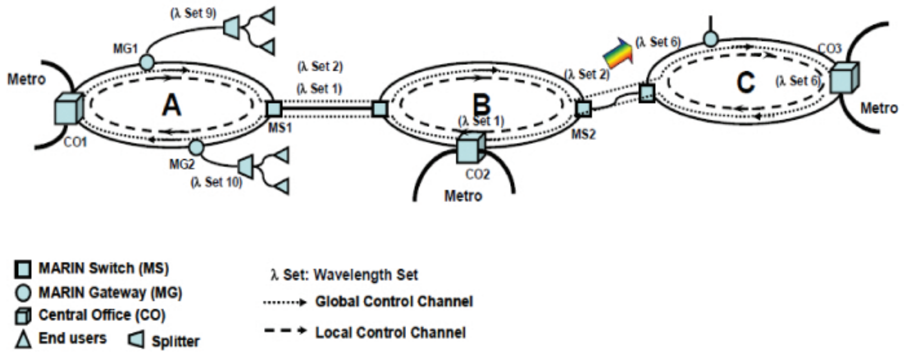

Figure 2.11: Network architecture of MARIN.

OLT and each RN, on the collector ring, where no wavelength is reused. Generally, each RN, links 16 to 64 WDM-PON ONU. Optionally, semi-passive RNs may be used to sense fiber cuts and change the orientation of their transmissions, if extra reliability is desired, in the access network. SUCCESS-HPON was successfully demonstrated with a total span of 40 km composed of four sections of the ring, where each section is the fiber between two RNs: two of these section have a length of 2.2 km and two others section have a length of 15 km; between each RN and ONUs there is a span of fiber of 5 km. The transmission rate, used in the demonstration is 1.25 Gbit/s.

2.2.2 MARIN (Stanford University)

Metro-Access Ring Integrated Network (MARIN) [33]-[34]-[35] is a novel integrated metro and access network architecture based on centralized resource sharing, proposed by the Photonic and Networking Research Laboratory of the Stanford University in 2006 and further developed in 2007.

Network Architecture

MARIN architecture, shown in Figure 2.11, is based on the interconnection of multiple access ring networks to form a mesh network integrating metro and access in a single network. Attached to ring networks, there are multiple passive tree networks to reach the end-users, which may be geographically distributed on a wide area. In particular, MARIN is composed of different sub-systems, which are connected together through a MARIN Gateway, each of which includes an access ring and multiple tree networks, compatible with TDM-PON infrastructure. The rings support DWDM. Each MARIN ring is connected to a metro area network (MAN) through a Central Office (CO), which transparently routes the MAN traffic to the others COs in the network. The connection between MARIN rings is then provided by MARIN Switches. Due to this particular configuration in MARIN, two different traffic types can be identified: the traffic coming from access users in the tree networks, and the tunneling traffic, coming from the MAN and not destined to the access users in the MARIN system but to another MAN. To manage these two traffics, two groups of wavelengths are used: one assigned to access traffic, and one which carries the MAN traffic. Wavelength sets are dynamically assigned to the MARIN Switches in a sub-system. Since each ring supports a DWDM system, each tree network is addressed with a set of wavelengths, which number changes according to the total number of wavelengths used in the system. In each TDM-PON tree, wavelengths are shared among users with a TDM system. The feasibility of this solution has been demonstrated through experimental testbed simulations, where the performance of key components in the physical layer is examined.

CO connects the metro network to a MARIN ring interfacing also with the hub of metro-core network and, in each sub-system, schedules the distribution and collection of access traffic to and from the end users. Furthermore, it coordinates with other COs to forward MAN traffic, through the MARIN network. A general CO architecture includes different sets of receivers (RXs) that are used to receive the upstream access traffic, managed with a CWDM system at a wavelength 1.3 μm, and the tunneling MAN traffic, which is handled with a DWDM system at 1.5 μm. The CO also contains transmitters (TXs) consisting of a set of regular tunable lasers (TLs) multiplexed by a cyclic AWG. The benefit of using this TX module is that TLs can be gradually added according to the real growth of the number of users connected to the tree network. TLs allow also to dynamically allocate the wavelengths in the network. For reception purposes the ONU contains a band splitter to separate the DS and the US traffic, followed by a DWDM filter to extract its own traffic on a particular λ and finally the receiver. In order to transmit the upstream signal there is a CWDM transmitter. A MARIN Switch interconnects two MARIN rings, hence, it is the key component enabling MAN traffic routing on MARIN. The MARIN Switch is controlled by the CO of the sub-system through a Local Control Channel (LCC) to dynamically reconfigure the drop/pass wavelength bands. This component separates the traffic signals and the control signal, which is converted to the electrical domain for processing. The core of a MARIN Switch is a 1x2 cyclic Wavelength Selective Switch (WSS) consisting of 3 cyclic AWGs and optical switches. With this component, an entire set of wavelengths transporting MAN traffic can be dropped or passed independently to each other. The switch configuration, which determines the dynamic wavelength routing, is set by an electrical unit in the MARIN Switch. Finally MARIN Gateway interfaces between the ring and the passive distribution network. This Gateway drops the set of wavelengths which carries the downstream traffic from the ring, returning it to the end users in the tree-network.

2.2.3 XL-PON (Nokia Siemens)

Extra-Large PON (XL-PON) [36] prototype was realized in the framework of the IST project MUSE belonging to FP6, by Michael Rasztovits-Wiech and Andreas Stadler, from Siemens IT Solutions and Services PSE (Austria), respectively, and Karl Kloppe, from Nokia Siemens Networks (Germany) in 2006 and completed in 2008. This work was partially funded by the European Commission.

Network Architecture

XL-PON prototype, shown in Figure 2.12, has a ring-and-spur based architecture with a total extension of 100 km, where 70 km is the span of the ring and 30 km is the length of tree PONs, connected to the ring. Tree networks have a total split size of 512 but also of 1024 in the later version and are attached to the ring through Metro Access Points (MAPs). The 512 splitting factor is achieved using a 1:8 splitter in the MAP and 1:64 splitter located at a Remote Node. The approach used in this solution is to reuse and adapt proven TDM based GPON technology,

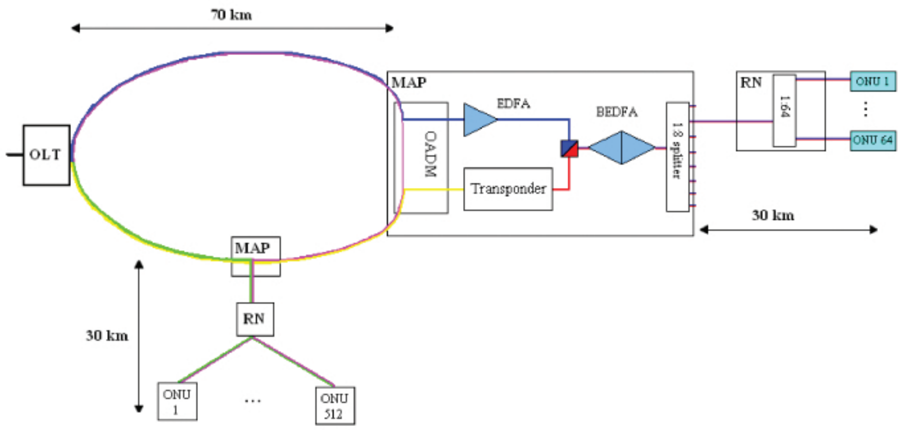

Figure 2.12: Network architecture of XL-PON.

increasing its data rate and splitting factor. In the ring, instead, WDM system is used to share the bandwidth. This access network solution has a transmission rate of 10 Gbit/s for downstream direction and 2.5 Gbit/s for upstream direction, using Reed-Solomon FEC. A transmission with a 2.5 Gbit/s rate, through a 100 km system and with a 1024 splitting factor is a word record, in 2008, according to the authors. The overall architecture has been tested through end-to-end experiments.

The implementation of the XL-PON prototype uses the same components for both OLT and ONT. For the downstream transmission the OLT uses commercial 10 Gbit/s transceivers, while the for the upstream transmission the colorless ONU uses self-designed burst-mode modules which are 2.5-Gbit/s-based transmitters and receivers. In particular all ONUs are able to receive all possible downstream wavelengths, in this case a couple of channels in a 100 GHz grid around 1555 nm. Further all ONUs use the same upstream wavelength, in this case 1531.1 μm.

MAPs are implemented with low power consumption components and are located on the ring to connect to TDM-PON networks. The MAP functions are:

- To drop wavelengths from the ring;
- To relay them to the end users of each tree sub-network;
- To add to the ring the upstream traffic.

For this purpose, MAP contains an OADM which is followed by a pre-amplifier (PEDFA) which operate at a constant output power to boost the signal before it is forwarded to the users and to pre-amplify the upstream signal. Another amplifier, a bidirectional EDFA (BEDFA), is then used to amplify both downstream and upstream signals. In this way it is possible to amplify the upstream signal bursts without distortion in an EDFA. The downstream output power at BEDFA is controlled to a constant power level. Therefore a BEDFA, located just before the splitter, allow bidirectional and burst-mode operations OAs are located at this point of the network to allow cost sharing among a high number of users. In the MAP, is also provided a 3R regeneration and, for this purpose, are installed a transponder, followed by a 1:8 splitter. This last component is used to split and combine the signal directed to and coming from the ONUs. The 2.5 Gbit/s burst transponder works on the upstream traffic to convert the local upstream wavelength to a wavelength which can be used on the ring. This component implements functionality like autonomous burst detection, high speed CDR and gap removal.

2.2.4 WDM-Ethernet PON (ETRI)

WDM-Ethernet PON [37]-[38] solution was proposed B.W. Kim et al., from ETRI, in 2007.

Network Architecture

WDM-Ethernet PON (WE-PON) architecture, shown in Figure 2.13, is based on a ring-and-spur scheme where 16 TDMA-based PON are attached to a central WDM ring. On the ring, 16 different wavelengths are transmitted one for each TDMA-PON in which the channel is split with splitting factors that may range from 8 to 32. These features describe the FTTC configuration of WE-PON architecture. WE-PON may be used also in FTTH configuration. In this case, the ring is composed of a set of fibers reaching different AWGs, where the wavelengths transported over each fiber are forwarded to ONUs. The FTTH configuration of this netwrok solution is shown in Figure 2.14. In order to lower the ONU cost in this access network solution, it is used a wavelength-reuse mechanism in which the upstream signal is obtained by flattening the

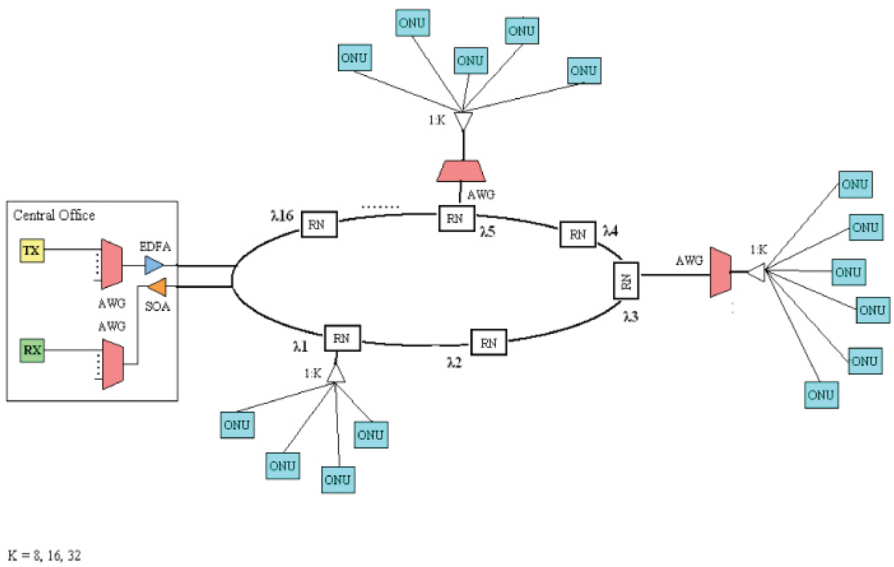

Figure 2.13: Network architecture of the WDM-Ethernet PON.

downstream signal and re-modulating it with the upstream data. In this way, it is not necessary to install a transmitter in each ONU but it is sufficient to use a reflective component. The authors obtained that, with this architecture, it is possible to have a transmission rate of a few tens of Mbit/s at a similar cost to GE-PON.

WDM multiplexer/de-multiplexers (WDM MUX/DEMUXs) are located both at CO and RN. At the CO, two WDM MUX/DEMUX are used. The first to merge together, over the same optical fiber, different wavelengths in order to forward them to ONUs, while the second splits the set of wavelengths coming from the ring to different receivers. At the RN, a single WDM MUX/DEMUX is used both to divide the set of wavelengths coming from the ring among ONUs and to multiplex all the wavelengths on the same fiber, in order to transmit them over the fiber ring. This functionality is accomplished when the WE-PON is used with a FTTH configuration.

A Reflective SOA (RSOA) is located at the receiver and its function is to reuse the signal received, with the aim to re-transmit the upstream signal at the same wavelength. It is then necessary to flatten the downstream signal, which carries downstream data, in order to have an optical carrier to modulate with upstream data. To erase the downstream data

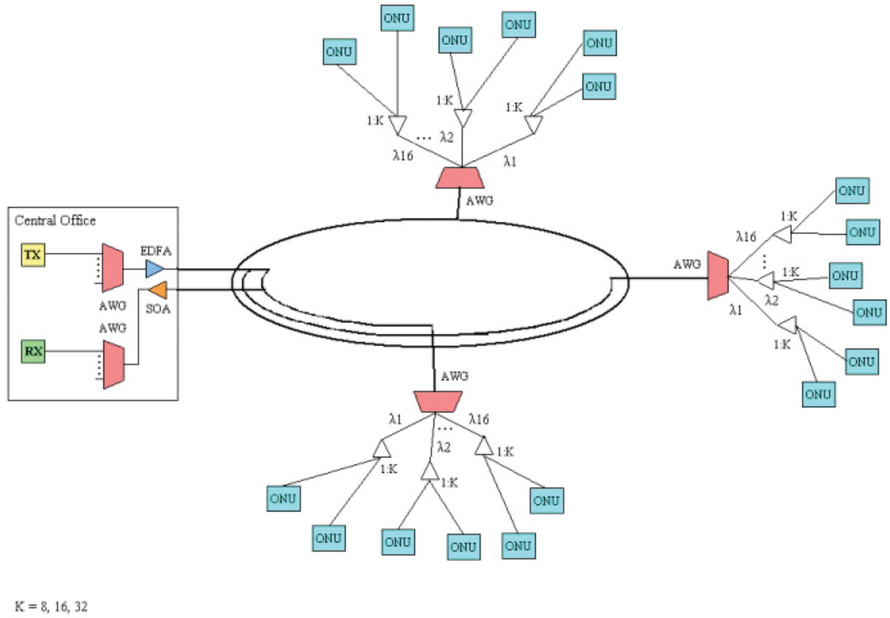

Figure 2.14: Network architecture of the FTTH configuration of the WDM-Ethernet PON.

in the injected light, the RSOA should operate in the gain saturation regime, requiring a high injection optical power. Therefore, it is imposed an upper limit of the allowable link loss between Central Office and ONTs. The authors of this work also proposed an additional electrical compensation scheme, called Feed Forward Current Injection (FFCI), which controls optical gain of RSOA by injecting different amount of current in the opposite direction to the level of downstream optical signal.

2.2.5 Scalable Extended Reach PON (SARDANA Consortium)

The Scalable Extended Reach PON (SARDANA) [39] is network access solution proposed by J.Q. Làzaro (UPC), J. Prat (UPC), P. Canclou (France Telecom R&D), G.M Tosi Beleffi (ISCOM), A. Teixera (IT Portugal), I. Tomkos (Research and Education Laboratory in Information Technologies, Athens), R. Soila (Tellabs Oy) and V. Koratzinos (Intracom S.A Telecom Solutions) in 2008. This work is supported by the FP7-ICT project "SARDANA".

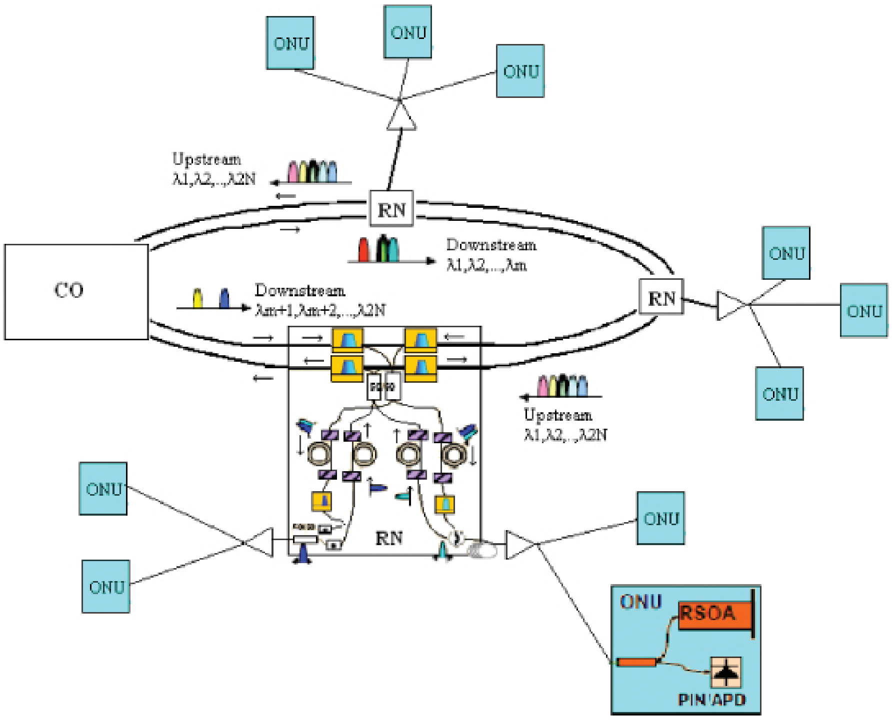

Figure 2.15: Network architecture of the Scalable Extended Reach PON.

Network Architecture

SARDANA has a ring-and-spur architecture where a WDM double-fiber-ring, with an extension of 100 km, supports TDM single-fiber tree sections and where transmission rates of 10 Gbit/s, for downstream, 1.25/2.5/5 Gbit/s, for the upstream, could be provided. This proposal, shown in Figure 2.15, has the aim of reusing standard G/EPON equipment from current and next generation 10G versions adapting ONT and OLT can be adapted to SARDANA PON by the corresponding optical interfaces. The WDM double-fiber-ring transports a minimum of 32 wavelengths each of which serves one TDM-PON with a minimum splitting factor of 32. With this configuration, the access network can support more than 1000 users. In a single TDM-PON, actually, is also possible to transmit several wavelengths enabling a number of operators to share fiber plant and allowing the users to select the operator by easily exchangeable filters at the ONU. To avoid Rayleigh-Backscattering impairments [40], WDM is implemented by a double fiber ring while in

TDM-PONs it is used a single fiber with bidirectional propagation.

The CO provides different functionalities to control the network. One of these tasks is routing the wavelengths on the ring, in case of fiber failure. This is possible because the ring structure allows two paths from the CO to each RN. If one of these two paths is involved in a fiber failure, the second one can be used to route the traffic through the network. Another functionality provided by the CO is the centralization of the light generation of the whole network, so that it is not necessary to install a light source in the ONUs, making them cheaper. For this aim, a stack of lasers is installed at the CO. While providing light source to the network the CO supplies also the optical pump.

A RN is used to connect the TDM-PONs to the ring providing a 2-to-1 fiber section interface. Employing athermal thin-film filters, RN can simultaneously select a wavelength from the ring and provide add-and-drop functionalities of the chosen wavelength, remaining transparent to the other wavelengths. To provide resilience against ring-fiber cuts, RN can receive the signal either from east or west fiber connection. Furthermore, this component contains remotely pumped EDFs in order to provide signal amplification.

As in previous solutions, ONU has to be simple and low cost. For this reason, a colorless ONU is used which are efficient for decreasing device cost by a mass-production and can also reduce costs of operation, administration and maintenance functions. Two solution to implement a colorless ONU are explored, the first using a RSOA and the second with a more advanced device which integrates SOA with an REAM.

2.2.6 STARGATE (INRS and Arizona State University)

STARGATE [41] is proposed by M. Maier and M. Herzog (INRS) with M. Reisslein (Arizona State University) in 2007.

Network Architecture

This proposal, shown in Figure 2.16, has a ring-and-spur architecture where an RPR-based ring is used integrated with EPON tree networks. At the ring is also connected a central double-fiber star-network managed through two optical devices, placed on the middle of the star. The CO,

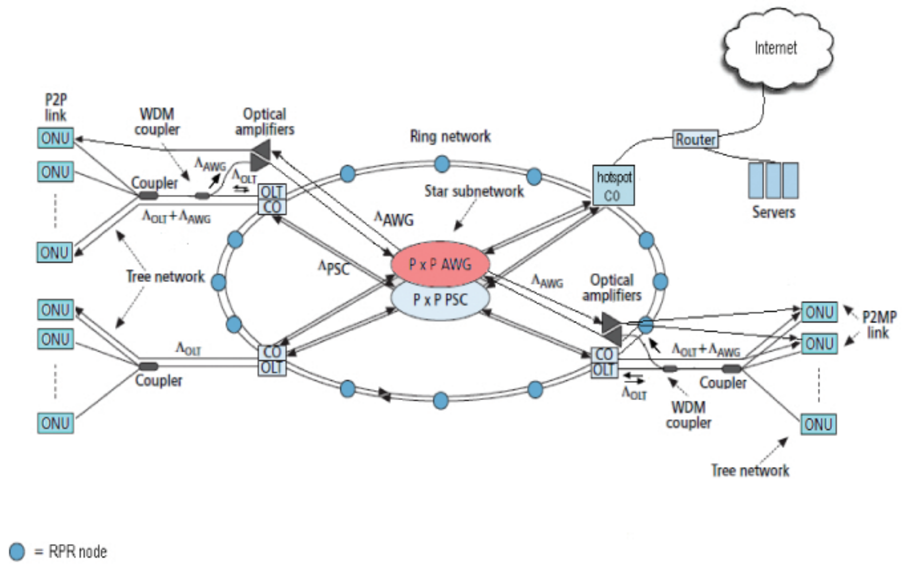

Figure 2.16: Network architecture of the STARGATE solution.

located on the ring together with the OLT, connects ONUs in EPON networks to the ring and to the central device, named Passive Star Coupler (PSC). In STARGATE, authors explored the possibility of deploying an additional point-to-point or point-to-multipoint fiber link in EPON, to connect the OLT to one or more ONUs in order to implement an evolutionary SDM upgrades. To connect these ONUs to the rest of the network, the CO may be bypassed with an all-optical connection through the second optical device located in the middle of the star, which is an AWG. In the experimental setup of this solution a span of 100 km for the RPR ring and a span of 20 km for EPONs have been achieved with a transmission rate of 1 Gbit/s in each tree network and of 10 Gbit/s in the ring. STARGATE implements a wavelength plan where different sets of wavelengths are used in different parts of the network, to address different devices. In particular, are used λ_{AWG} channels, one for each CO, over each fiber going to and coming from the central AWG. To communicate with the PSC there will be used λ_{PSC} = 1 + H + $(P-1)$ channels, over each fiber going to and coming from the Passive Star Coupler, where P is the number of COs and H is the number of dedicated home channels. These set of channels consists of: 1 control channel, H dedicated home channels for the hotspot at the CO, where

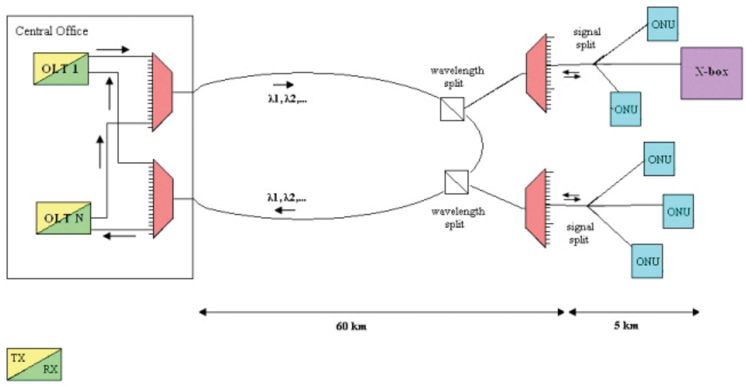

Figure 2.17: Network architecture of the Wx-PON system.

$1 \leq H \leq (P-1)$, and $(P-1)$ dedicated home channels, one for each remaining COs. Finally, two sets of λ_{OLT} channels, for upstream and downstream, plus one set of λ_{AWG} for upstream are used in each WDM EPON. Another set of λ_{AWG} is used over a different fiber for the downstream transmission to the subset of ONUs connected in an all-optical way by means of the central AWG. The bandwidth, in this solution, is shared among users through a WDM system.

2.2.7 Wx-PON system (ETRI and Chungbuk National University)

Wx-PON [42] was proposed in 2009 by Jea-Hoon Yu (ETRI), Byoung-Whi Kim (ETRI) and Nam Kim (Chungbuk National University).

Network Architecture

This network architecture, based on ring-and-spur scheme, provide network coverage of 60 km, in the ring section, and 5 km of conventional TDM-PONs. On the ring the bandwidth is shared through a WDM system with 32 wavelengths, each of which has a transmission rate of 1.25 Gbit/s. The connection function between the WDM and TDMA sectors is performed at the X-box, which has also this function as well as that of conventional TDMA-PON ONU. The network architecture of this solution is shown in Figure 2.17.

The X-box component, working at a 1.25 Gbit/s data rate, provides conversion from C-band DWDM signal into the TDMA downstream signal and from TDMA upstream signal to C-band DWDM signal. It also provides a wavelength reuse function through the employment of a reflective SOA as a colorless transmitter and a specially designed electric circuit which allow the utilization of the downstream signal as seed light for the RSOA. In particular, as in WE-PON solution, a FFCI, which is the specially designed electric circuit already mentioned, is used to help flattening the downstream signal After providing this functionality, the X-box, modulates the downstream light to transform it into the upstream light, which is modulated with upstream data. The total wavelength reuse scheme is very similar to that proposed in WE-PON solution.

Chapter 3

Dynamic Bandwidth Allocation Schemes

In this chapter we present Dynamic Bandwidth Allocation (DBA) schemes for LR-PONs. First of all we explain the signalling protocol used by the allocation algorithms that we propose and evaluate. Then we explain the functionalities of the Interleaved Polling with Adaptive Cycle Time which is one of the first solutions to dynamically allocate the bandwidth in PONs. After introducing this algorithm, we present another allocation scheme, based on IPACT, which is instead designed specifically for LR-PONs. This algorithm, named Multithread Polling, is implemented to reduce the average packet delay of LR-PON and to achieve a better upstream channel utilization.

3.1 Multi-Point Control Protocol

All the algorithms presented in this work use as a signalling protocol the Multi-Point Control Protocol (MPCP), specified in the IEEE 802.3ah standard [2], in which five types of control frames are defined: REGISTER REQUEST, REGISTER, REGISTER ACK, REPORT and GATE. While the first three are used by the ONU during the discovery and registration procedure, the last two are used to plan the data transmissions. In particular the REPORT message is used by the ONU to communicate to the OLT the status of the queue. The GATE instead is used by the OLT, which is the network element which manages the scheduling policy, for granting the upstream timeslot to each ONU. MPCP is not concerned with a particular bandwidth allocation scheme but it is a supporting mechanism that can facilitate the implementation of different bandwidth allocation algorithms in PONs and LR PONs.

3.2 Interleaved Polling with Adaptive Cycle Time

In this section we will give an overview on the Interleaved Polling with Adaptive Cycle Time (IPACT) algorithm [43]. This scheduling scheme has been designed for PONs, more precisely for EPONs. Based on the main principle and functionalities of this algorithm, a large number of other allocation schemes have been presented. For this reason it is important to clarify in this section what is the basic idea on which IPACT is designed. We assume that we have a PON with three ONUs as shown in Figure3.1:

1. Assume that at time t_0 OLT knows exactly how many bytes buffered at each ONU and the round trip time (RTT) to each ONU. OLT stores this information on its polling table and starts sending a GATE message to ONU_1. The GATE message should contain the ID of ONU_1 as well as the size of the granted window.

2. Once ONU_1 receives its GATE message and it starts sending its buffered data up to the granted window size which is 8000 bytes in this example. At the end of the transmission window, ONU_1 will generate and send its REPORT control message, which allows the OLT to know exactly the newly requested window size for the next cycle. In this example ONU_1 asks for a transmission window of 600 bytes.

3. Since the OLT knows exactly the RTT of ONU_1 and how many bytes this ONU will send, it can schedule the control GATE message of ONU_2 so that there will be no data collision.

4. Upon receiving data and REPORT message from ONU_1, the OLT updates its polling table for the next polling cycle.

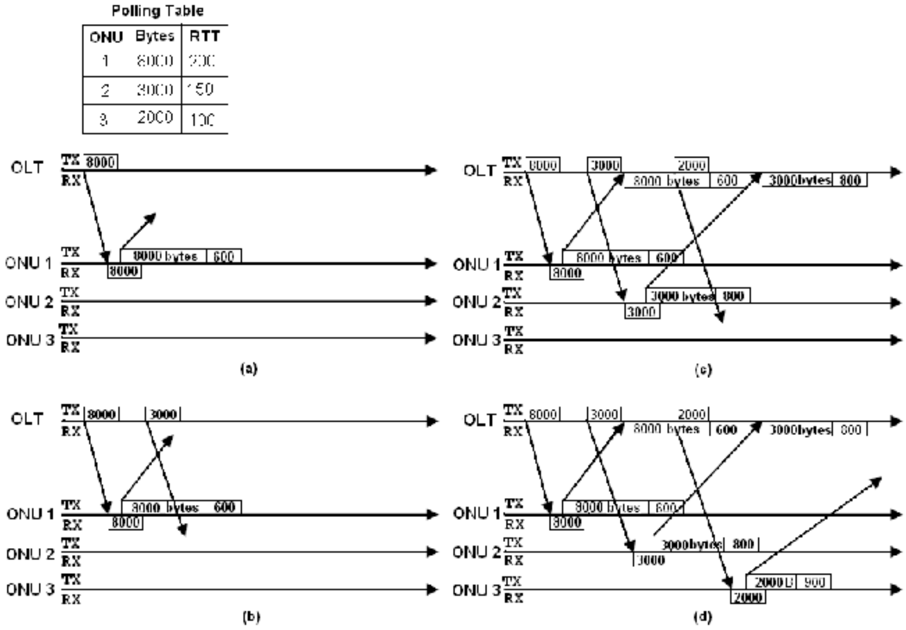

Figure 3.1: Basic idea of the IPACT algorithm.

5. Similarly, the OLT can schedule the transmission of ONU_3 GATE message as it knows the RTT of ONU_2 and how many bytes ONU_2 will send.

If the OLT authorizes each ONU to send its entire buffer contents in one transmission, ONUs with high data volume might monopolize the entire bandwidth. To avoid this, the OLT will limit the maximum transmission size to a maximum limit B_{max}. Thus, every ONU will be allowed to send as many bytes as it has requested in a previous polling cycle, but no more than some maximum limit B_{max}. Actually many other types of service can be applied within this allocation scheme, however is shown in [43] that the limited service discipline is the most conservative scheme and has the shortest cycle of all the other schemes. In this work, the limited service implemented in IPACT is then used in all the proposed allocation schemes to choose the length of data that each ONU can send in each polling cycle.

As shown in many works, IPACT has degraded performance when it is applied in LR-PONs. This is due to the high network span and to the consequently increased RTT of LR-PONs with respect to PONs. For

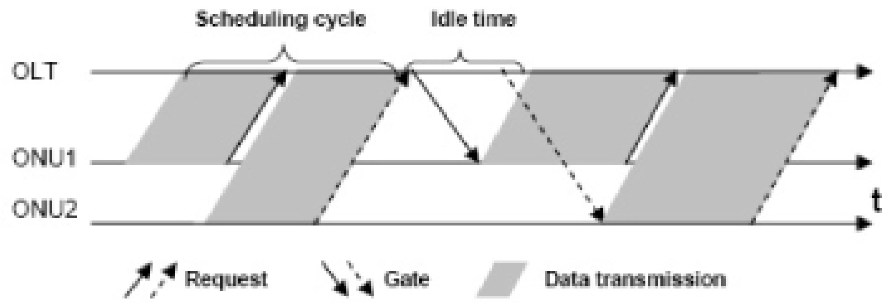

Figure 3.2: Basic idea of the Single-Thread algorithm.

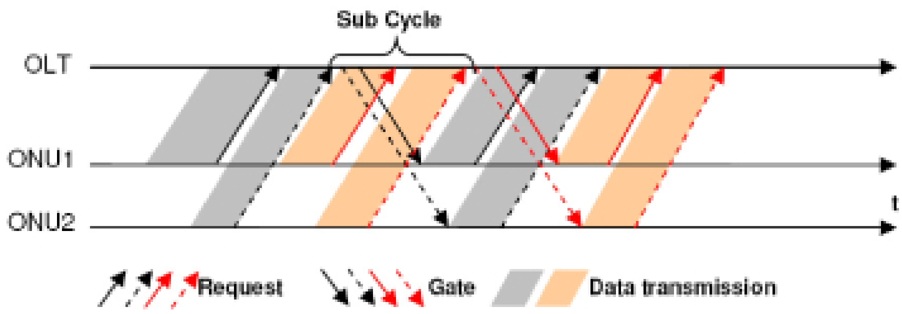

Figure 3.3: Basic idea of the Multithread algorithm.

this reason the Multithread Polling is proposed for LR-PON systems.

3.3 Multithread Algorithm

Mutltithread (MT) algorithm [44] has been proposed as a solution to overcome the problem of the increased RTT in a LR TDM PON, with respect to TDM PONs, which leads in general to an increased average packet delay. Therefore, to achieve better performance in terms of packet delay in a LR-PON, the basic idea of the Multithread algorithm is to allow an ONU to send its REPORT before the previous GATE message is received. Practically, this allocation scheme exploits the benefits of having multiple polling processes running simultaneously. Users are then enabled to send bandwidth requests before receiving acknowledgement from the OLT for the previously requested data. The basic idea of the Multithread polling where two ONUs and two threads (denoted by red and black) are used is shown in Figure 3.3. The black polling process (also called thread) is, in this example, the same shown in Figure 3.2

where a single-thread polling scheme is exemplified. Before the GRANT message for this first thread is received, the ONUs start a new polling process (denoted by red) sending to the OLT a new REPORT message. In such way, the ONUs do not have to wait until the end of data transmission of the first thread to send a new REPORT message asking for a new transmission opportunity.

Chapter 4

Survey of Dynamic Bandwidth and Wavelength Allocation Schemes

In this chapter we explain some of the most significant Dynamic Bandwidth and Wavelength Allocation algorithms which have been proposed during the last few years. The scheduling problem is described by the authors in [45] as a layered scheme. The first layer is defined scheduling framework, and the second layer is the scheduling policy. The scheduling policy is a method for the OLT to produce the schedule whereas the scheduling framework is a logistical framework that determines when the OLT makes scheduling decisions. The scheduling framework can be divided in three main categories: Online scheduling, offline scheduling and just-in-time scheduling. This last method is a new scheduling framework defined by McGarry et al. in [45]. However simulation results [46] comparing Online and Offline scheduling show that the former significantly outperform the latter with respect of average queue length.

Moreover, the DBWA problem can be divided in grant sizing and grant scheduling problem. The grant sizing problem denotes the amount of bandwidth to be assigned to each ONU while the grant scheduling problem stands for the time and wavelength to transmit data in an efficient resource-wise manner, for example by minimizing the packet delay within the network. The main issue of the bandwidth distribution is the grant scheduling problem.

We divide this survey in: *Architecture Dependent DBWA Schemes* and *Architecture Independent DBWA Schemes*. The first base their scheduling policy on specific characteristics of a particular architecture. For this reason they can hardly be applied in different network configurations. The second, instead, have a generic allocation policy and they can be implemented in different network topologies.

4.1 Architecture Dependent DBWA Schemes

4.1.1 Optical Burst Switching Dynamic Bandwidth Allocation Protocol

The Optical Burst Switching Dynamic Bandwidth Allocation (OBS-DBA) Protocol [47] is an algorithm designed for SARDANA which aims to schedule transmissions considering different priorities for different Classes of Service. In such way, this allocation scheme considers Quality of Service requirement of different ONUs. Within this scheduling policy, the OLT and the ONUs wait until the number of packets reach a maximum burst length and then they transmit. In this way, large optical bursts are sent on the channel in order to achieve a great transmission efficiency with less tuning and synchronization. While in the downstream direction the OLT can send its data bursts using all the available bandwidth, the upstream channel transmissions are coordinated through a polling cycle managed by the OLT. This polling cycle is divided into two different parts: The signalling period and the transmission period. In particular the transmission period is divided into N slots with a fixed duration, where N is the number of ONUs in the network, used to send the request messages of each ONU to the OLT. By receiving this information from ONUs periodycally, the OLT is always aware of the network traffic needs. The transmission period is then used to sent bursts of packets by the ONUs which requested to transmit during the signalling phase.

4.1.2 Dynamic Bandwidth Allocation for STARGATE

This is an ad-hoc DBA designed for the STARGATE-EPON (SG-EPON) [48] and its operation is based on the particular architecture of this network. The SG-EPON is designed to enable a smooth migration from already placed network structures to future metro-scale PONs. In fact, it allows to upgrade single nodes (OLT and ONUs) in a pay-as-you-grow manner, according to traffic demands and cost constraints. At the same, this approach, time protect existent ONU infrastructure investment. For this reason, in this network architecture, there are different types of ONUs with different specifications and capabilities. Therefore the bandwidth allocation schemes and the transmission scheduling act differently depending on the type of ONU.

In particular there are three types of ONU: TDM ONUs, WDM ONUs and, Long-Reach ONUs (LR ONUs). A TDM ONU is provided of a couple of wavelength, therefore is equipped with one fixed-tuned transmitter to send upstream control and data traffic on upstream wavelength channel and one fixed-tuned receiver to receive downstream data and control traffic on downstream wavelength channel. WDM ONU is designed to operate on multiple wavelengths in both the downstream and upstream directions. Also in this case the upstream wavelength is different from the downstream wavelength. Finally, LR ONU has the same transmitting and receiving capabilities as a WDM ONU. In addition, LR ONU can communicate with another LR ONU in a different or in the same WDM/TDM EPON, without the need of electro-optical conversion of the signal.

As the channels are shared among different ONUs, it is required a DBA algorithm in order to arbitrate the transmission and avoid collisions, while efficiently utilizing the wavelengths. This scheduling management is done by the OLT which is responsible of the assignment of both bandwidth and wavelength for upstream transmission. Since different kind of ONUs use the channels in a different manner, the bandwidth is assigned to ONUs through different scheduling policies according to the ONU behavior.

The scheduling of the transmission on the TDM channel is done in a round-robin fashion. Instead, to schedule the transmission of a WDM ONU on WDM wavelengths, only one upstream wavelength per cycle is allowed, and the first available wavelength is allocated. For LR ONUs, scheduling transmissions becomes more complicated because the ONUs may have traffic to send on multiple wavelengths in a cycle. These ONUs can be scheduled on WDM channels using the same principle to schedule the transmission of WDM ONUs.

To schedule transmissions on AWG wavelengths, the OLT assigns to each LR ONU a transmission opportunity on one or more wavelengths. Of course, to avoid collisions, on each channel only one ONU can send traffic in a certain time period. On determining the transmission opportunities for each ONU, the OLT schedules the transmissions on WDM wavelengths first and then on AWG wavelengths. Clearly a simple scheduling of these opportunities may result in many unused voids in the channel, which yields to a poor resource utilization. In general, a void in the channel is the time period between two subsequent transmissions where the channel is available. One method for reducing the formation of these voids is through splitting transmission opportunities into different time intervals in order to fill the gaps. Although this latter solution is suggested by the authors, they only implement the basic algorithm without taking care of the void reduction.

4.1.3 Slotted Media Access Control

Like the SG-EPON DBA, also the Slotted Media Access (SMAC) protocol [27] is ad-hoc designed for a specific LR-PON architecture. In this case the SMAC is the DBA for the Slotted Long-Reach PON (SPON). As explained in the previous chapter, in the SPON, traffic is divided in inner-traffic and public-traffic which are, respectively, data for an ONU in the same network and data directed to external networks. Each ONU, in order to support the simultaneous transmission of public and inner traffic, maintains dedicated queues for the two traffic types: One queue for the public traffic and D separated inner queues, one for each Internetworking Group (IG). An IG is composed by a set of ONUs attached to same splitter/combiner. If a generic ONU in the SPON wants to communicate with an other ONU belonging to a particular IG, it needs only to determine the wavelength on which to send data. This is possible because the SPON uses a cyclic AWG that routes wavelengths through different output ports, and then to different splitters. Using a cyclic

AWG, wavelengths which enter into the AWG through a particular input port are cyclically routed to all the output ports, according to the features of this device [49]. Through the AWG, data frames directed to different IGs, are transmitted simultaneously on the same wavelengths, provided that they are launched into different input ports. This property allows to spatially reuse all the wavelengths, and maximize the use of the available bandwidth in the upstream link.

SMAC divides the upstream channel into contiguous scheduling frames composed by two sub-frames: The inner subframe and the public subframe. The former is dedicated to the scheduling of the inner traffic and the latter is for public traffic transmissions. Besides these two sub-frames in each frame, the first slot (called Bandwidth Reservation (BR) slot) is used by the ONUs to ask the OLT for a permission to transmit. In the BR slot, the bandwidth for each upstream wavelength is partitioned in mini slots where just a single Request message can fit. The total number of these mini slots is $S = N / W$ where N is the total number of ONUs and W the total number of wavelengths. Each mini-slot is assigned to a single ONU. Therefore there are not collisions between request messages. Furthermore, with this slot assignment the available bandwidth is fairly shared among all the ONUs in the network. The arrival of a BR slot is notified to the ONUs through an advertisement (ADV) message which is broadcasted on the downstream channel, in this way ONUs are aware that they have to prepare a Request message announcing to the OLT the state of their queues and asking for a transmission slot. When a ADV is received, an ONU decides to reserve a slot in a hybrid timer/length-based approach. This means that an ONU decides to ask for a slot to transmit traffic when either a queue become longer than the maximum length of a time slot, or the first packet in the queue has been waiting for longer than a specific time-out parameter.

Regarding the data traffic allocation scheme two different scheduling policies exist in the SMAC protocol. The first assignment method is used to allocate the transmission slots to the inner traffic. Due to the AWG spatial-reuse feature, for this particular traffic, the wavelengths can be fully exploited. Even if these frames are directed to other ONUs in the network and then are routed by the AWG to their destinations, in any cases the signal propagates to the OLT which need to drop all the received inner data. Otherwise, these data frames would be forwarded to the attached router and consequently they will come back to the OLT and then to ONUs causing duplicate inner data receptions at ONUs. The public subframe is established after all the inner-slot reservation had been granted. In the SPON architecture the upstream resource for the public traffic is shared among all the ONUs, for this reason each public slot is permitted to grant just one public data transmission and no spatial reuse is allowed. Once a scheduling for a frame is decided, the OLT send an ADV message to ONUs to allow them to send new requests for public or inner traffic.

Simulation results presented by the authors show that the average queueing delay is really dependent to the AWG features. This means that, under the same simulation characteristics, the average queueing delay of a SPON network which does not use an AWG to route its inner traffic is higher than the same network where a cyclic AWG avoid that the inner traffic has to reach the OLT to be routed to each ONUs in the SPON. Moreover, increasing the degree of the AWG, the number of times that each data wavelength can be spatially reused is increased and this leads to a lower average queueing delay and to a higher bandwidth utilization.

4.2 Architecture Independent DBWA Schemes

4.2.1 Gate-Driven Dynamic Wavelength and Bandwidth Allocation for WDM EPONs

GATE-Driven Dynamic Wavelength and Bandwidth Allocation (GD-DBA) [50] is an allocation scheme which emulates polling algorithm based on the Multi-point control protocol (MPCP). Unlike the classical polling algorithms, as IPACT for example, where each ONU is polled with a GATE message and answer, after data transmission, with a REPORT message notfying the OLT of the length of its queue, in the GD-DBA algorithm GATEs are decoupled from REPORTs. In this way, the OLT is allowed to poll ONUs according to a freely defined sequence. For simplicity, the authors assume that the polling sequence is round robin and that the GATEs messages are sent independently for each wavelength. Another assumption is that all the ONUs are able to transmit on every wavelength. This last hypotesis makes easier the evaluation of the total network capacity. In practice, GD-DBA allows the OLT to sent GATE messages to the ONU spontaneously based on its current information of ONU requirements aquired from REPORT frames sent previously. In such way, the grants do not relate to the current queue occupancy but to the occupancy observed at some random time in the past, as informed by the last Report to be received at the OLT. Authors compare the GB-DBA with a REPORT-Driven scheduling in a single-wavelength scenario, and show how their proposal, at high loads, performs better than the REPORT-Driven scheme. Particularly, the average packet delay of the latter rapidly increases to very high values for low loads when a GRANT with a maximum length of 2 Kbytes is used. Increasing this length the REPORT-Driven scheduling shows a better average packet delay which grows unboundedly for medium and high loads, instead of low loads. Anyway, even if the GD-DBA's average delay has a trend which is similar to the one of REPORT-Driven scheme, it has a better performance for all lengths of the GRANT message.

4.2.2 Just-In-Time Algorithm

Just-In-Time (JIT) algorithm [45] can be viewed as a compromise between the offline scheduling and the online scheduling approaches. Within this algorithm ONUs are added to a scheduling pool as their REPORT messages are received by the OLT. When a channel becomes available, all the ONUs in the same pool are scheduled togheter according to a chosen scheduling policy. ONUs scheduled such that their transmissions will start shortly after the time when their scheduling is produced are classified as *"imminent"* and, for these ONUs, the current schedule is considered firm and the OLT transmits then GATE messages to inform them of their granted transmission window. For the other ONUs in the pool the scheduling is classified as *"tentative"* and it could be rearranged in the next scheduling round when new REPORT messages from other ONUs arrive, providing new information to the OLT. An alternative approach is to firmly schedule the transmissions of all ONUs in each scheduling round. Authors refer to this second method as online JIT while the first case, where the tentative ONUs participate in future scheduling rounds, is classified as online JIT Tentative. The online JIT scheduling framework has the ability to make better scheduling decisions if compared with the online scheduling framework because JIT accumulates a set of REPORT messages before choosing a scheduling. Such behavior gives the possibility to the OLT to better organize the upstream transmissions in order to have a better channel utilization. Moreover, the JIT framework because it gives a lower average transmission delay if compared with the offline framework, as it does not wait for all the REPORT messages of all ONUs, but it collects only the REPORT transmitted until the moment when a channel becomes available.

4.2.3 Distance Based Grouping Algorithm

Distance Based Grouping (DBG) algorithm [51] is based on the observation that in Long Reach Access Networks, the ONUs can be positioned at very different distances and this leads to a considerable spread of RTT values among the various ONUs. Due to this feature, in the upstream channel, it is possible observe time periods between two subsequent transmissions where the channel is unutilized. It is referred to periods as scheduling voids. The aim of the DBG algorithm is to minimize the existence of voids. This objective is achieved by producing a mapping of ONUs with similar RTTs to the same set of upstream wavelengths. Since in each group the differential RTT delays will be much lower and each of these groups operate on a different wavelength, the scheduling voids produced are expected to be significantly shorter. In this way, the upstream channel will be better utilized and consequently the average packet delay will be much lower. This particular algorithm can be also used in combination with other scheduling disciplines where these algrotihms are runned on each individual group of ONUs separately.

4.2.4 Earliest-Finish Time Algorithm

The most straightforward and less complex algorithm to dynamically allocate the bandwidth and the wavelength in a LR WDM/TDM PON is the Earliest-Finish Time (EFT) algorithm [51]. Within this algorithm we scheduling is producing according the rule that no other transmission in the same wavelength should have been programmed after the selected schedule, while the selected wavelength should have the earliest finish time among all channels. Despite its simplicity and multiplexing gain due to the possibility of solving upstream contention in the wavelength domain, in the EFT algorithm the upstream channels are not utilized as efficiently as possible. In fact it is expected to create scheduling voids between two subsequent scheduled transmissions on the same wavelength. This issue is more accentuated when the ONUs have distances from the OLT which are very different from one another. In such way EFT leads to a waste in the upstream bandwidth and resulting in increased frame queuing delay.

4.2.5 Latest-Finish Time Algorithm

The Latest-Finish Time (LFT) algorithm [51] is a variation of the EFT algorithm. To issue the scheduling and the wavelength assignment, this scheme follows the constraint that no other transmission in the same wavelength should have been programmed after the selected schedule. However the selected wavelength must now have the latest finish time among all channels, if this is not later than the time needed to the GATE message to propagate to a particular ONU_k, plus the RTT to this same ONU_k. If the wavelength chosen has a finish time which is higher than this time period, the scheduling for ONU_k will be delayed if compared with EFT algorithm. This constraint is then needed to avoid delayed scheduling.

which means that choosing this scheduling

4.2.6 Latest-Finish Time with Void Filling Algorithm

The Latest-Finish Time with Void Filling (LFT-VF) [51] algorithm is based on the same observation of DBG but, in this case, the void filling part of this scheme leads to fill of the possible voids created on the upstream channel. The LFT part, instead, consists of choosing the upstream wavelength where the previously scheduled transmission have the latest finish time among all channels. The aims of this scheme is to minimize as much as possible the formation of voids. This same approach to choose the transmission wavelength is used to schedule transmissions in voids. The rationale behind this rule is to create new voids later in time because, usually, it is more likely for the OLT to fill such voids.

4.2.7 Earliest-Finish Time with Void Filling Algorithm

Earliest-Finish Time with Void Filling (EFT-VF) [51] algorithm follow the same rationale of the LFT-VF algorithm trying to fill all the possible voids in the upstream channel. The main difference between these two schemes is that, in EFT-VF, the upstream channel where to transmit is the one where the previously scheduled transmission must have the earliest finish time among all wavelengths. This same behavior is followed during the void filling part of the scheme. However it is expected that EFT-VF and LFT-VF exhibit similar performance because, in general, new voids created after performing void filling are too short to be usable in future and then it does not matter if these new voids are created earlier in time (with EFT-VF) or later (with LFT-VF). Authors compared EFT, pure LFT and EFT-VF algorithms and they show that the latter is the one with the lowest average packet delay among all the others. Moreover it is shown that the EFT-VF scheme has also the best channel utilization among all the aforementioned algorithms. When EFT-VF is combined with DBG approach a poorer performance in terms of average packet delay is highlighted.

Among all the previous proposals for DBWA schemes the EFT-VF is the one which gives better performance togheter with the fact that is a more generic scheme, which means that it could be applied to different network topologies without the need of any change in its implementation. New proposals for DBWA schemes for LR WDM/TDM PONs are presented in the next chapter.

Chapter 5

Proposals of New DBWA Schemes for LR WDM/TDM PONs

In this chapter we propose, analyze and compard DBWA schemes for LR WDM/TDM PONs. All the subsequent algorithms are derived from two already existent schemes: EFT-VF and Multithread algorithm. The former, explained in section 4.2.7, is a bandwidth and wavelength allocation solution specifically designed for hybrid WDM/TDM access network and it has already been implemented for both PON and LR PON solutions. Multithread algorithm, instead, has been specifically proposed for LR PONs in order to overcome the problem of the performance degradation due to the increased network span and to the consequently increased RTT. However, to the best of our knowledge, this technique has never been tested within a LR WDM/TDM PON. In this work different implementations of the EFT-VF algorithm, which leads to significantly different performance, are presented. Moreover, this same algorithm is used as a basic scheme for the implementation of different DBWA solutions which try to improve the channel utilization while trying to maintain as low as possible the average packet delay. Besides these schemes, it is also introduced an implementation of the Multithread algorithm in LR WDM/TDM PON since this scheme has always been used only in LR TDM PONs. Finally, a new scheduling algorithm which exploits the benefits of the combination of the EFT-VF and Multithread is presented. The aim of this solution, together with trying to improve network performance in terms of packet delay and channel utilization, is to find a combination of the positive features of the two schemes which leads to overcome possible negative behaviors of both EFT-VF and Multithread. We evaluate then the performance of all the proposed schemes through a simulator and results provided by simulations are subsequently discussed. Particularly the algorithms are compared with each others in terms of average packet delay, average queue length and channel occupation. Whereupon the performance of each allocation scheme is evaluated under different network topology characteristics such as the number of wavelengths and the distribution of the distances from ONUs to OLT. We finally explain and evaluate the results of these simulations justifying them according to the behavior of each algorithm.

The simulator we used to evaluate the performances of the different allocation schemes is based on the Discrete Event Simulation Library (DESL) [52]. The original simulator implemented the IPACT [43] algorithm in an basic EPON. This tool has then been modified in order to simulate a LR WDM/TDM PON, ann implement the DBWA schemes to be evaluated.

All the presented algorithms use as a signalling protocol the Multi-Point Control Protocol (MPCP).

5.1 EFT-VF Implementations

In this section, we describe possible different implementations of the EFT-VF algorithm. Below we define the notation used hereafter:
R_k: Round-trip propagation time between OLT and ONU_k.
$T_{k,j}$: Start Time for the j-th transmission of the ONU_k which is the time when an ONU can start its transmission according to its R_k.
W_k: Set of wavelength supported by ONU_k.
t_c: time needed for the transmission of REPORT or GATE frame.
$S_{i,j}$: Arrival time at the OLT of the first bit of the j-th scheduled transmission on the i-th wavelength.
$F_{i,j}$: Finish time of the j-th transmission on the i-th wavelength corresponding to the reception of the last bit of the control frames which is piggy-backed to the data packets.
L_i: Finish time of the last transmission scheduled on the i-th wavelength.

t: Time needed by the ONU to transmit the granted length of data.
$B_{max,k}$: Maximum length for a transmission of ONU_k, in each cycle time, in order to ensure fairness among the ONUs and grant the maximum capacity achievable from each of them.
V_k: Set of eligible voids for ONU_k calculates according to the its R_k and its requested length of data which must be granted.
G:Length of data, in bytes, which an ONU asks to transmit.
t_g: Time needed to transmit the length of data which an ONU asks to transmit.
w_{eft}: Chosen upstream wavelength for the EFT algorithm.
n_{eft}: Position index of the reservation within the wavelength w_{eft}.
w_{vf}: Chosen upstream wavelength for the Void Filling algorithm.
n_{vf}: Position index of the reservation within the wavelength w_{vf}.

5.1.1 EFT-VF Algorithm with Earliest Start Time Priority

The aim of the EFT-VF algorithm with earliest Start Time priority (EFT-VF early-ST-priority) is to minimize the transmission delay while trying to fill all the possible voids. This version of the EFT-VF algorithm corresponds, in fact, to the already proposed EFT-VF [51]. When a REPORT is received by the OLT, it runs both EFT and VF algorithms. The first one will choose the wavelength w_{eft} on which an ONU can transmit as soon as possible according to its R_k and to the end of the previous transmission on that same wavelength. In other words, the EFT scheme chooses the channel with the earliest $F_{i,j}$ where, thus, no other transmission is scheduled after this moment. The Void Filling algorithm, after calculating all the eligible voids for the specific ONU, chooses among these the one which allows the user to transmit earlier.

The EFT-VF early-ST-priority algorithm operation is shown in Figure 5.1. In this first implementation an eligible void is defined, as shown in (5.1), as a void which is long enough to allow the transmission of the requested length of data G, if this is minor or equal than the $B_{max,k}$, or at most $B_{max,k}$ otherwise.

$$V_k = \{F_{i,j}\,|S_{i,j+1} - max(F_{i,j}\,, t + R_k + t_c) \geq t_g + t_c\}, \quad i \in W_k \quad (5.1)$$

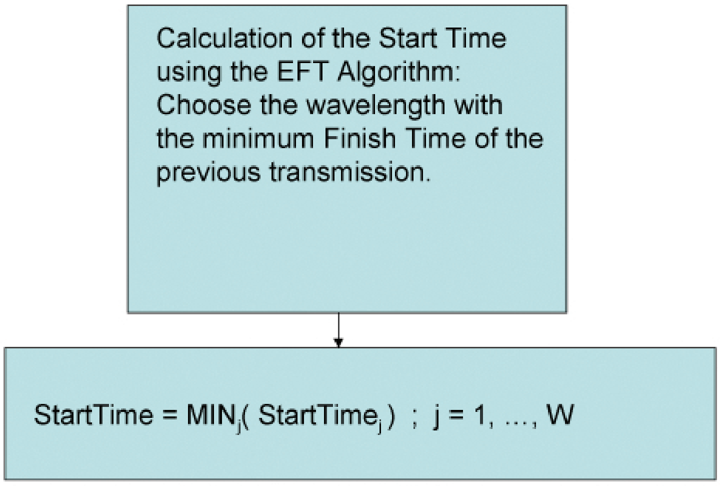

Figure 5.1: Scheme of the EFT-VF with earliest Start Time priority algorithm. W is the total number of wavelengths.

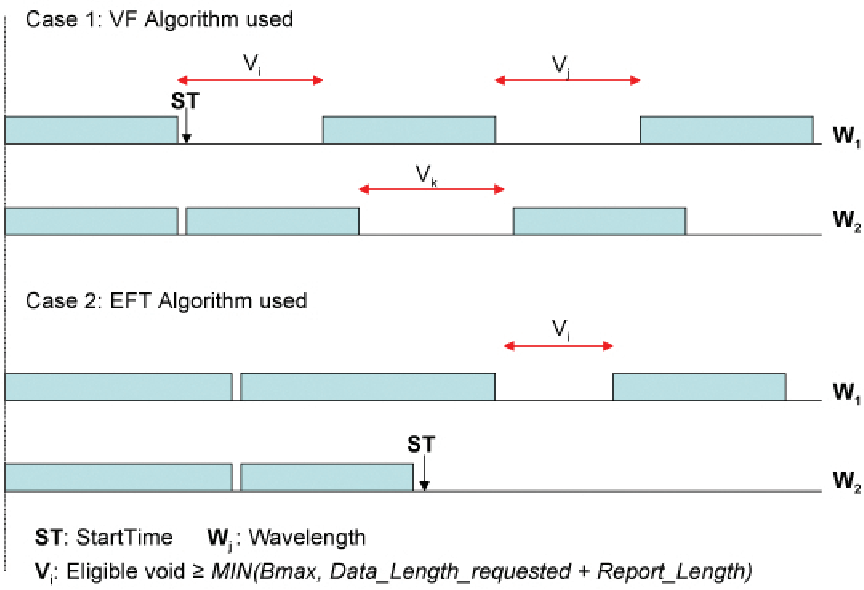

Figure 5.2: Operation of the EFT-VF Algorithm with Earliest Start Time Priority.

After calculating the two values of $S_{i,j}$, one for the EFT algorithm and the second for the VF, the smaller between them is chosen and the corresponding $T_{k,j}$ is assigned to ONU_k, as shown in (5.2). An example of the operation of this first implementation of the algorithm is shown in

Figure 5.2. Figure 5.2 shows the two cases when the different parts of the scheme are used. The first case is when the ONU can transmit as soon as possible if the transmission is scheduled in the void. Instead, the second case happens when the way to minimize the transmission delay for an ONU is to allow it to send its data on the first available wavelength, chosen by the EFT algorithm.

$$T_{k,j} = S_{i,j} - R_k, \quad i \in W_k \tag{5.2}$$

The wavelength assignment and the scheduling, according to EFT algorithm, are defined by:

$$w_{eft} = \arg\min_i (L_i), i \in W_k \tag{5.3}$$

$$n_{eft} = \arg\max_j (F_{w,j} + 1) \tag{5.4}$$

Instead, for the Void Filling part the equations are:

$$w_{vf} = \arg\min_i (F_{i,j} \,|F_{i,j} \in V_k), i \in W_k \tag{5.5}$$

$$n_{vf} = \arg\min_j (F_{w,j} \,|F_{w,j} \in V_k) + 1 \tag{5.6}$$

Finally, the wavelength and scheduling which are assigned for a transmission are chosen according to:

$$w = min(w_{eft}, w_{vf}), \;\; n = min(n_{eft}, n_{vf}) \tag{5.7}$$

5.1.2 EFT-VF Algorithm with Void Priority

The EFT-VF algorithm with void priority (EFT-VF Void Priority), shown in Figure 5.3, aims to maximize the channel utilization giving priority to the void filling part of the algorithm. After receiving the REPORT from the ONU, the OLT calculate all the eligible voids described by (5.1) for the transmission that must be scheduled. Also in this implementation, an eligible void is defined as a time period which is long enough to accommodate the length of the requested data or at maximum $B_{max,k}$. In this case, the EFT algorithm is applied only if there is not any eligible void in which to schedule the transmission and then (5.3) and (5.4) are applied.

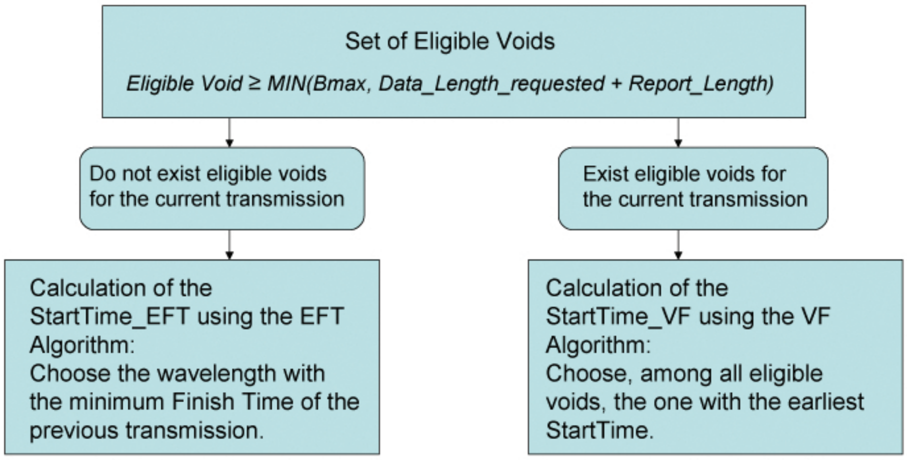

Figure 5.3: Scheme of the EFT-VF with Void Priority Algorithm.

The operation of this scheme is shown in Figure 5.4 where, in the first case, the void filling part of the algorithm is used. In this case, unlike in the EFT-VF early-ST-priority scheme, it is chosen to schedule the transmission in a void even if it would be possible to transmit at an earlier time using the EFT algorithm. This behavior is justified by the objective of this algorithm which has as a first priority to minimize the waist of bandwidth or equivalently to maximize the number of filled eligible voids.

Instead, in the second case the EFT part of the algorithm is applied because there are no eligible voids in which to transmit. Thus, when the set of eligible voids for a particular transmission is not empty, the

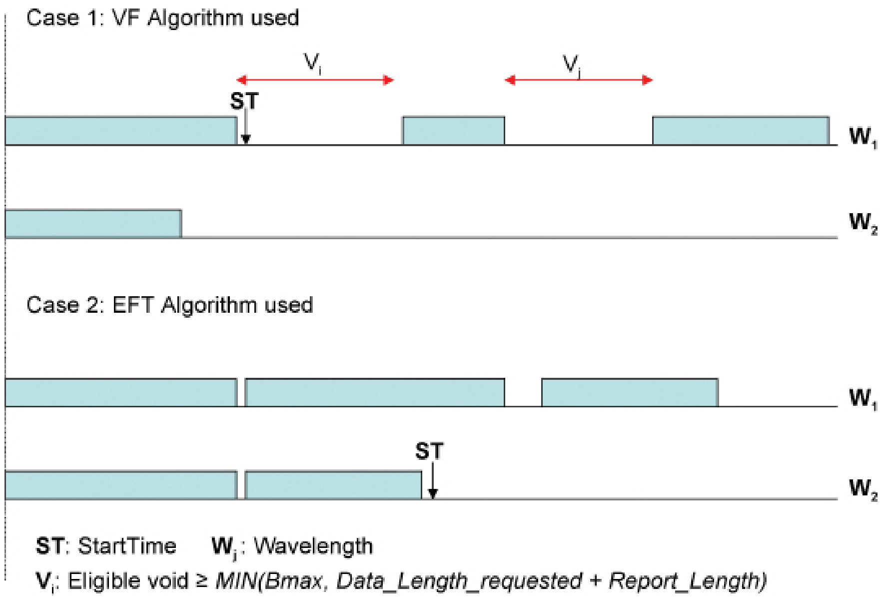

Figure 5.4: Operation of the EFT-VF Algorithm with Void Priority.

wavelength and the scheduling assignment, according to Void Filling algorithm, are defined by:

$$w_{vf} = \arg\min_{i}(F_{i,j}\,|F_{i,j} \in V_k), i \in W_k \tag{5.8}$$

$$n_{vf} = \arg\min_{j}(F_{w,j}\,|F_{w,j} \in V_k) \tag{5.9}$$

5.1.3 EFT-VF Algorithm with Partial Void Filling

The EFT-VF algorithm with partial void filling (EFT-partial-VF), shown in Figure 5.5, tries to maximize the utilization of the upstream channel while minimizing the transmission delay allowing some ONU to transmit at the earliest possible time even if the length of data granted is lower than the length of data requested. An eligible void for ONU_k is the one where the size of empty time periods is longer or equal to a fraction N of the requested timeslot of ONU_k, for data G, as defined in (5.10).

$$V_k = \{F_{i,j} \,|S_{i,j+1} - max(F_{i,j}, t + R_k + t_c) \geq t_g/N + t_c\}, \quad i \in W_k \quad (5.10)$$

Again the maximum value which can be assumed by G is $B_{max,k}$. The wavelength assignment and the scheduling are chosen exactly using the same principles and equations of the first implementation described above. Within this scheme, if an eligible void which is not long enough to accomodate the whole requested length G is found, the OLT schedules the transmission in this void and grant only the number of bytes which fits into this time period. The residual length of data is left in the queue of the ONU and then it will be added to a subsequent REPORT message sent in the future by this same ONU. This implementation, shown in Figure 5.6, can lead to a higher utilization factor if compared with the first EFT-VF scheme because it counts as eligible voids also lower time periods which can be instead excluded by the latter. In this way, the algorithm will find a higher number of voids which can be filled.

As EFT-partial-VF does not grant all the capacity requested from each ONU, but at least a fraction N of this length, it consequently does not grant the maximum assigned capacity per user. This maximum capacity is indeed provided allowing the ONU to transmit the requested length of data, if this is less than $B_{max,k}$, or $B_{max,k}$ otherwise. For this reason EFT-partial-VF needs an enhancement in order to achieve fairness among the ONUs. Therefore, in the following section, we present a new solution which enhances the EFT-partial-VF algorithm guaranteeing all the requested data.

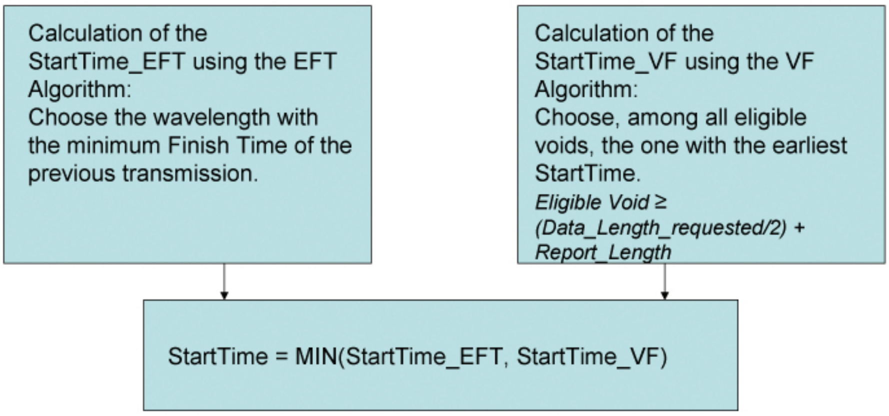

Figure 5.5: Scheme of the EFT-VF with Partial Void Filling Algorithm.

5.1.4 EFT-VF Algorithm with Partial Void Filling Enhanced

The EFT-VF algorithm with partial void filling Enhanced (EFT-partial-VF Enhanced), like the EFT-partial-VF, tries to maximize the utilization of the upstream channel while minimizing the transmission delay allowing some ONU to transmit at the earliest possible time even if the length of data granted is lower than the length of data requested. At the same time it also provides fairness among users since, if a particular transmission is scheduled in a void which is long less then the requested data length G, this algorithm assign to the same ONU another transmission period where the remaining part of data is granted. Also for this algorithm, an eligible void for ONU_k is the one where the size of empty time periods is longer or equal to a fraction N of the requested timeslot of ONU_k, for data G, as defined in (5.11).

$$V_k = \{F_{i,j} \,|S_{i,j+1} - max(F_{i,j}\,, t + R_k + t_c) \geq t_g/N + t_c\}, \quad i \in W_k \quad (5.11)$$

The maximum value assumed by G is $B_{max,k}$. Also with this algorithm, the wavelength assignment and the scheduling are chosen exactly using the same principles and equations of the EFT-VF early-ST-priority algorithm described above. If the first part of the transmission is scheduled in an eligible void where does not fit all the requested length of data

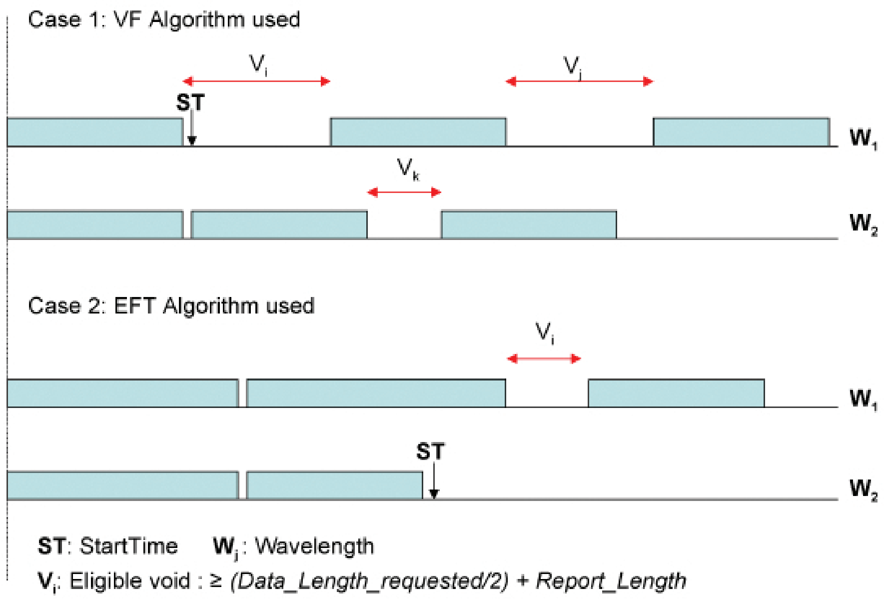

Figure 5.6: Operation of the EFT-VF Algorithm with Partial Void Filling.

G, then the OLT must choose a time period where to allocate the residual data. This latter is assigned with the same algorithm used to allocate the first fraction of requested bytes which means that the $S_{i,j}$ is chosen between the earliest $S_{i,j}$ assigned using the EFT algorithm and the $S_{i,j}$ chosen by the VF rule. Within this implementation the ONU is allowed to send its REPORT message only at the end of the last transmission block. The residual length of data G_n is computed by difference from the total requested length G where the already granted portion of data is substracted. According to the definition of eligible void given in (5.11), the requested number of bytes G can be divided at most in N fraction and then, in the worst case, N portion of data must be scheduled.

The equations used to define the wavelength assignment and the scheduling, according to EFT algorithm, are:

$$w_{eft} = \arg\min_i (L_i), i \in W_k \tag{5.12}$$

$$n_{eft} = \arg\max_j (F_{w,j} + 1) \tag{5.13}$$

Whereas, for the Void Filling part of the algorithm we have the wavelength assignment and the scheduling are chosen according:

$$w_{vf} = \arg\min_{i}(F_{i,j}\,|F_{i,j} \in V_k), i \in W_k \tag{5.14}$$

$$n_{vf} = \arg\min_{j}(F_{w,j}\,|F_{w,j} \in V_k) + 1 \tag{5.15}$$

Then, the wavelength and scheduling which are finally assigned for a transmission are chosen according to the equations:

$$w = min(w_{eft}, w_{vf}), \;\; n = min(n_{eft}, n_{vf}) \tag{5.16}$$

As an example it is considered a situation where in the definition of the eligible void is used $N = 2$ and therefore the requested data length is divided, at most, into two transmissions. Figure 5.8 shows, in the second case, the basic circumstances where the pure EFT algorithm is used. The first case shown in Figure 5.8, the scheduling is assigned in a void which can accomodate all the requested length G. In Figure 5.9 is described a situation where the first chunk of data is transmitted in an eligible void with a time duration which is lower than the time needed to transmit the length of data G and then the VF algorithm is used to schedule also the second data length. In Figure 5.10 is shown the alternative in which, for the second transmission, is used the EFT algorithm. For this latter case, we show two sub-cases dependent on the policy with which the $S_{i,j}$ is chosen within the EFT algorithm when this is applied to schedule the second block of data. It is reffered to these two sub-cases as EFT-partial-VF Enhanced Maximizing Void Formation and EFT-partial-VF Enhanced Minimizing Void Formation. Basically the former, shown in Figure 5.11, corresponds to the application of the LFT algorithm only to the second portion of data. The latter represents the case when for the second transmission is applied the EFT algorithm. This option is shown in Figure 5.10.

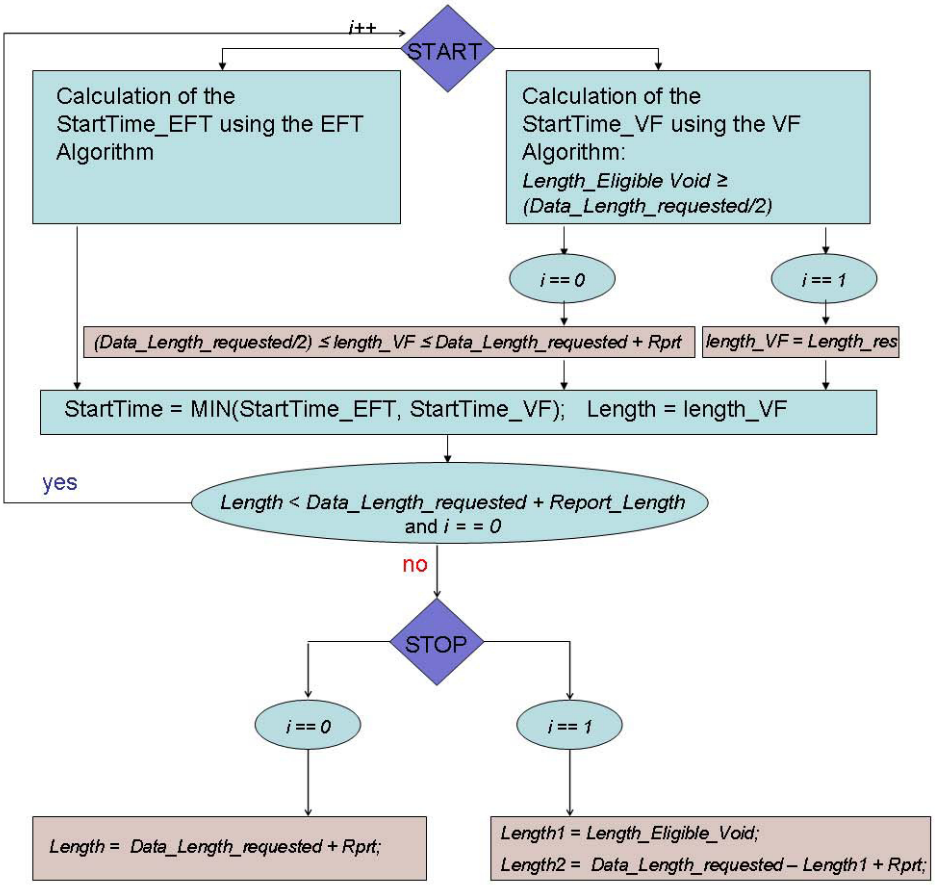

Figure 5.7: Scheme of the EFT-VF Algorithm with Partial Void Filling Enhanced. i refers to the iteration number. In this example we shows the scheme of the algorithm applied in a case where the $N = 2$ which means that, at most, the transmission can be divided in two blocks of data.

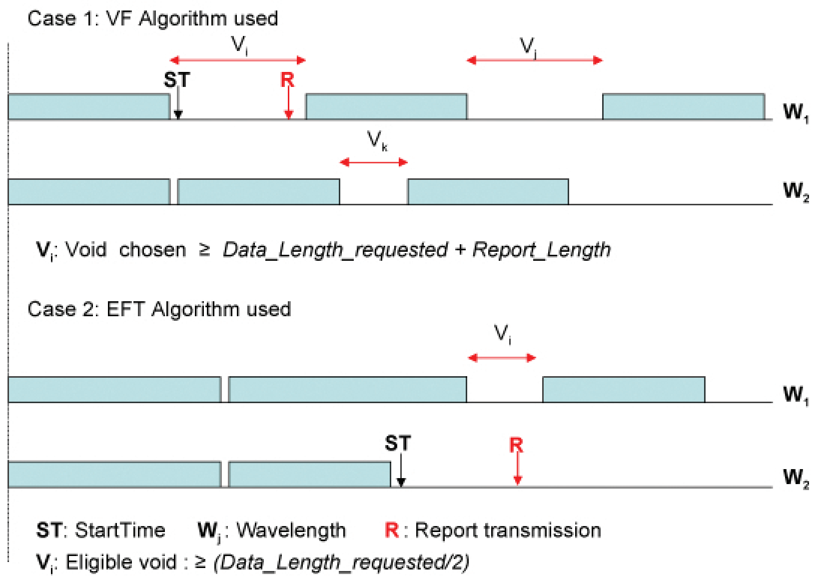

Figure 5.8: Operation of the EFT-VF Algorithm with Partial Void Filling Enhanced.

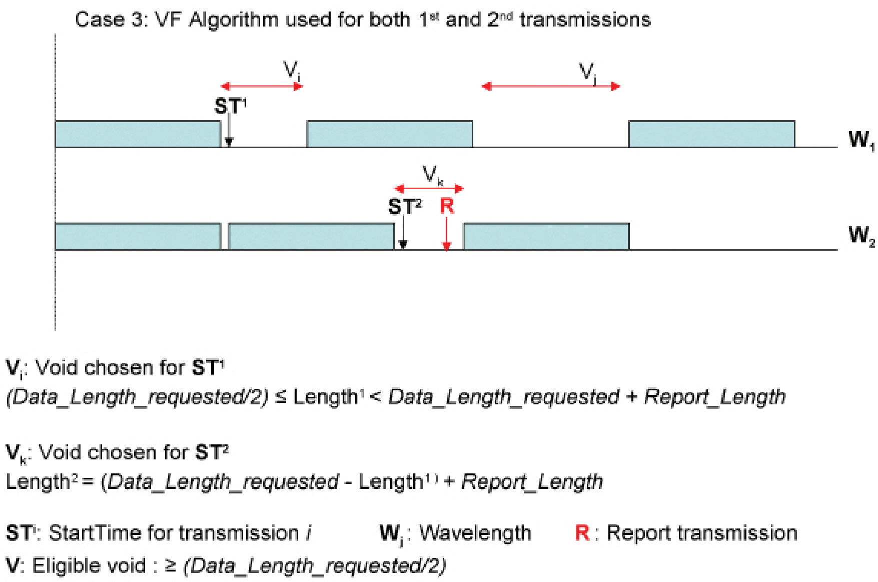

Figure 5.9: Operation of the EFT-VF Algorithm with Partial Void Filling Enhanced: Case where the Partial Void Filling is applied for both first and second transmission.

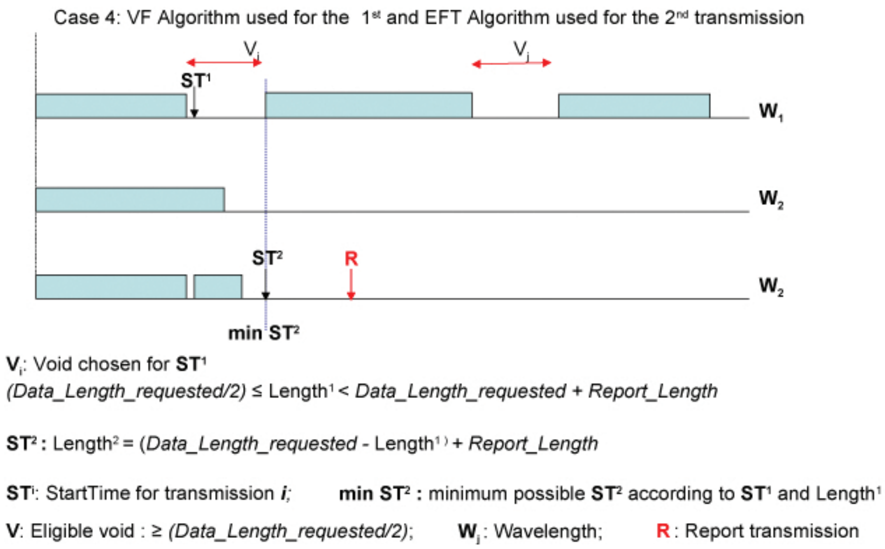

Figure 5.10: Operation of the EFT-VF Algorithm with Partial Void Filling Enhanced:Case where the Partial Void Filling is applied for the first transmission and EFT is applied for the second transmission.

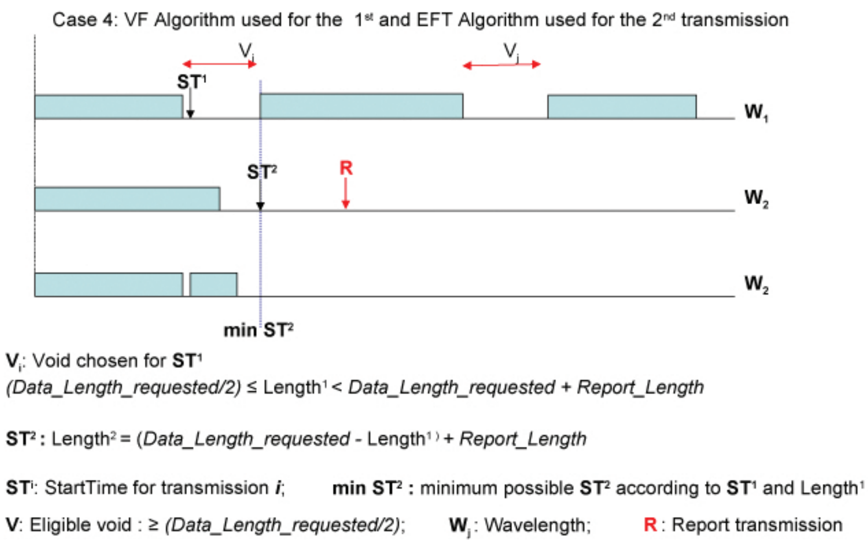

Figure 5.11: Operation of the EFT-VF Algorithm with Partial Void Filling Enhanced: Case where the Partial Void Filling is applied for the first transmission and LFT is applied for the second transmission.

5.2 Multithread Algorithm

In this section is introduced the Multithread algorithm implementation over hybrid LR WDM/TDM PONs. This is an already existing algorithm designed for LR TDM PONs in order to overcome the problem of the performance degradation due to the increased RTT caused by an increased network span of LR PONs with respect to PONs. This allocation scheme has never been applied in LR WDM/TDM PONs.

5.2.1 Multithread implementation in LR WDM/TDM PONs

When MT is implemented in a WDM/TDM network the basic idea remains the same and furthermore the benefits of having more wavelengths are exploited. Figure 5.12 shows an example of wavelength assignment and scheduling with two ONUs and two threads.

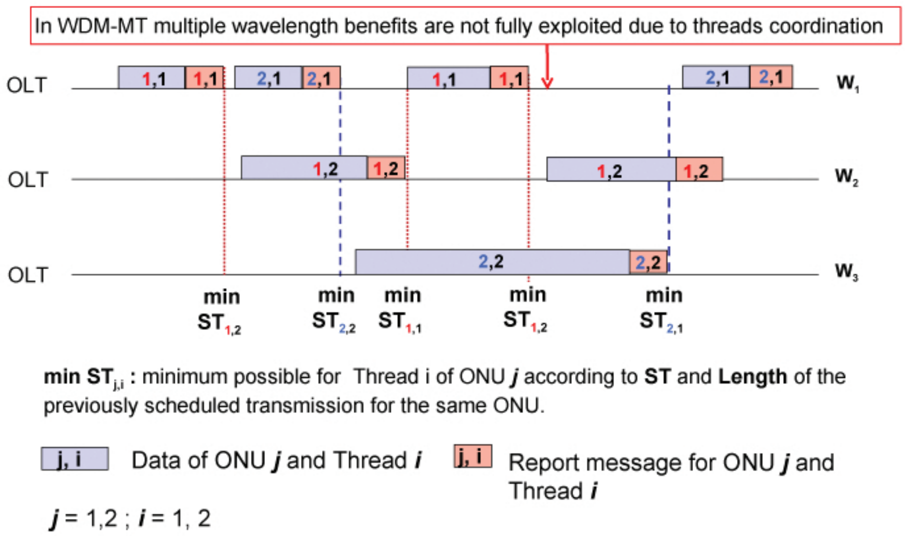

Figure 5.12: Multithread algorithm operation in a LR WDM/TDM PON: scheduling and wavelength assignment with two ONUs and two threads.

In this example the transmissions scheduled for both thread 1 and 2 for ONU 1 are denoted by read numbers while transmissions for ONU 2 are labeled with blue numbers. In both cases, the second number (in black) indicates the number of thread to which each transmission belongs.

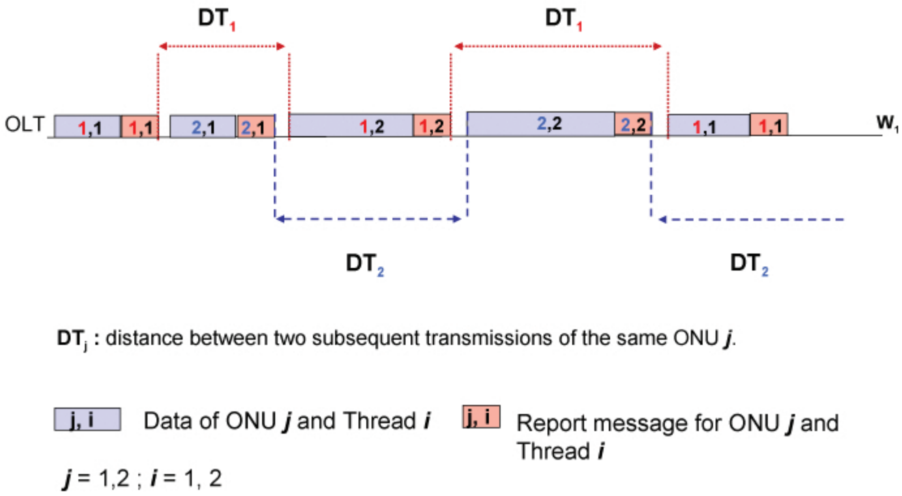

Figure 5.13: Multithread algorithm operation in a LR TDM PON: scheduling with two ONUs and two threads.

If compared with the basic operation of Multithread algorithm in a LR TDM PON, shown in Figure 5.13, it is possible to notice that using multiple wavelengths the average time between two subsequent transmissions of the same ONU_k is significantly decreased. Particularly, Figure 5.13, shows the transmission scheduling of two ONUs where two threads are used. In this example we highlight how the average difference in time between two subsequent transmissions of the same ONU_k depends not only by the value of R_k but also by the length of the other transmissions scheduled on the channel. On the other hand, Figure 5.12 shows, how scheduling transmissions on several wavelengths makes this difference less dependent on the transmissions of the other ONUs. Then, this dependence decreases with increasing the number of wavelengths. However, it is possible to notice that, the more we increase the number of wavelengths used, the more the scheduling of the second thread depends on the transmission of the first thread, and viceversa. This means that the transmission of the a generic thread i, for ONU_k, must be scheduled after the end of the transmission of thread $i-1$ because a single ONU can only send one transmission at a time. As a consequence, may happen that on a particular wavelength a transmission is not scheduled as soon as possible according to the availbilty of the channel but only after the end of the previously granted transmission for the same ONU. This scheduling constraint may lead to inefficiencies in the utilization of the channel.

In the subsequent section we present then an allocation scheme which tries to overcome the inefficiencies of both EFT-Partial-VF Enhanced and Multithread algorithms.

5.3 EFT-Partial-VF Multithreaded

The EFT-Partial-VF Multithreaded (EFT-partial-VF MT) is an allocation scheme which combines features of the EFT-Partial-VF Enhanced with features of Multithread algorithm. This algorithm is basically composed of two different phases namely the Single Thread (ST) operation and the Multithread (MT) Operation. The scheme switches from the ST operation to the MT operation independently for each ONU according to the traffic load provided by each user. This means that, within this scheme, at the same time some ONU can be in MT operation while some other ONU can be in ST opeation. Practically an ONU_k switches from ST operation to MT operation when its traffic load becomes high and conversely switches from MT operation to ST operation when its data load returns to low values. In the ST operation this algorithm behaves like the EFT-Partial-VF Enhanced scheme. An example of the basic operation of this algorithm, where all the data are transmitted in a single block, is shown in Figure 5.14. Also in this case, an eligible void during ST operation is defined, through (5.17), as the time periods which is long at least a fraction N of the time needed to transmit the requested amount of data G.

$$V_k = \{F_{i,j} \,|S_{i,j+1} - max(F_{i,j}\,, t + R_k + t_c) \geq t_g/N + t_c\}, \quad i \in W_k \tag{5.17}$$

Examples of the EFT-Partial-VF MT operations, when the transmission is divided into different blocks, are shown in Figure 5.15 and Figure 5.16. Figure 5.15 shows a situation where the partial void filling algorithm is applied for both first and second transmission. Conversely Figure 5.16 shows the case where the first transmission is scheduled through the partial void filling algorithm while the second transmission is assigned using EFT rule. In all these examples, we use $N = 2$, which means that at most a transmission will be split in two blocks of data.

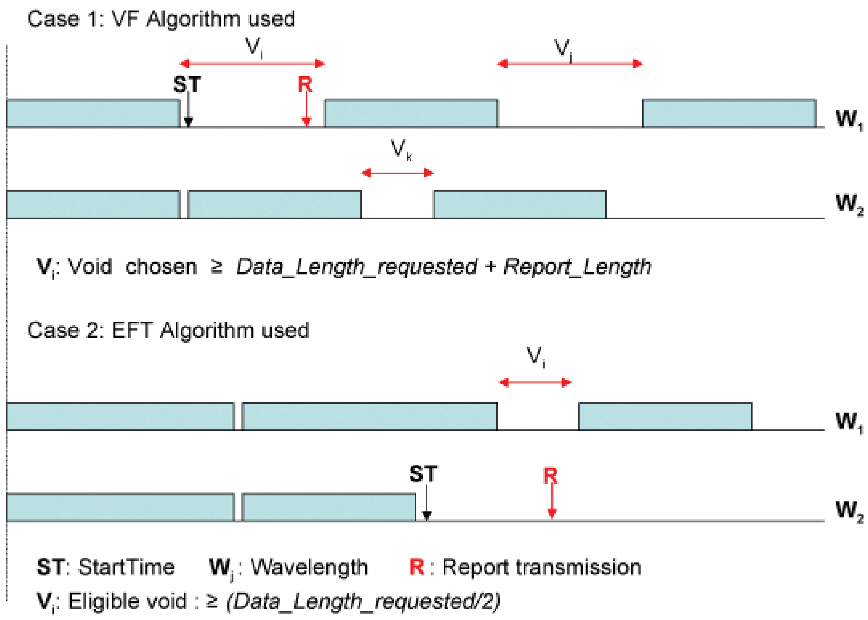

Figure 5.14: Operation of the EFT-VF Algorithm with Partial Void Filling Multithreaded.

In ST operation, when the transmission for the ONU_k is divided into different portions of data, the algorithm switches to MT operation where, at most, N threads are assigned to this same ONU_k. The number of threads assigned to an ONU correspond to the number of chunks in which its transmission is partitioned. The switch from ST to MT operation is possible because, in this scheme, the ONU is allowed to send a REPORT message after each transmission block. Each of these REPORT message, when it is received by the OLT, initiates a new thread. In fact, for each REPORT received, the OLT sends a new GATE message for the ONU indicating when this latter can start the transmission for this new thread. As an example, when the *n-th* REPORT, $n \in 1, 2, ..., N$, is received, the OLT generates a new scheduling for the length of data requested by the ONU. The OLT sends then the GATE message which will make start the *n-th* thread. When an ONU is in MT operation, it behaves like in the EFT-VF early-ST-priority algorithm which means that the scheduling for each thread is done choosing the $S_{i,j}$ between the earliest

$S_{i,j}$ assigned using the EFT algorithm and the $S_{i,j}$ chosen by the VF rule. Therefore, during the MT operation, an eligible void is defined through (5.18).

$$V_k = \{F_{i,j} \,|S_{i,j+1} - max(F_{i,j}\,, t + R_k + t_c) \geq t_g + t_c\}, \quad i \in W_k \quad (5.18)$$

As a result, all the requested length of data for a single thread is not divided into multiple transmissions. This behavior is due to the fact that it is necessary to prevent an uncontrolled proliferation of threads. Moreover it is expected that, since there are more threads, each REPORT of each thread will asks to the OLT for a smaller length of data. This happens because, with more threads, data and REPORT packets are sent more often with respect of ST operation. Then the length of data in the ONU queue decreases faster. Consequently, this feature of having smaller REPORTs allows the algorithm to fill also small voids without the need to cut the requested length G into multiple transmissions. When the traffic load of the ONU_k decreases, the ONU_k will send REPORT messages to the OLT where the length of data required becomes smaller and smaller. This means that the queue of the ONU is becoming shorter since the number of packets reported into a REPORT message corresponds to the queue length of the ONU measured in the moment when the REPORT is sent. Therefore, if the number of bytes required in a REPORT is zero this REPORT is ignored by the OLT. In this way, if the ONU was transmitting in N threads it will now uses only $N-1$ threads. When the OLT receives $N-1$ REPORT messages reporting zero bytes in the ONU queue, the algorithm switches again to ST operation.

In the following chapter we show and discuss results provided by these allocation schemes, both comparing among them the various algorithms, under the same network conditions, and evaluating each allocation scheme varying network characteristics such as the number of wavelengths used and the distribution of the distances from ONUs to the OLT.

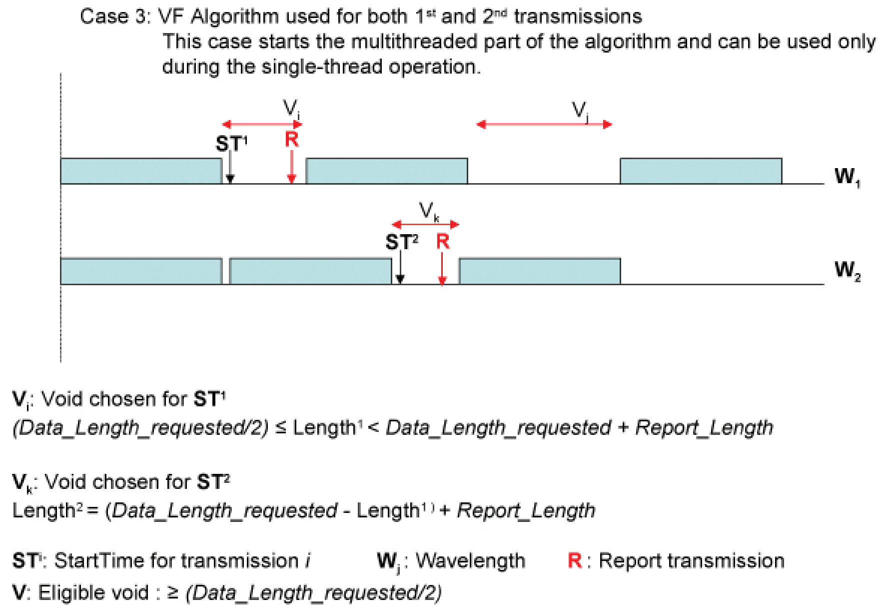

Figure 5.15: Operation of the EFT-VF Algorithm with Partial Void Filling Multithreaded.

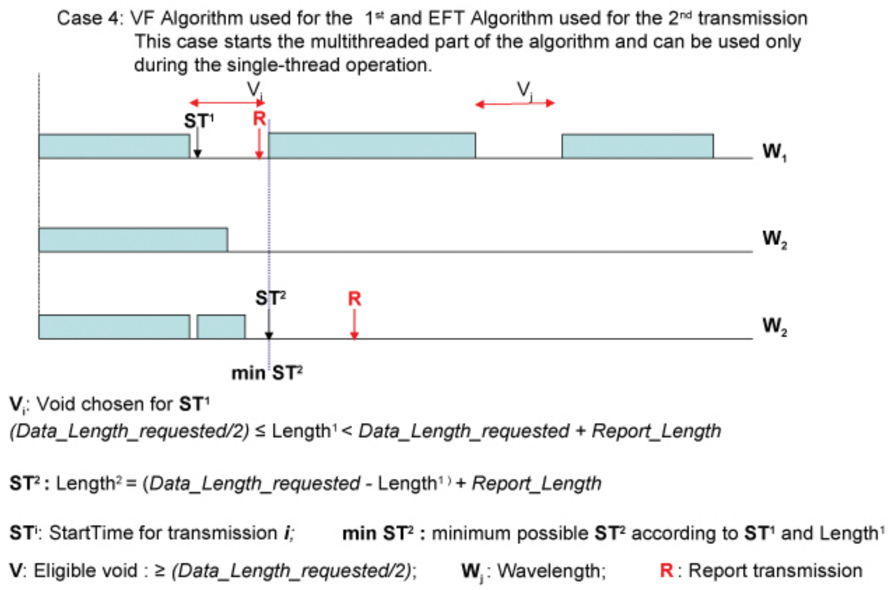

Figure 5.16: Operation of the EFT-VF Algorithm with Partial Void Filling Multithreaded.

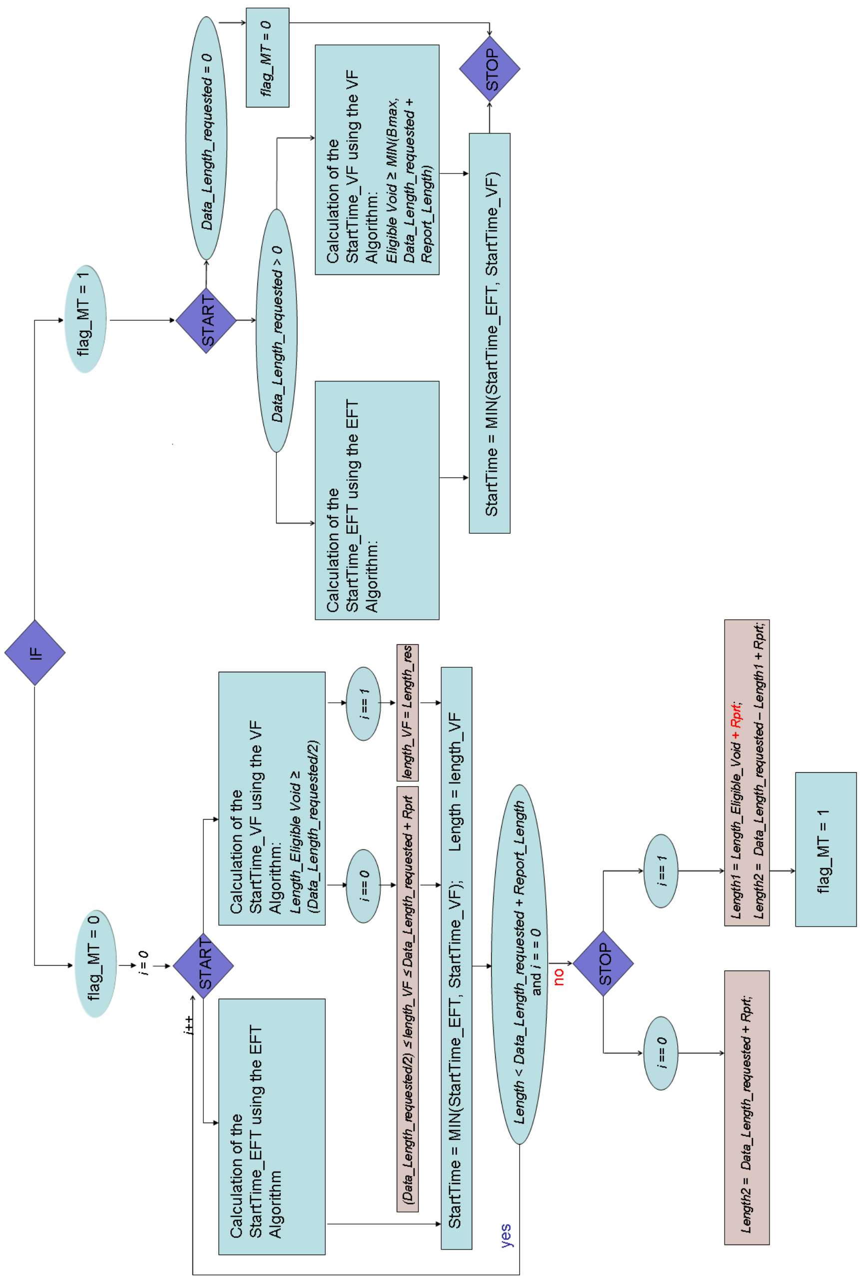

Figure 5.17: Scheme of the EFT-VF Algorithm with Partial Void Filling Multithreaded. i refers to the iteration number. In this example we shows the scheme of the algorithm applied in a case where the $N = 2$ which means that, at most, the transmission can be divided in two blocks of data. $flag_M T = 1$ identify the Multithread operation of the algorithm; $flag_M T = 0$ identify the Single Thread operation of the algorithm.

Chapter 6

Numerical Results and Discussion

This chapter presents the simulation scenario and the results obtained from simulations. First of all we compare the allocation schemes with each other through different parameters like the average packet delay, the average queue length of the ONUs, the channel utilization and, for the EFT-VF options, the fraction of eligible voids filled. Then each DBWA scheme is evaluated varying parameteres of the network such as the number of wavelenghts supported by the LR WDM/TDM PON and the distribution of the distances from the OLT to the ONUs. Therefore, in order to highlight different behaviors, all the algorithms are tested in different simulation scenarios. In particular, all the DBWA schemes are tested in three main simulation frameworks: A general simulation framework, a Branch and Tree simulation framework, and a Ring and Spur simulation framework.

6.1 General Simulation Framework

In order to evaluate the performances of the proposed algorithms, we implemented a network simulator based on the Discrete Event Simulation Library (DESL) [52], modified to simulate a LR WDM/TDM PON. In this tool only the upstream transmission is considered. To reflect the property of the real Internet traffic we use a self-similar traffic which is generated by aggregating multiple sub-streams, each consisting of alternating Pareto-distributed ON/OFF periods, with a Hurst Parameter of 0.8. The simulator generates packets in the forms of Ethernet frames with a length distributed between 64 and 1518 bytes. The buffer size of each ONU has a limited length of 10 Mbytes. The polling cycle time is 2 ms and, according to this value, the $B_{max},_k$ that each ONU can transmit in each cycle time is 14625 bytes. We state then that the $B_{max},_k$ is the same for each ONU wich correspond to assign the same capacity to each end user. The guard band time between two subsequent transmissions is 1 μs. The topology includes 128 ONUs all transmitting over all the 8 wavelengths. Each channel, consisting of a single wavelength, has a bit rate of 1 Gbit/s which gives a total capacity of 8 Gbit/s. The distances from the OLT to the ONUs are uniformly distributed between 500 m and 100 km. The load offered to the network by the ONUs varies during the simulation from 0.05 to 1 and, at this load the bit rate of each ONU is 62.5 Mbit/s. For the EFT-Partial-VF implementations, we use an $N = 2$ but other values of this variable can be considered.

Simulation parameters used for Multithread over LR WDM/TDM PON and for all the Void Filling versions are summarized in table 6.1.

Table 6.1: Simulation Parameters

	EFT- VF Algotihms	WDM-MT Algorithms
Number of ONUs	128	128
Number of wavelengths	8	8
Capacity per wavelength	1 Gbit/s	1 Gbit/s
Capacity per ONU	62,5 Mbit/s	62,5 Mbit/s
Total Capacity	8 Gbit/s	8 Gbit/s
Cycle time	2 ms	2 - 10 ms
Bmax per Cycle time	14625 byte	6812 - 38062 byte
Guard Band Time	1 μs	1 μs
Distances OLT-ONUs	500 m -100 km (fixed)	500 m -100 km (fixed)

6.1.1 Results and Discussion

All the results are compared with pure EFT algorithm to see first what is the improvement due to Void Filling and to Multithread solutions, and then we compare the results given by the different implementations of these schemes. In Figure 6.1 we plot the average packet delay versus the offered load. We can observe that all the EFT-VF algorithms introduce a real improvement regarding the packet delay compared to

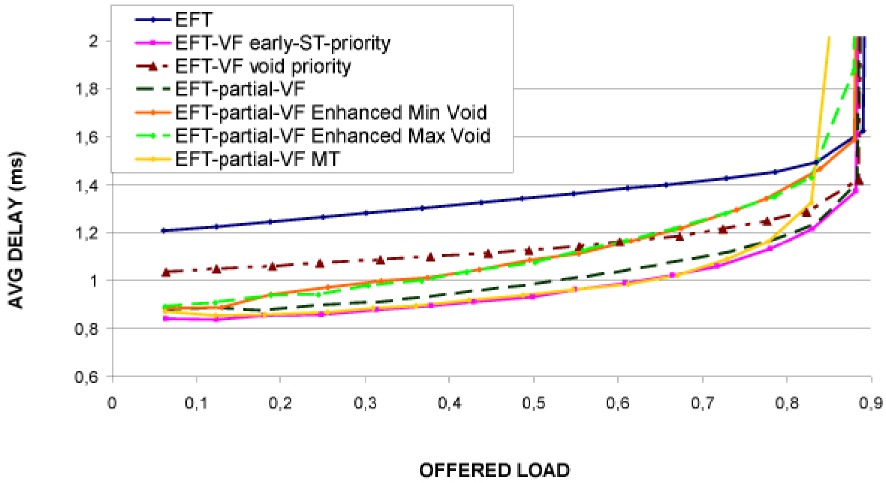

Figure 6.1: Average packet delay comparison between EFT algorithm and EFT-VF solutions, for the Generic simulation scenario. Distance distribution between [500 m; 100 km]

EFT. The difference in the average delay between EFT and EFT-VF algorithms is more significant at low loads it decreases when the network load increases, and disappears at very high loads, when the network saturates.

Among the EFT-VF algorithms, the one which gives the better performance is EFT-VF early-ST-priority.

Instead, the one that gives the worst performance at low loads is the EFT-VF Void Priority. At medium and high loads, the one that performs worse is the EFT-Partial-VF Enhanced algorithm. Regarding the EFT-Partial-VF, its performance is very similar to that of EFT-VF early-ST-priority. However, EFT-Partial-VF does not grant the minimum capacity per ONU since it is allowed to cut the requested length of data to fill voids and leaving the remaining part of data in the queue of the ONUs. The minimum capacity per ONU is in fact guaranteed allocating for each transmission the bandwidth needed to transmit the requested length of data, if this is less than $B_{max;k}$, or otherwise $B_{max;k}$. The EFT-Partial-VF Enhanced, which instead guarantees all the requested length of data, has a good performance at low loads, which tends to deteriorate faster than the other void filling strategies when the network load grows up. This is due to the fact that, within this algorithm, REPORT messages are sent only at end of the last transmission block, which means that they are sent less frequently with respect of the basic EFT-Partial-VF scheme. In fact, the latter scheme always sends only a single transmission with a piggy-backed REPORT for each ONU, therefore REPORT messages are sent more frequently. Within the EFT-Partial-VF Enhanced algorithm, the time period between the transmission of two subsequent REPORTs is longer than in EFT-Partial-VF, and the queue length of each ONU of this algorithm grows more than in all the other void filling schemes, as discussed in detail in Figure 6.4. Furthermore this negative feature becomes more pronounced when the network load increases. For this reason EFT-Partial-VF Enhanced algorithm has an average packet delay which increases faster with respect of all the other void filling schemes. Another consequence of having infrequent REPORTs is that the number of packets reported in each of these messages can be very high.

In such way, a portion N of the total length G will be longer if compared with a fraction of data N usually obtained in the basic EFT-Partial-VF. As a consequence, in EFT-Partial-VF Enhanced, the length of a single portion of data is longer if compared with EFT-Partial-VF and then, for the first one there are less chances to find a void to fill.

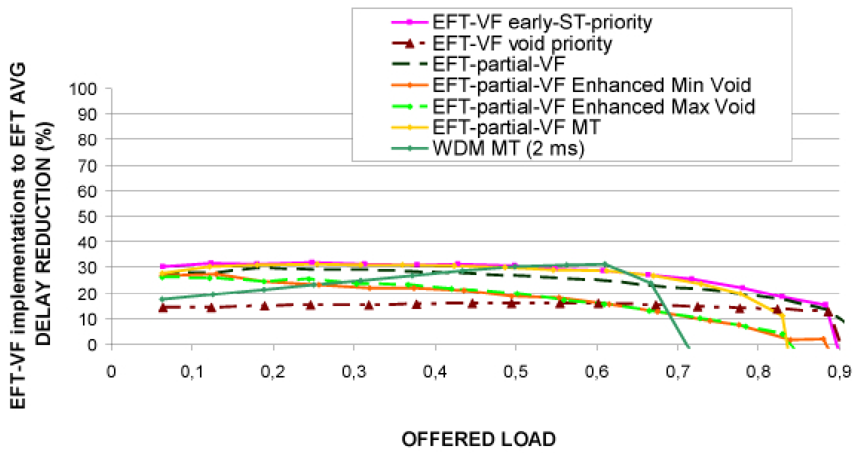

Figure 6.2: Average delay reduction of EFT-VF solutions and Multi-thread over WDM/TDM with respect of EFT algorithm, for the Generic simulation scenario. Distance distribution between [500 m; 100 km].

Concerning the EFT-partial-VF MT its average delay is very similar to the packet delay given by EFT-VF early-ST-priority, except for high loads where the first performs worse. Nonetheless, as shown by the Figure 6.2, the difference between the average delays of the different solutions is almost constant for low loads, whereas at medium loads this difference starts to decrease. For high loads, instead, the different solutions have similar performances. This is due to the fact that, for such loads, the number of packets transmitted is very high and then the number of voids which can be filled is very low. For this reason, as expected, the performance of the EFT-VF algortihms becomes similar to the one of pure EFT scheme.

Finally, from Figure 6.3 it is possible to see that the average delay given by the Multithread algorithm implemented over a WDM/TDM network is higher than all the void filling versions but, still this first algorithm gives improvements over the pure EFT scheme.

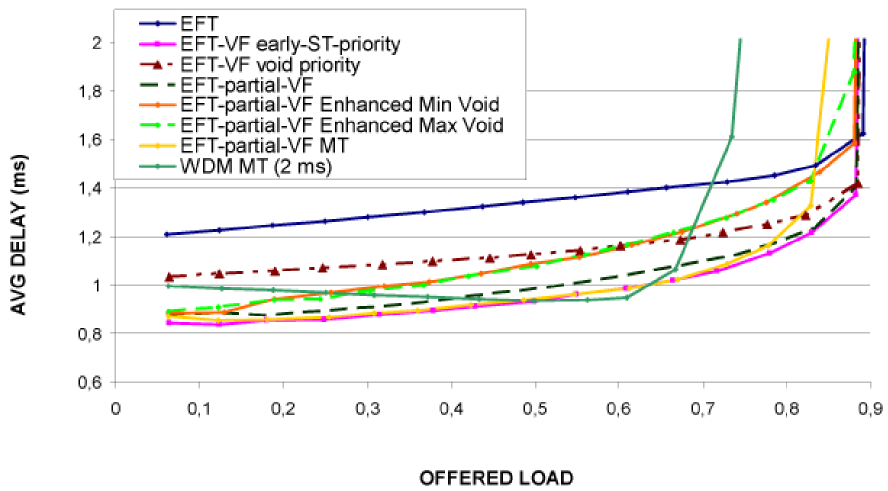

Figure 6.3: Average packet delay comparison among EFT algorithm, EFT-VF solutions, and Multithread over WDM/TDM algorithm for the Generic simulation scenario. Distance distribution between [500 m; 100 km]

Figure 6.4 shows that the pure EFT algorithm has the greater average queue length. In fact, to a higher packet delay corresponds a higher queue size, and viceversa. All the EFT-VF schemes have instead lower queue sizes compared with the EFT algorithm. Among the algorithms which give a better performance, the best is EFT-VF early-ST-priority. In practice, the trend of the average queue length follows the one of the

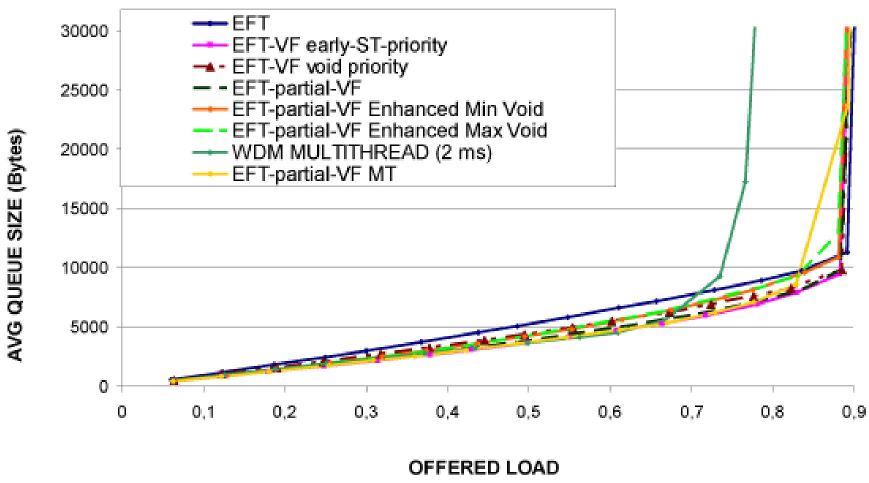

Figure 6.4: Average queue size comparison among EFT algorithm, EFT-VF solutions, and Multithread over WDM/TDM algorithm , for the Generic simulation scenario. Distance distribution between [500 m; 100 km]

average packet delay. In fact, more packets are accumulated in the queue and more the average delay of the packets increases. Regarding the Multithread algorithm over WDM/TDM network, the average queue length is the same as EFT-VF early-ST-priority until a load of approximately 0.6. From this point, the value of the average queue size start growing very fast. Again this feature describes the same behaviors already depicted by the graph of the average delay.

In Figure 6.5, are presented results on fraction of void filled, which is the number of void filled over the total number of eligible voids. We observe in Figure 6.5 that the EFT-Partial-VF Enhanced, the EFT-Partial-VF MT, and the EFT-Partial-VF have higher fraction of voids filled. This happens because these solutions allow more voids to be labeled as eligible for a transmission of a specific ONU_k, and hence, the chances to fill these time periods are increased. In addition, using the partial void filling implementations there are more chances that a residual void (formed after that a previously existent void is partially filled) will be used for a transmission. Moreover, the EFT-partial-VF Enhanced and EFT-partial-VF MT have the best value of fraction of voids filled because they always allocate all the requested length of data

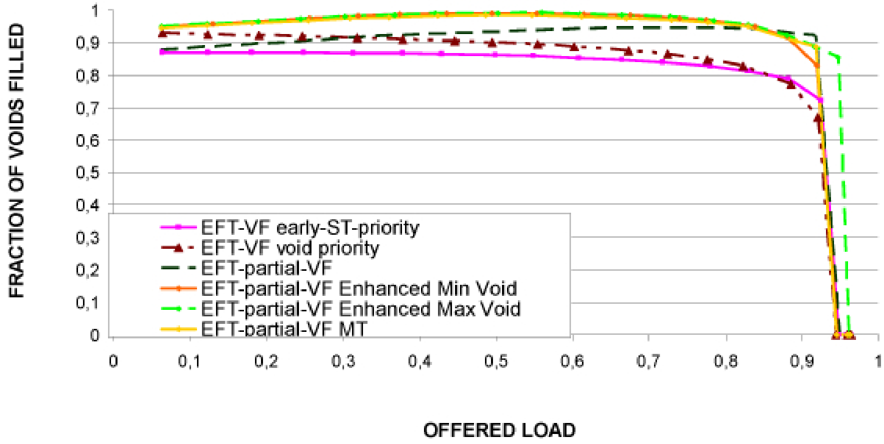

Figure 6.5: Fraction of void filled comparison among all EFT-VF solutions, for the Generic simulation scenario. Distance distribution between [500 m; 100 km]

and, if a transmission is cut into different portions, they schedule all the chunks. In this latter case, it is possible for these two algorithms to fill a higher number of voids because they are able to fill also small voids. For low loads, the EFT-Partial-VF instead fills a lower fraction of eligible voids having a performance similar to the one of EFT-VF early-ST-priority. Indeed, at low loads the lengths of data requested by ONUs are small if compared with the length of voids and, for this reason, it is possible to fill the voids on the channel without slice transmissions. Therefore, we can observe that EFT-Partial-VF and EFT-VF early-ST-priority behaves in the same way, for low loads. Conversely, the EFT-VF early-ST-priority, among all void filling implementations, is the one which has the lowest fraction of void filled. This occurs because, for this scheme, a void is labeled as eligible only if it is long enough to accomodate all the requested length of data. In this way, voids which are shorter than this length can not be filled by this algorithm. Between the two bounds given by these algorithms lies the EFT-VF with Void Priority. This scheme, indeed, aims to fill all the eligible voids, by prioritizing the scheduling of a transmission in a void. However, the length of an eligible void is defined in the same way in which is defined in the EFT-VF early-ST-priority. For this reason, also within this algorithm, it is not possible to fill voids which are shorter than the requested data length. The fraction of voids filled is almost constant for low and medium loads, for EFT-VF early-ST-priority and EFT-Partial-VF solutions, and becomes zero when the network saturates. In fact, the number of voids decreases when the load increases. Concerning all the EFT-Partial-VF implementations, we can notice that the fraction of voids filled slowly increases with the load. This happens because as load increases there are fewer voids and tend to be smaller in length. Therefore, these solutions can also fill the small voids, given that the requested length can be partitioned and allocated to a smaller void or, for the EFT-partial-VF Enhanced and for EFT-Partial-VF MT, to a set of smaller voids. It is interesting that all the EFT-Partial-VF solutions, except for EFT-Partial-VF Enhanced which leads to maximize voids formation, go to zero at high load before the other two approaches. The reason is that the total number of eligible voids for EFT-VF early-ST-priority and EFT-VF Void Priority becomes smaller at very high loads, therefore, their fraction of voids filled is higher than the EFT-Partial-VF. Whereas, for this last solution, the total number of eligible voids is higher compared to the other two schemes, and as a consequence the fraction of voids filled becomes very small earlier (at lower load). Instead, the EFT-Partial-VF Enhanced that aims to maximize the formation of residual voids in the channel (identified by the light green line in Figure 6.5) exploits its feature of voids formation to create voids which can be easily filled.

6.2 Branch and Tree Simulation Framework

In this framework, we vary network parameters to simulate a Branch and Tree network. Within this scenario the distances among the ONUs are less spreaded. Unlike in the previous case all the values between the maximum and the minimum defined distances can be assumed by the ONUs. Comparing the results of this scenario with the results given by the General scenario, we can analyze how the sparsity of these distances affects algorithm performances. Therefore, the distances from the OLT to the ONUs are uniformly distributed between a maximum and a minimum distance which are varied in the different scenarios. Particularly in the scenario that we define, the distances from OLT to the ONUs are uniformly distributed between [50 - 100] km. All the others parameters are the same already used in the Generic scenario and presented in section 6.1.

Simulation parameters used for Multithread over LR WDM/TDM PON and for all the Void Filling versions are summarized in table 6.2, for the first scenario, and in table 6.3, for the second scenario.

Table 6.2: Simulation Parameters for the Branch and Tree Simulation Framework: First scenario

	EFT- VF Algotihms	WDM-MT Algorithms
Number of ONUs	128	128
Number of wavelengths	8	8
Capacity per wavelength	1 Gbit/s	1 Gbit/s
Capacity per ONU	62,5 Mbit/s	62,5 Mbit/s
Total Capacity	8 Gbit/s	8 Gbit/s
Cycle time	2 ms	2 - 10 ms
Bmax per Cycle time	14625 B	6812 - 38062 B
Guard Band Time	1 μs	1 μs
Distances OLT-ONUs	[50 - 100] km	[50 - 100] km

Table 6.3: Simulation Parameters for the Branch and Tree Simulation Framework: Second scenario

	EFT- VF Algotihms	WDM-MT Algorithms
Number of ONUs	128	128
Number of wavelengths	8	8
Capacity per wavelength	1 Gbit/s	1 Gbit/s
Capacity per ONU	62,5 Mbit/s	62,5 Mbit/s
Total Capacity	8 Gbit/s	8 Gbit/s
Cycle time	2 ms	2 - 10 ms
Bmax per Cycle time	14625 B	6812 - 38062 B
Guard Band Time	1 μs	1 μs
Distances OLT-ONUs	[80 - 100] km	[80 - 100] km

6.2.1 Results and Discussion

First simulation scenario

For what concern this first simulation scenario, we notice that in Figure 6.6 the EFT-partial-VF MT is the algorithm that performs better.

All the other EFT-VF algorithms have a worst average delay, for almost all loads, compared with the average delay of the EFT-partial-VF MT.

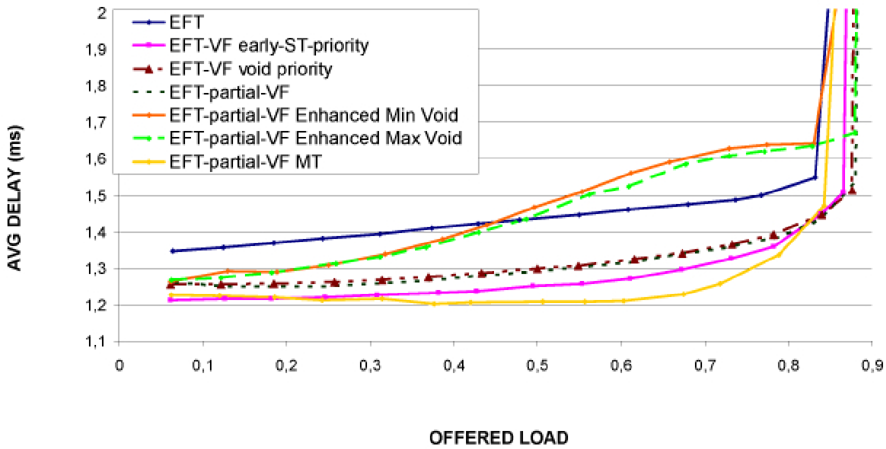

Figure 6.6: Average packet delay comparison between EFT algorithm and EFT-VF solutions in the First Branch and Tree scenario. Distance distribution between [50; 100] km.

The degraded performance of the EFT-partial-VF Enhanced, already observed in the General scenario, is much more stressed in this case. The reason of this behavior is that the number of void created in this network configuration is lower with respect of the General case, where the distances of the ONUs from the OLT were very spreaded. Moreover, as the length of voids formed on the channel depends on the difference among the RTT of the ONUs, in this case the voids have lower length with respect of the General scenario. For this reason, the transmissions are often split into multiple chunks. As there are few voids, it is difficult for this algorithm to schedule the subsequent fractions of the transmission in a void. These latter are then often scheduled using the EFT algorithm. This means that the subsequent chunks of a transmission can be much delayed, specially if on the channel there are a lot of other ONUs transmitting. In fact, at medium loads, when the channel starts to be overloaded, the average delay of the EFT-partial-VF Enhanced increases fast. Moreover, if a void can be found for the transmission of subsequents block of data, these could be also delayed because the voids on the channel are very rare. The trend of all the others Void Filling algorithms is

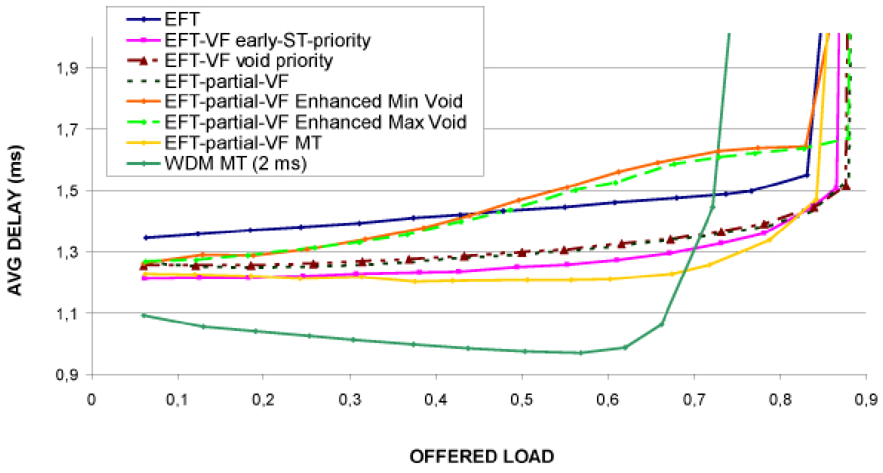

Figure 6.7: Average delay comparison between EFT algorithm, EFT-VF solutions, and Multithread over WDM/TDM algorithm in the First Branch and Tree scenario. Distance distribution between [50; 100] km.

the same than the one observed in the Genereal case. However, it is possible to notice that the difference between the average delay of the EFT algorithm and the average delays of the others Void Filling algorithms is lowered in this network scenario. This happens because the more the distances between the OLT and the ONUs are similar among them, the lower the number of voids in the channel.

Regarding the Multithread algorithm implemented over a WDM/TDM system, we observe in Figure 6.7 that the trend is similar to the General scenario. Though, in the Branch and Tree configuration, its average delay is scaled up due to the minimum distance between OLT and ONUs that is much higher with respect the General scenario. Equivalently, for all EFT-VF solutions and Multithread over WDM/TDM algorithm, the same features can be noticed from Figure 6.8, where the average delay reduction with respect of the EFT algorithm is represented.

The scarcity of voids within this network scenario is shown also by Figure 6.9. In fact, this Figure shows that all the Void Filling algorithms fill a fewer number of voids. This is mainly due to two different features: the rarity of voids in the channel and the shortness of these voids. The first of these two causes lower the probability to fill a void. Whereas, due to the second one, it is more difficult for the Void Fililng algorithms

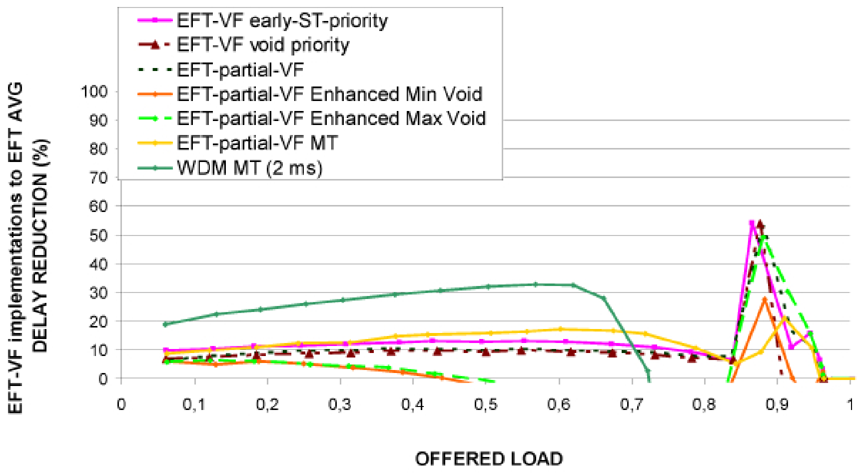

Figure 6.8: Average delay reduction of EFT-VF solutions and Multi-thread over WDM/TDM with respect of EFT algorithm, in the First Branch and Tree scenario. Distance distribution between [50; 100] km.

to schedule a transmission in a void. Among all the algorithms, the one which fills the higher number of void is the EFT-VF Void Priority because it always tries to find a void where to schedule a transmission. The EFT-VF early-ST-priority, has a trend similar to the General scenario, however, within the Branch and Tree configuration, the number of void filled is much lower. Concerning all the EFT-Partial-VF versions of the algorithm, we can remark that they behave all in the same way. In fact, at low loads, they all fill a low number of voids. As the network load increases, also the fraction of voids filled by this algorithm increases. This happens because, for low loads, the ONUs ask for shorter transmission window and then a lot of voids between two subsequent transmissions are formed. Moreover, as the ONUs have to transmit few packets, there are little probabilities to fill a large number of voids. Furthermore, when the load increases, as these algorithms have the skill to divide the transmission for an ONU in more block of data, higher numbers of voids are filled. When the loads become very high and then the network starts to saturate, the voids on the channel are very rare and ONUs aks for very long transmission windows. For this reason it is very hard to find a void in which to schedule transmissions and then the fraction of voids filled fastly goes to zero.

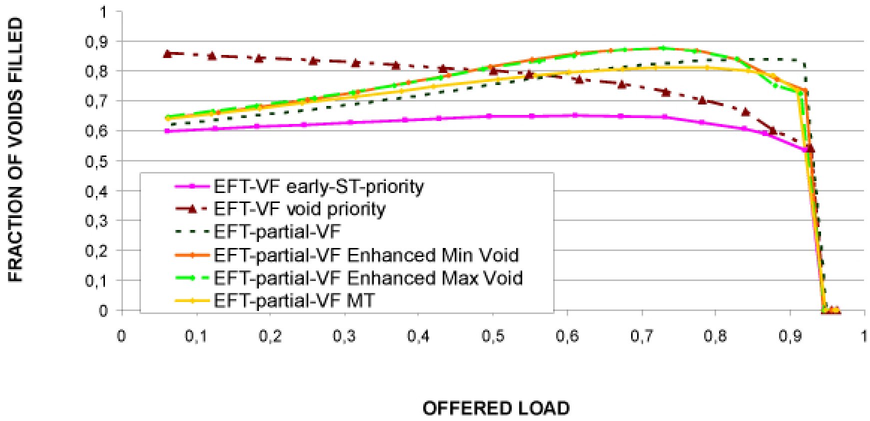

Figure 6.9: Fraction of void filled comparison between EFT algorithm and EFT-VF solutions in the First Branch and Tree scenario. Distance distribution between [50; 100] km.

Second simulation scenario

For the second simulation scenario, we observe in Figure 6.10 that the algorithm which performs better is the EFT-partial-VF MT. All the other EFT-VF algorithms have a worst average delay compared with the average delay of the EFT-partial-VF MT, except for very high loads where the network saturates. Basically, for this network configuration, the same observations made for the first scenario can be done. Comparing the results of the two Branch and Tree scenarios, we notice in Figure 6.13 that the difference between the average delay of the EFT algorithm and the average delays of the others Void Filling algorithms decreases when the spread of the distances from ONUs to OLT decreases. This happens because the more the distances between the OLT and the ONUs are similar among them, the lower the number of voids in the channel. Consequently the Void Filing strategies can not exploit their feature of scheduling transmission in voids to improve performance in terms of average packet delay. This can be noticed in Figure 6.12.

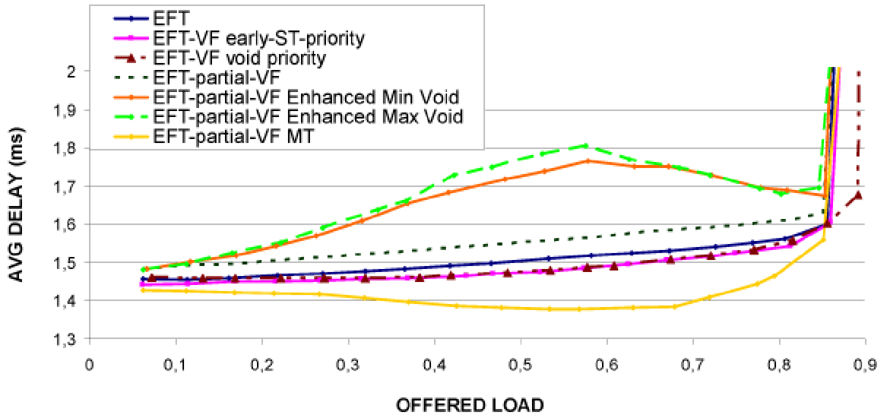

Figure 6.10: Average packet delay comparison between EFT algorithm and EFT-VF solutions in the Second Branch and Tree scenario. Distance distribution between [80; 100] km.

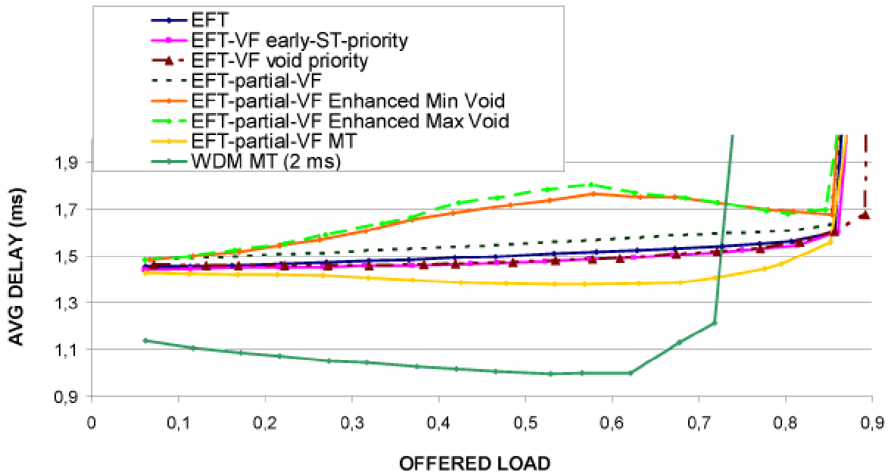

Figure 6.11: Average delay comparison between EFT algorithm, EFT-VF solutions, and Multithread over WDM/TDM algorithm in the Second Branch and Tree scenario. Distance distribution between [80; 100] km.

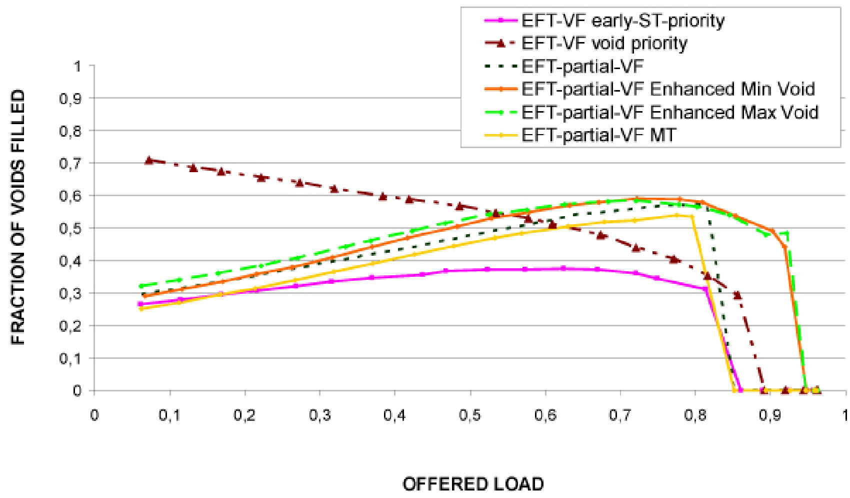

Figure 6.12: Fraction of void filled comparison between EFT algorithm and EFT-VF solutions in the Second Branch and Tree scenario. Distance distribution between [80; 100] km.

Concerning the Multithread over LR WDM/TDM PON we can see in Figure 6.11 that the trend is the same than in General scenario and First Branch and Tree scenario. We can affirm that the behavior of this algorithm does not depend on the distribution of the ONU-to-OLT distances. However, the average delay of the Multithread algorithm is increased due to the minimum distance between OLT and ONUs which is much higher with respect of both General scenario, and First Branch and Tree scenario.

6.3 Ring and Spur Simulation Framework

In this framework, network parameters are varied to simulate a Ring and Spur network. In this LR WDM/TDM PON, ONUs are connected to the fiber ring through a Remote Node (RN). Within this simulation scenario 4 RNs are settled and the distances from the OLT and these RNs are assumed fixed and predefined. Moreover, to each RN is connected the same number of ONUs. The distances between the RN and ONUs, instead, are randomly distributed. In order to simulate this network the distances from the OLT to the RNs are set to 12.5 km, 37.5 km, 62.5 km

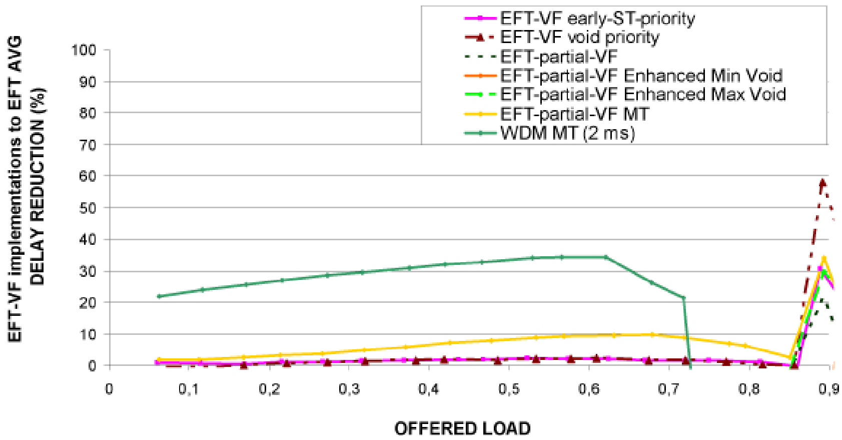

Figure 6.13: Average delay reduction of EFT-VF solutions and Multithread over WDM/TDM with respect of EFT algorithm, in the Second Branch and Tree scenario. Distance distribution between [80; 100] km.

and 87.5 km which corresponds to install 4 RNs uniformly distributed on a fiber ring of 100 km. Then the distances from each RN and the ONUs range between 0 and 12.5 km, in such way that only some sets of distances can be taken. In these simulations the lengths between the OLT and the ONUs can assume values from 12.5 km and 25 km, from 37.5 and 50 km, from 62.5 km and 75 km and from 87.5 km and 100 km. Given that the number of ONUs is 128 and the splitting ratio of the RNs 1:X, then each RN is connected to 32 different ONUs. All the others parameters are the same already used in the General scenario and presented in section 6.1.

Simulation parameters used for Multithread over LR WDM/TDM PON and for all the Void Filling versions are summarized in table 6.4 and 6.5.

Table 6.4: Simulation Parameters for EFT-VF Algorithms in the Ring and Spur Simulation Framework

	EFT- VF Algorithms	
Number of ONUs	128	
Number of wavelengths	8	
Capacity per wavelength	1 Gbit/s	
Capacity per ONU	62,5 Mbit/s	
Total Capacity	8 Gbit/s	
Cycle time	2 ms	
Bmax per Cycle time	14625 B	
Guard Band Time	1 μs	
Distances	Distance OLT-RN	Distance OLT-ONUs
	12.5 km	[12.5 - 25] km
	37.5 km	[37.5 - 50] km
	62.5 km	[62.5 - 75] km
	87.5 km	[87.5 - 100] km

Table 6.5: Simulation Parameters for WDM-MT Algorithms in the Ring and Spur Simulation Framework

	WDM-MT Algorithm	
Number of ONUs	128	
Number of wavelengths	8	
Capacity per wavelength	1 Gbit/s	
Capacity per ONU	62,5 Mbit/s	
Total Capacity	8 Gbit/s	
Cycle time	2 ms	
Bmax per Cycle time	6812	
Guard Band Time	1 μs	
	Distance OLT-RN	Distance OLT-ONUs
Distances	12.5 km	[12.5 - 25] km
	37.5 km	[37.5 - 50] km
	62.5 km	[62.5 - 75] km
	87.5 km	[87.5 - 100] km

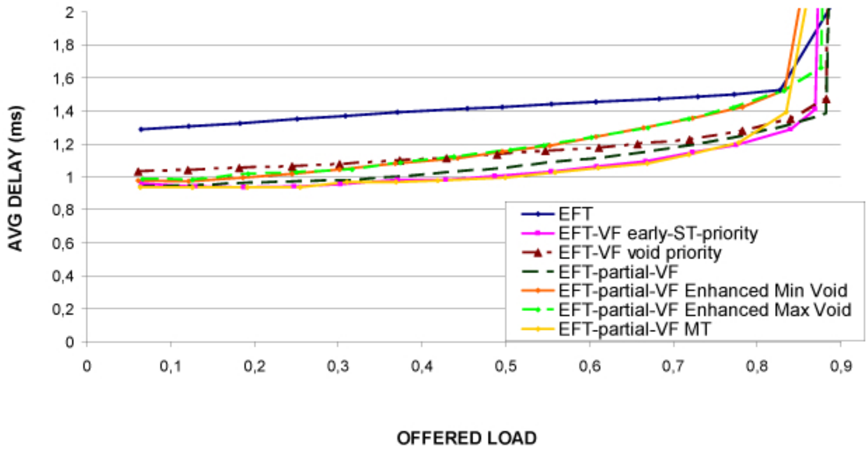

Figure 6.14: Average packet delay comparison between EFT algorithm and EFT-VF solutions in the Ring and Spur scenario.

6.3.1 Results and Discussion

In Figure 6.14, we notice that the trend of all Void Filling solutions and Multithread over WDM/TDM is similar to the one outlined in the Branch and Tree scenario. This means that, again, the more spreaded is the distribution of the distances from ONUs to the OLT and the more the Void Filling strategies outperform the Multithread and the EFT algorithm. Conversely, when these distances become more similar among them, all the EFT-VF algorithm suffer a performance degradation. We observe in Figure 6.15 that the behavior of the Multithread scheme, instead, does not vary depending on the network configuration. However, since in this scenario the distances from ONUs to OLT are very spreaded, the EFT-VF algorithms have a good performance and consequently in general they are not outperformed by the Multithread polling. These considerations are confirmed by Figure 6.16 where we plot the average delay reduction of all the schemes with respect of the EFT algorithm, used as a reference.

All the consideration made for the Branch and Tree scenario are then supported also by the results provided by the simulations run in the Ring and Spur network. In fact, we observe in Figure 6.17 that the trend of all the void filling strategies is similar to the one described in the General scenario, where the distances from ONUs to OLT are very spreaded.

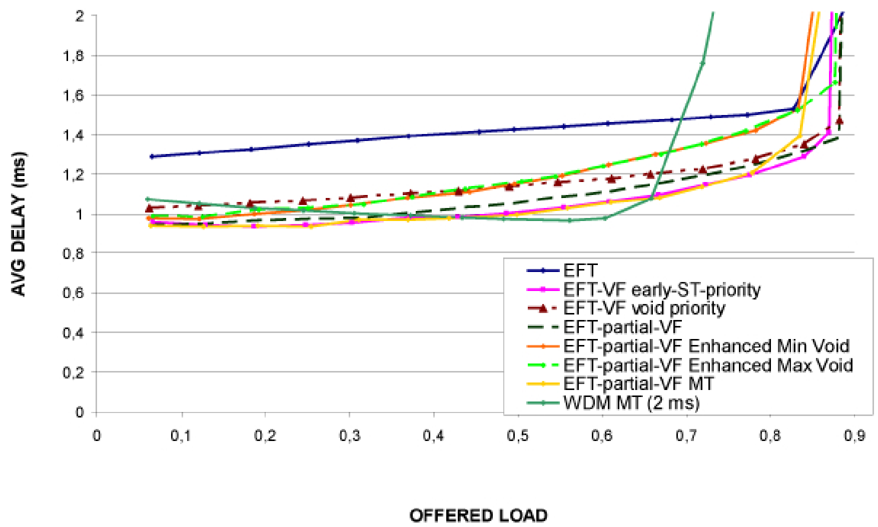

Figure 6.15: Average delay comparison between EFT algorithm, EFT-VF solutions, and Multithread over WDM/TDM algorithm in the Ring and Spur scenario.

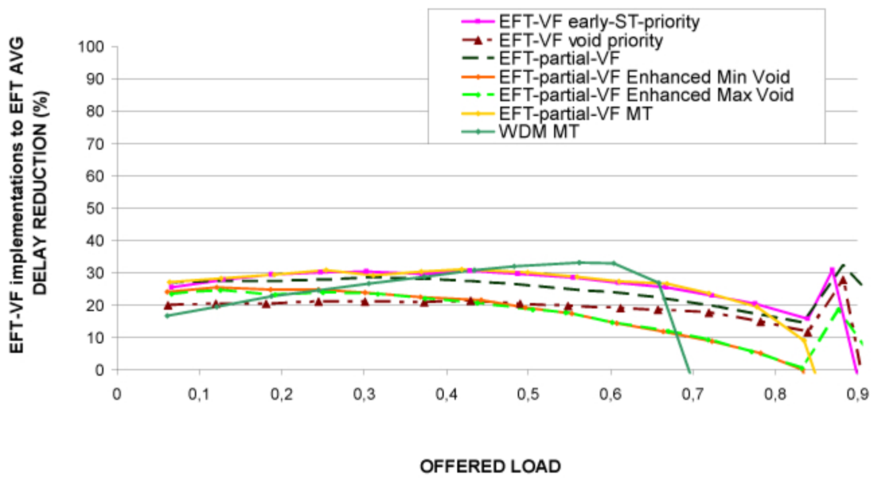

Figure 6.16: Average delay reduction of EFT-VF solutions and Multithread over WDM/TDM with respect of EFT algorithm, in the Ring and Spur scenario.

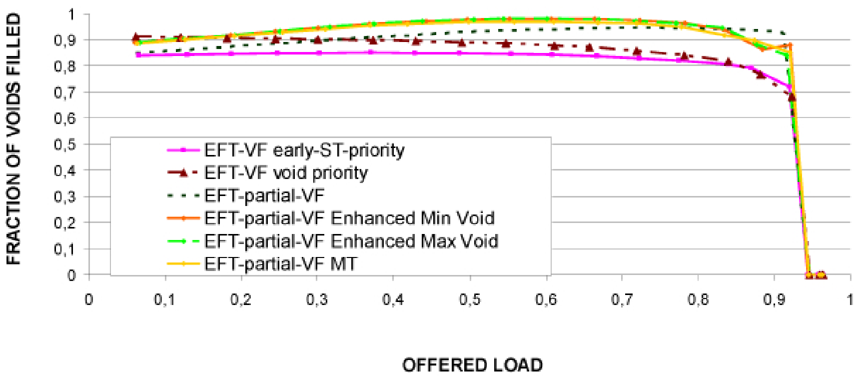

Figure 6.17: Fraction of void filled comparison between EFT algorithm and EFT-VF solutions in the Ring and Spur scenario.

Chapter 7

Conclusion

The objective of this work was to design dynamic bandwidth and wavelength allocation (DBWA) strategies in a LR WDM/TDM PON which efficiently exploit the available bandwith and which lead to reduce the average packet delay. We investigate different allocation schemes in order to find a solution which gives improvements with respect of the already existent strategies. These improvements are evaluated in terms of average packet delay are efficient bandwidth exploitment.

The proposed DBWA strategies are based on the Earliest-Finish Time with Void Filling (EFT-VF) and Multithread algorithms. Regarding the Void Filling solution, some Enhancement has been proposed in this work which lead to improve both the average packet delay and utilization of the available bandwidth. We implement then the Multithread algorithm over a LR WDM/TDM PON and we compare its performance with the other schemes, both from literature and proposed. To the best of our knowledge, the Multithread algorithm has never been implemented and evaluated into a hybrid WDM/TDM network. Finally, we propose a combination of Void filling strategies and Multithread algorithm which tries to overcome the negative features of these schemes. All the proposed algorithms are always compared with the EFT algorithm, which is used as a reference in order to evaluate the performances and the improvement introduced by the new schemes.

During this work, we evaluated the allocation schemes through a C++ simulator where all the proposed solutions and the already existent algorithms, used as a reference, have been implemented. The simulations provide as output several network parameters by means of which we compared the performances of the algorithms.

The results obtained in such way show that all the allocation schemes have significantly different performances when applied in different simulation scenarios. All the void filling strategies, in fact, outperform the EFT algorithm when they are applied in a network configuration where the distances from the OLT to the ONUs are very spreaded. When the distances become more similar among them, the performance of all the void filling schemes tends to be very similar to the performance of the EFT algorithm. Moreover, when all the ONUs are exactly at the same distance from the OLT, the strategies using a void filling mechanisms have the same performance of the EFT scheme, used as a reference. In the General scenario where the distances are very spreaded, the algorithm which performs better is the one called EFT-VF early-ST-priority which corresponds to the basic EFT-VF already proposed in literature. In this same scenario, our proposed EFT-Partial-VF Multithreaded algorithm has a performance very similar to the one of the EFT-VF early-ST-priority. However, when we apply these same algorithms in a pure Long-Reach scenario, which means that all the ONUs are at a long distance from the OLT (more than 20 km), our proposed EFT-Partial-VF Multithreaded is the one which has the best performance. This happens because we combine together Void Filling and Multithread in a proper way, in order to overcome the negative features in these schemes. Regarding the Multithread over WDM/TDM networks, its performance is similar in all the simulation scenarios, without respect of the distribution of the distances from ONUs to OLT. In such way, when we compare the Multithread algorithm with void filling strategies within a network where the ONU-to-OLT distances are more spreaded, we observe that the first is outperformed by the second, at least for low and medium loads. Conversely, the Multithread has a lower average delay when compared with void filling schemes, in a network configuration with all ONUs having similar distances from the OLT.

In this work, some issues remain open for possible future research. One of these possible future works is the investigation of DBWA in LR WDM/TDM PONs where ONUs are not allowed to use all the available wavelength but just a subset these. In such way different wavelengths might be used by a different number of ONUs. Another possible investigation field is provided by LR WDM/TDM PONs where different modulations are used depending on the distances between OLT and ONUs and depending on the transmission rate of different ONUs. As this latter can vary according to the need of each user, also the modulation can be changed. For this reason there could be the need to design DBWA schemes which are aware of these changes and which vary their behavior according to the different modulations and transmission rates.

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