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TRIUMPH

Transparent **R**ing **I**nterconnection

Using **M**ulti-wavelength **PH**otonic switches

Specific Targeted Research Project (STREP)
Information Society Technologies (IST)

Concept paper of TRIUMPH router and Manufacturability plan

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Abstract:
This is a public document containing a Concept paper and a first draft of the manufacturability plan for the TRIUMPH router.

Executive Summary

This is a public document containing a concept paper and a first draft of a manufacturability plan for the TRIUMPH router.

The main objective of this deliverable is to disseminate the TRIUMPH project within the scientific community. To do that a concept paper with some technical details about the TRIUMPH router is presented. Some of the presented matters are already a product of the work performed during the first months of the project.

In a second section of this document a manufacturability plan for the TRIUMPH router is presented. This plan is divided in three different steps: Step 1 - The TRIUMPH project; Step 2 - From prototypes to commercial devices; Step 3 – System integration. An explanation about each referred step is then presented.

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1- Introduction

This deliverable, as a public document, aims for the dissemination of the TRIUMPH project within the scientific community.

For those who do not know the TRIUMPH project, the concept paper will give them an idea of how the TRIUMPH router will be constructed. For those already familiar with the project, some new improvements resulting from the work performed in the first months of the project will also be presented.

In a second section of this document, a first draft of a manufacturability plan is presented for the TRIUMPH router. This plan doesn't aim for a detailed study but rather gives a general idea of how it will be possible to take the TRIUMPH router from a European Project into a commercial system.

2- Concept paper of the TRIUMPH router

TRIUMPH is developing Multi-wavelength Photonic switches that perform multi-wavelength 2R optical regeneration and transparent optical grooming/aggregation. These switches allow a transparent interconnection between rings in a Metropolitan Area Network.

2.1- Motivation

Internet data communication has shown persistent growth over the last years. Studies based on actual traffic data from providers, indicate a yearly increase of 115% for aggregate average international Internet traffic [1]. The applications behind this growth are now familiar to most computer users (email, file transfer, web browsing, peer-to-peer applications, online gaming, etc…). Besides the traditional voice and data transactions, a variety of new content-intensive applications and associated services are emerging in today's telecommunication market: Video distribution, Video conferencing, Large image transfer, Virtual reality, Very high-speed internet access, Point-to-point Ethernet (1 Gbit/s, 10 Gbit/s and 100 Gbit/s in a near future), Feed Storage Area Networks (transfer of large amounts of stored data), Virtual Line Services (VLAN connectivity, optical VPN), and so on.

The possibility of offering the end users integrated TV, broadband Internet access and telephone services (triple-play) is a strong driving force for the end-user telecommunications market. At the same time, high-bandwidth connections and advanced services are expected to drive the enterprise market where large amounts of data have to be transferred to assure database replication, business continuity, disaster recovery, etc.

All these new applications and services impose demanding performances to the network. Besides the large bandwidth requirements, network flexibility and service differentiation are also highly desired. Offering large bandwidth services on-demand is a challenging goal for access and metro networks which at the same time should provide reconfigurability, dynamic grooming and aggregation schemes, protection, priority and quality of service assurance mechanisms in order to support a functional, efficient, cost effective and secure network infrastructure.

On the end-user side, the deployment of fibre-based access infrastructures in its different varieties (fibre to the Home/Premises/Curb) and different flavours of Passive Optical Networks (xPON) is paving the way to deliver all those "bandwidth-hungry" applications. At the same time, in the regional/long-haul network, several technologies are mature enough to guarantee high connectivity and supply the high bandwidth requirements of lower network levels.

This is why the literature refers to the "metro gap" [2] meaning that Metropolitan Area Networks (MANs) will need an upgrade in order to cope with future traffic demands. In fact, legacy metro networks face many limitations in terms of capacity, scalability and flexibility. They are mostly SDH/SONET based networks with low provisioning and service flexibility where each new optical connection has to be planed carefully. Scalability problems arise from the complex electronic multiplexing-demultiplexing schemes necessary before switching and recombining signals to the outbound side. An additional problem comes from the "multilayering" paradigm which makes reconfigurability and (re)provisioning across multiple rings a complicated and slow process.

Therefore, new technologies and network architectures urge for MANs.

2.2- Goals and Objectives

The TRIUMPH project proposes the development of network architectures and system solutions that will increase functionality and capacity of next-generation MANs. The effort is focused on Transparent Ring Interconnection Using Multi-wavelength PHotonic switches. The proposed network architecture is based on a transparent interconnection node that can efficiently replace, complicated and expensive electronic Digital cross-Connects (DXCs) and adds further advantages to reconfigurable networks by providing functionalities currently unavailable in the optical layer such as transparent traffic aggregation/grooming and multi-channel regeneration in a cost effective way. The node transparency will enable a variety of data rates, protocols and formats that are used in the metro and access network environments and are associated with the requirements of the emerging services and applications discussed in the previous section.

2.3- Network Scenario

The scenario refers to a high capacity network with the transparent interconnection node between core/regional-metro rings supporting data rates up to 160Gbit/s and metro-access rings supporting up to 40Gbit/s.

A topological study was made applying the TRIUMPH network architecture to the European reality. This study was based on statistical data of 177 European cities. It was concluded that for most cities (where around half of the considered population lives), a network such as the one sketched in Fig.1 would have a good performance when considering future traffic demand scenarios.

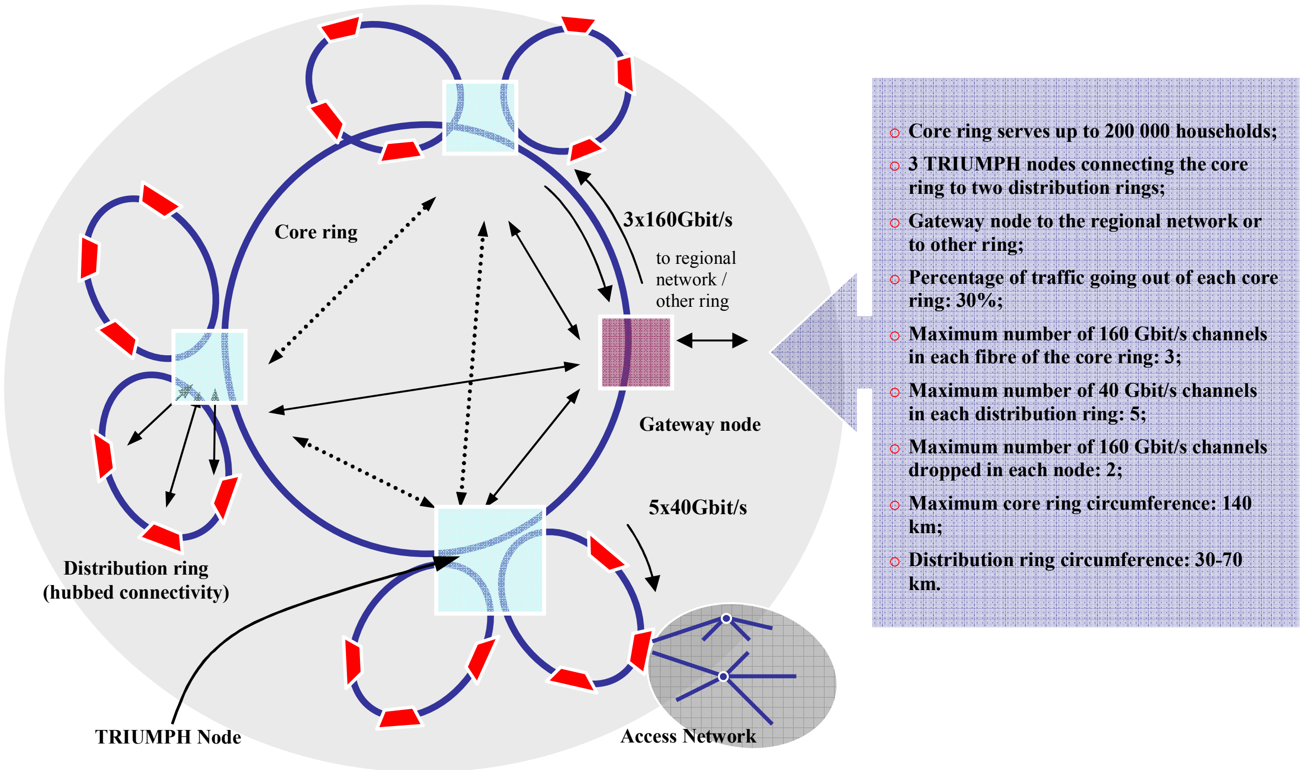

Figure 1 – Reference Network

Based on this reference network, simulations at system level, taking into account the physical impairments of the network, are now being performed. The output of this work will define the system specifications for the TRIUMPH node [3]-[5].

2.4- Technical Approach

The TRIUMPH node performs ring interconnection according to the schematics in Figure 2. It uses Reconfigurable Optical Add-Drop Multiplexers (R-OADMs) in the metro-core and collector rings which are interconnected by an optical switch to selectively choose the channels to be routed to the appropriate fibre ring.

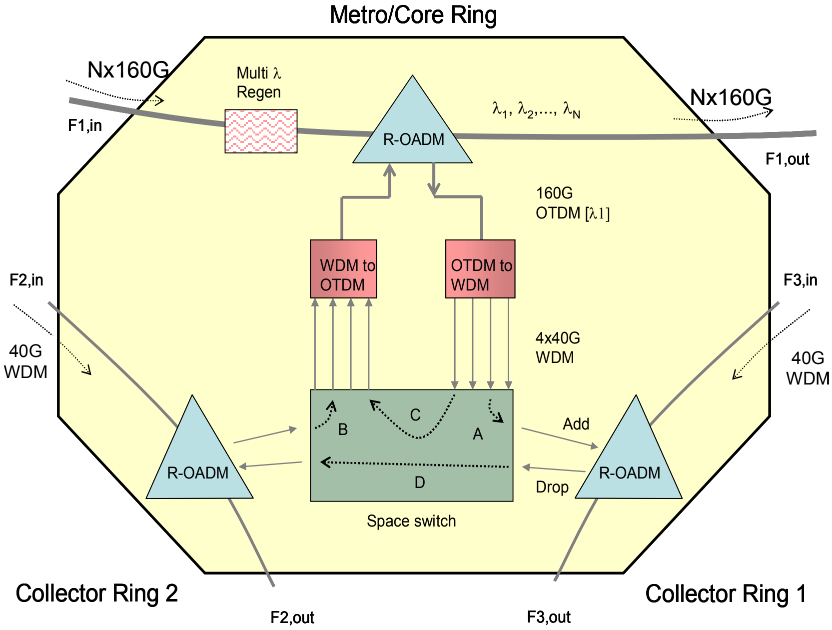

Figure 2– Optical switching node architecture

The node components are R-OADMs and a space switch which are now commercially available devices. The 2R multi-wavelength regenerator, the WDM to OTDM and the OTDM to WDM converters are based on disruptive technologies and are the main scientific breakthroughs of the TRIUMPH project.

2.4.1- Optical Switching Functionality

Fast, simple and dynamic provisioning of connections is a requirement for future MANs as it will give the ability to supply broadband services to end-users without latency delays due to electronic processing. This feature requires transparent nodes with the ability to dynamically allocate optical bandwidth on demand. In order to support dynamic service provisioning and bandwidth allocation, the TRIUMPH solution includes switching at the optical layer offering protocol and data type transparency required in this network segment.
Within the context of the project, the optical switching capability will be supported through existing R-OADM and OXC technologies [6]-[8]. The OXC will allow wavelength selectivity of individual channels that can be routed dynamically to the appropriate fibre ring when and as requested in order to establish the appropriate connections and support the end-user service requests. It should be noted that the add/drop ports of the metro-core ring R-OADM are connected to the optical switch based on Micro-Electro-Mechanical Switches (MEMS) after they have been passed through the OTDM to WDM and WDM to OTDM converters in order to perform the traffic groom/aggregation required.

2.4.2- Transparent Traffic Agregation/Grooming

As this type of networks support a very wide variety of client protocols, offering transparency will be a very important feature with a significant impact on the cost-efficiency of the system. Different traffic types at lower data rates need to be aggregated, either at the edge between metro-access and core-metro segments or core-metro and backbone network into high data rate channels and vice versa, it is important to offer transparent mechanisms for traffic aggregation and grooming, i.e. sub-wavelength switching granularity. This will assist in simplifying the network architecture and eliminate unnecessary opto-electronic conversions having a direct impact on the cost of the overall system. In the proposed solution, the capability of creating high data rate signals e.g. 160 Gbit/s, by multiplexing a number of individual lower data rate channels e.g. at 40Gbit/s from the collector ring, and vice versa, will be provided. This will be supported utilizing conversion between WDM and OTDM formatted signals through optical circuits.
More specifically, at this stage, it can be anticipated that the final network implementation is probably going to look like the sketch in figure 3.

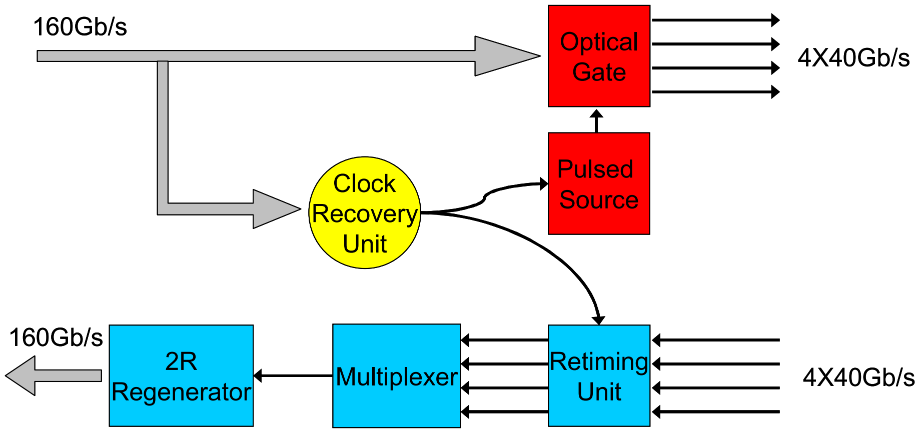

Figure 3 - Sketch of the expected implementation of the all optical traffic grooming and aggregation

The OTDM to WDM converter is likely to comprise a 160 Gbit/s clock recovery unit, generating a drive signal for a 40 GHz chirped pulse generation unit or a multiwavelength pulsed source. The 160 Gbit/s data signal and these chirped or multiwavelength pulses are input to a single broadband optical gate, either based on ultra fast SOA Technology [9], or a fibre based broadband optical switch [10] followed by an AWG to separate the individual channels.
For networks requiring a fully non-blocking WDM ring network, the WDM to OTDM converter is likely to comprise a local optical clock source suitable for multiplexing to 160 Gbit/s, and driven by the independent local node clock or the 160 Gbit/s clock recovery unit used in the opposite path. This signal is split and used as probe for four Asynchronous Digital Optical Regenerator (ADORE) units. Figure 4 shows the system architecture of a WDM-to-OTDM converter using four ADOREs. Four individual WDM channels, each carrying a 40 Gb/s RZ signal, in collector rings can be time division multiplexed to 160 Gb/s for the metro/core ring. At the input of each ADORE, a photodiode, which is wavelength insensitive, is used to OE convert the RZ signal from the collector ring. This provides an electrical gating signal to open the gates inside the ADORE. The four ADOREs can share the same high quality local clock pulse train to generate the 160 Gb/s OTDM signal at the desired output wavelength.

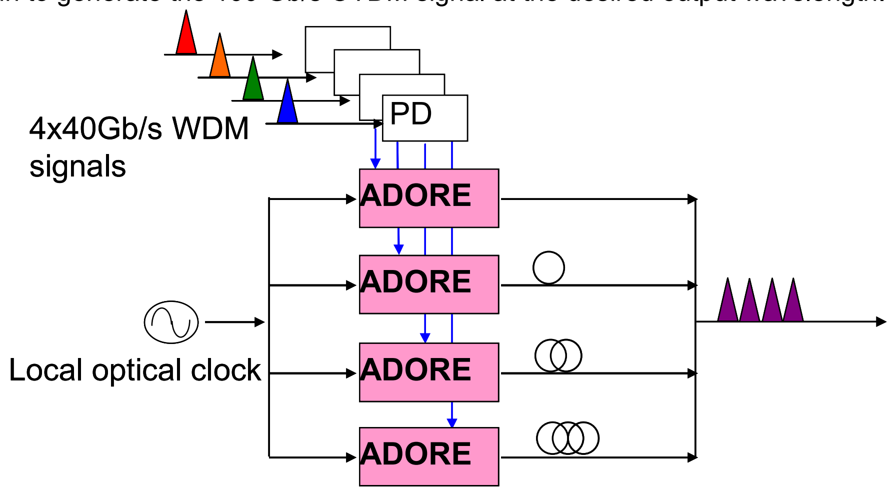

Figure 4 - WDM to OTDM conversion performed using four ADOREs

Here, the same approach used in the Asynchronous Digital Optical Network [11] (ADON) for optical burst or packet regeneration is proposed. Rather than performing traditional clock recovery for bit-level synchronization and phase alignment at each node for signal processing and routing, the ADON simultaneously regenerates an incoming packet and converts the bit-rate and phase of the packet to that of an individual local clock at each node. The ADORE [12] used in ADON, not only performs re-synchronization and regeneration, but also re-shapes the signal pulses, allowing simple WDM-to-OTDM conversions between collector rings and metro/core ring.

Figure 5 shows a functional diagram of a single ADORE device. The incoming data bits from a remote source are used to modulate a high quality continuous pulse train produced by a synchronous local source, thus regenerating the original data. Each "mark" in the incoming data triggers the gate to switch to transmission mode for a fixed time (the gating window), allowing a single pulse from the local source to pass through. In this way, the regenerated bits have substantially the same pulse shape, spectral quality, amplitude and timing stability as the local source.

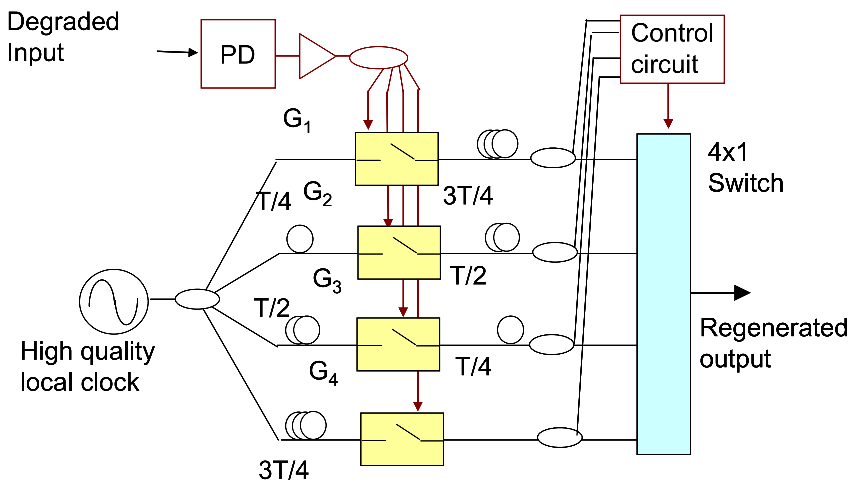

Figure 5 - Functional diagram of the ADORE. G: gate, T: nominal bit period, PD: Photo Diode

In figure 6 a simpler alternative of ADORE is proposed **[13]**. This new configuration, operating at 40 Gb/s, uses a single electro-absorption modulator (EAM) based loop. By making use of the clockwise and anti-clockwise paths, as well as the TE and TM polarizations, the 4 gating windows needed can be constructed using only one EAM. The ADORE based on one EAM loop can potentially be more tolerant to environment fluctuations, since the four channels share the same optical path. The ADORE architecture was even more simplified by using combined output gates (by adding up the optical power of two neighbouring channels); hence a simple 2x1 optical switch can be used instead of a 4x1 optical switch.

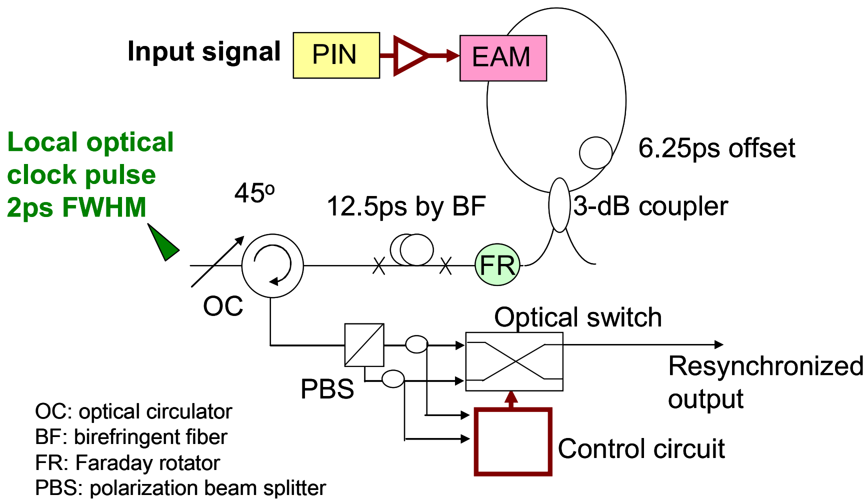

Figure 6 – Simplified ADORE based on a single EAM loop

2.4.3- Optical Multi-wavelength 2R Regenerator

Considering the future metro network and requirements for capacity, distances, reconfiguration capabilities and granularity, it is clear that they involve sophisticated design and engineering taking into consideration a number of parameters and trade-offs. Optical amplification is foreseen as a necessary technology used in this type of networks, as they may span to distances up to 250km, while the

presence of transparent nodes will introduce additional loss. The presence of optical amplification will impact the performance of the optical signals through noise accumulation. It should be noted that for distances ranging up to 250 km and data rates at 10Gbit/s and above, effects such as chromatic dispersion and PMD become significant. Also effects such as crosstalk and filter concatenation associated with the use of OXCs and OADMs will penalize the overall system performance and limit the transmission capabilities of the optical signals. In order to overcome these effects associated with the analogue nature of the optical networks and to ensure improved performance, optical 2R regeneration will be used.
The TRIUMPH project is designing and developing 2R optical regenerators that will offer multi-wavelength operation, i.e. regeneration of multiple wavelengths through a single device. In order to significantly improve the cost viability of the system, it is important to handle a number of channels using a single regeneration element, rather than having to de-multiplex the individual wavelength channels and apply regeneration discretely to each one of them. In addition, the proposed optical 2R regeneration technique should be able to support operation at high data rates (160Gbit/s). The current commercial status of regeneration technology is based mostly on opto-electronic regeneration techniques, whereby the optical signal is received, regenerated in the electronic domain and reconverted to optical. This is a costly solution particularly for systems supporting a large number of channels at high data-rates. An improvement to this approach was the integration of a number of these O/E/O regenerators using large scale integrated photonic circuits [14]. Regarding all-optical regeneration, most of the techniques that have been reported in the literature [15], [16] or are available as product offerings [17] support single wavelength regeneration and are not suitable for very high data rates beyond 40Gbit/s.
For the 2R Multi-wavelength regenerator the consortium of the project is following two alternative approaches. Both techniques appear to be relatively simple in terms of implementation and operation and can offer significant performance improvement supporting at the same time Multi-wavelength operation at high data rates. Next, a brief explanation of these techniques is given.

2.4.3.1 Optical Regenerator based on Active Technology
The active technology proposed to be used in this project is exploiting the fast relaxation dynamics observed in quantum-dot (QD) semiconductor optical amplifiers (SOAs) (Figure 7).

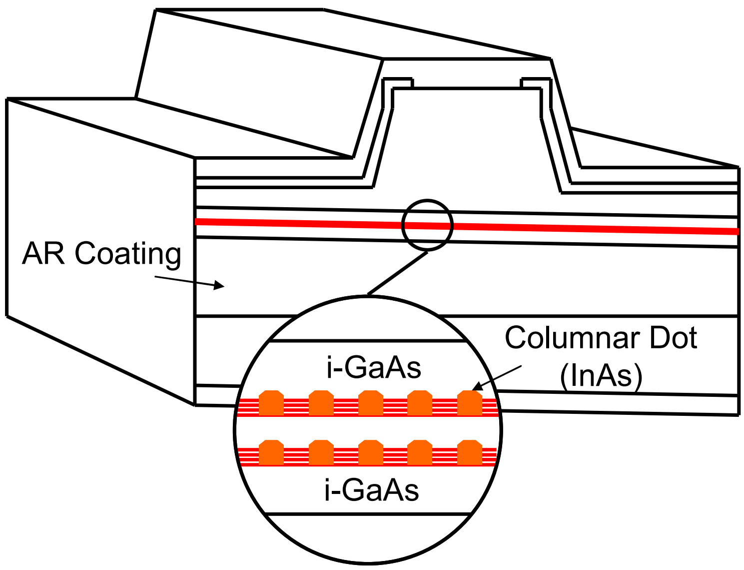

Figure 7 - Schematic of a QD SOA

QD SOAs are proposed to be used because they offer advantages over conventional bulk or even quantum-well based SOAs. Typically, conventional SOAs are characterized by:
- Carrier relaxation times in the order of 50 ps to 1 ns.
- Significant pattern effects due to the slow relaxation times.
- Significant cross-phase and cross gain modulation all across the optical spectrum due to one large single active region.

On the other hand QD SOAs offer:
- Fast relaxation times, primarily limited by spectral hole burning (SHB) with relaxation times in the order 100 fs to 1 ps. As a consequence one finds negligible patterning.

- An ultra-broad optical spectrum of up to 100 nm, which is a consequence of the non-uniform quantum-dot size distribution.
- Spectrally localized effects. Spatial isolation of dots prevents transfer of carriers among different spectral regions, provided these are outside the inhomogenous broadening region. This has a positive impact on the suppression of crosstalk between WDM channels under gain saturation conditions.
- Conversely one expects a strong interaction of channels that have a similar energy level, i.e. that are affected by isolated QDs of the same size. Effective cross-gain modulation (XGM) saturation is therefore expected and can be utilized for switching when channels are within the homogeneous broadening bandwidth.

Optical regeneration in QD SOAs is based on the use of inhomogeneously-broadened gain of self-assembled quantum dots. In these non-linear devices spectrally localized transmission modulation of spectral hole-burning can be applied for multi-wavelength operation [18]. Techniques based on the gain saturation, Four Wave Mixing or cross-gain modulation (XGM) can be used to explore the QD SOAs for multi-wavelength regenerative applications. For example, figure 8 a) proposes a specific configuration to explore the XGM effect of the QD-SOA in order to achieve multi-wavelength regeneration [19].

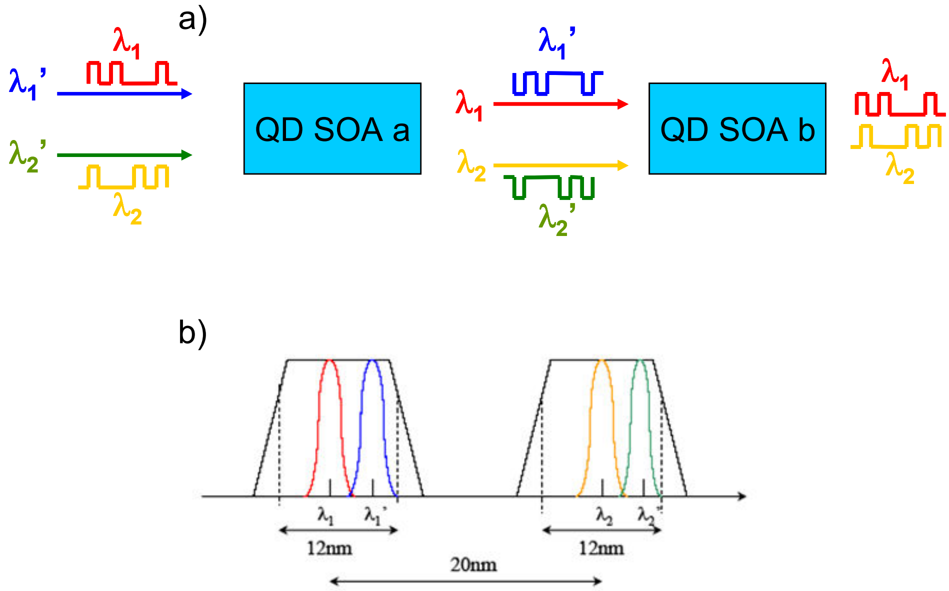

Figure 8 - a) Proposed configuration to explore the XGM effect in QD-SOAs to perform multi-wavelength regeneration. b) Two channels within the inhogeneously broadened gain spectrum of the QD-SOA.

This technique, in addition to the input data signals (λ_1 and λ_2 in this case) requires also CW signals (λ_1' and λ_2'). The input signals are fed into the QD SOA together with the CW signals. The incoming signals (at wavelengths λ_1 and λ_2) modulate the carrier density, which results in modulation of the refractive index, the phase and the gain of the SOA. The gain modulation is experienced by the probe signals (λ_1' and λ_2'), which are simultaneously transmitted through the device. Therefore, the data of the input signals is copied to the probe signals. The converted data is inverted compared to the original data due to the saturation characteristics of the SOA gain with the optical input power. At the output of the QD SOA an optical filter is used to remove the original signals. The first stage of the regenerator is completed at this point. To re-invert the regenerated signals so that they have the same polarity as the inputs and to assign them the original wavelengths, a second regenerator stage is included using a second QD-SOA. Various realizations of this architecture and other similar schemes can be thought of and will be investigated.
Multi-wavelength operation is achieved as QDs within the SOA device support certain narrow bands of the spectrum of the device. The bandwidth supported by each QD group is around of 12nm. In order to provide regeneration of individual channels using the technique mentioned above there is a requirement for a CW signal that falls within the QD bandwidth per channel to be regenerated. Figure 8 b) illustrates the spectral response of the regenerator assuming that there are two wavelength channels at $\square_1$ and $\square_2$ that are regenerated.

Considering the configuration of Figure 8 a) these wavelength channels will be regenerated through conversion to wavelengths λ_1' and λ_2' and then back to λ_1 and λ_2. Both λ_1 and λ_1' lie within the homogeneous broadening bandwidth of a single QD group while λ_2 and λ_2' also lie within the bandwidth of a different QD group present in the same SOA device.

The development of appropriate QD-SOA technology is under detailed investigation [20], [21]. Studies to test the suitability of this technology for applications using high data rate signals [22]-[24] and optical multi-wavelength regeneration are being pursued [19], [25].

2.4.3.2 Optical Regenerator based on Passive Technology

2R optical regeneration can be provided through the use of optical non-linear fibre. A technique first introduced by Mamyshev [26] has been attracting many attentions due to its simple implementation (Figure 9). Owing to recent studies [27], [28], the design of this kind of regenerators is now well understood. The principle of operation is based on the effect of self-phase modulation (SPM) that arises when optical pulses are transmitted through a Non-linear medium (e.g. optical fibre) causing broadening of the spectral bandwidth of the pulses. An optical band pass filter follows the non-linear medium at a frequency shifted with respect to the input signal carrier frequency. As this scheme produces a steep transfer function (close to binary) it offers reshaping of the optical pulses through suppression of the noise in the zeros and amplitude fluctuations in the ones. An interesting feature of this technique is that it can support very high data rates as it does not suffer of any carrier-transport limitation. The performance even increases for higher data rates as the higher the modulation rate the wider the spectral width of the optical signal, making it particularly suitable of high data-rate applications (>160Gbit/s).

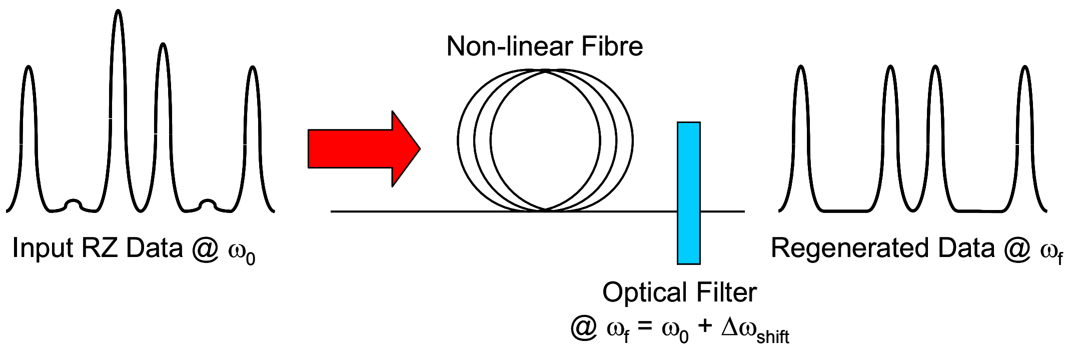

Figure 9 - Configuration of a fibre based optical regenerator [3.13]

This technique can be applied to both single and multi-wavelength input signals. However, in the case of multi-wavelength operation it is important to highlight the performance constraint arising by the presence of cross-phase modulation (XPM). This is due to the interaction of the different wavelength channels as they are transmitted through the non-linear medium. This problem promoted the appearance of new versions of this technique where the XPM effect can be suppressed, to a certain extent, with the use of an appropriately designed dispersion map that suppresses non-linear inter-channel interactions (four wave mixing and cross-phase modulation) by ensuring sufficient walk-off between pulses and minimizing their interaction [29], [30]. A detailed investigation of these and other variations of this technique and the performance improvement it offers is under way.
In order to provide optimized fibre based regenerators to be used in the system an activity involving the development of special fibres will be carried out, with the aim to produce optical fibre with a set of specifications that will enhance the performance of these devices.

2.4.4- Final Demonstrator

At the end of the project a validation of the functionality and performance of the developed sub-systems in a network environment based on a laboratory testbed, consisting of optical nodes and emulated transmission impairments will be provided.
In figure 2 the functional block diagram of the optical switching node was already presented. For the lab validation, a possible traffic pattern may consist of two channels at 160Gbit/s in the metro/core ring, four 40Gbit/s WDM channels in collector ring 1 and one 40Gbit/s channel in collector ring 2. The incoming

traffic from the metro/core ring ($F1_{,in}$) at $\lambda_1$and λ_2, first undergoes 2R regeneration and then enters the R-OADM which is configured to pass through the channel at $\lambda_1$and drop the channel at λ_2. The dropped channel passes through an OTDM-to-WDM converter, which converts it into four channels at 40Gbit/s. These four channels subsequently enter the space switch fabric. The other input ports of the space switch connect to the drop ports of the R-OADMs of the two collector rings; whereas, the output ports of the space switch connect to the add ports of the R-OADMs and the input ports of the WDM-to-OTDM converter.
As a result, the space switch can realise the following possible types of connections:

- An individual WDM channel from the OTDM-to-WDM output connects to an add port of the R-OADM of either collector ring 1 or 2 (example path A in Figure 2).
- An individual WDM channel from the OTDM-to-WDM output connects to an input port of the WDM-to- OTDM (loop-back). This type of connection is necessary in the case that only *part* of the original 160Gbit/s OTDM channel needs to be dropped to a collector ring, as the rest of it will have to be looped back (example path C).
- A collector ring channel connects, via a drop port of an R-OADM, to the WDM-to-OTDM sub-system (example path B).
- A collector ring channel connects directly to the other collector ring via the two R-OADMs (example path D).

The lab validation activities will include:

- 2R Regeneration of a multiple of channels in the metro/core ring.
- WDM-to-OTDM conversion of four collector ring channels (40Gbit/s -> 160Gbit/s) and switching to the metro ring.
- OTDM-to-WDM conversion of metro ring channels (160Gbit/s -> 40Gbit/s) and switching to the collector rings.
- Partial add/drop of one 160Gbit/s channel: Drop of one 40Gbit/s channel from a 160Gbit/s OTDM metro/core channel to a collector ring. Loop-back of the rest of the three 40Gbit/s channels and aggregation with one 40Gbit/s channel from the collector ring, to form, again, a 160Gbit/s OTDM channel to be added to the metro/core ring.
- OTDM traffic aggregation of collector ring 1 channels at 40Gbit/s with collector ring 2 channels at 40Gbit/s and switching of the resultant 160Gbit/s channel to the metro ring.

In figure 10 a first draft of the actual lab setup is presented. Here it can be seen that the metro/core and collector rings will be replaced by transmitters and receivers which will feed and detect light to and from the node, respectively.
In the metro/core ring, since that for validation only two channels at 160Gbit/s will be used, the R-OADM can be replaced by two splitters and two band-pass filters without affecting the final results. Also without putting at stake the validation of the experiments, in the WDM-to-OTDM setup, only one channel will pass trough the ADORE subsystem as the other three 40Gbit/s channels will be aligned by hand using adjustable optical delay lines.
It is expected that the actual line rates that will be used are 170.8Gbit/s in the metro/core ring and 42.7Gbit/s in the collectors. This choice has to do with the foreseeable utilisation of Forward Error Correction (FEC) in future applications of the developed network.

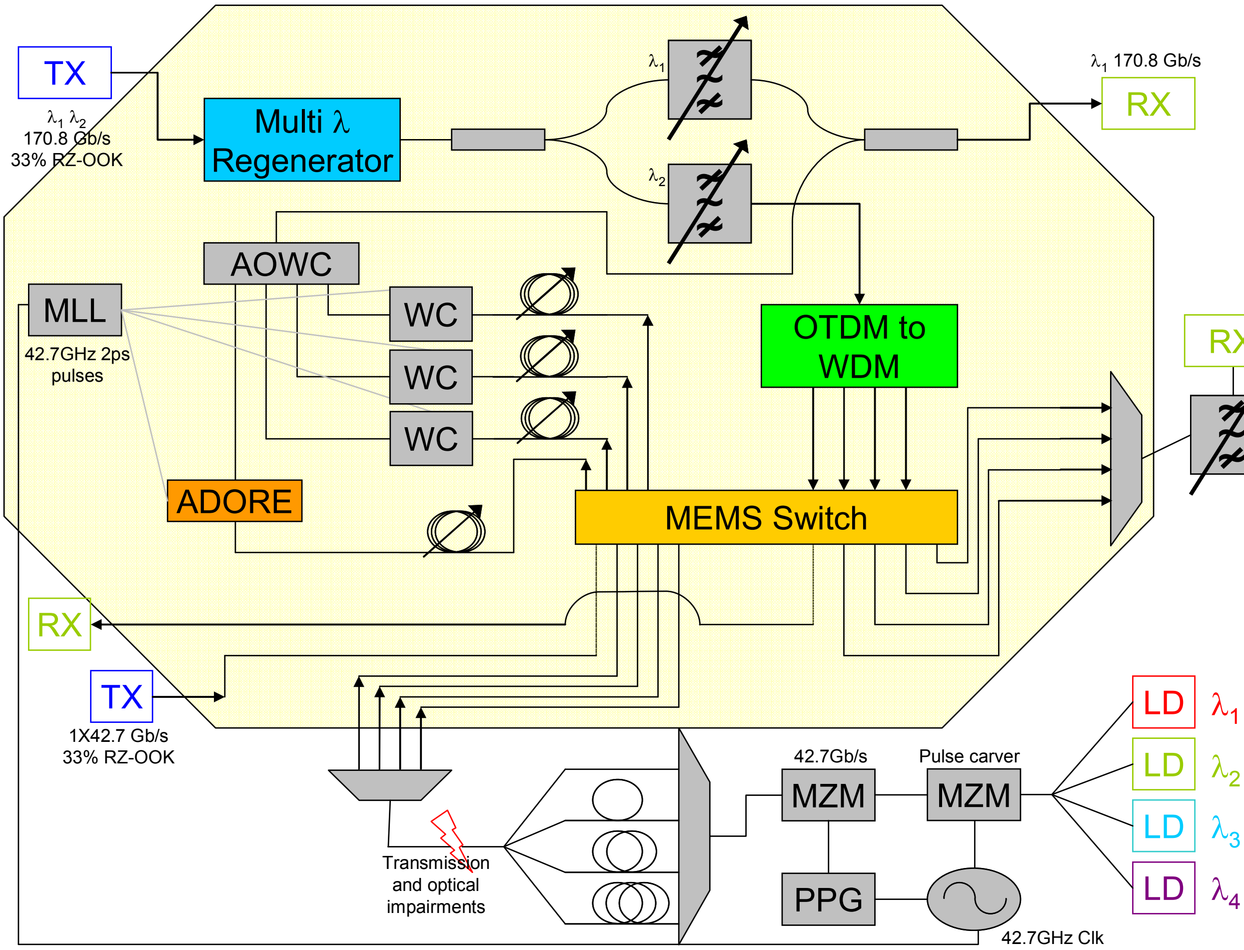

Figure 10 – Draft of the configuration to be used in the lab validation of the developed sub-systems.

2.4.5- Organization

The consortium of the TRIUMPH consists of a very strong group of partners with significant and complementary expertise in the relevant areas. More specifically, the consortium comprises 8 partners, providing a balanced combination between academia (University of Karlsruhe, (DE), University College Cork, (IR), Optoelectronics Research Centre, University of Southampton, (UK), Technical University of Berlin, (DE), University of Essex, (UK)) research centre (Athens Information Technology, (GR)) and industry (Siemens Networks S.A., (PR), Kailight Photonics, (IS)). Industrial partners include a major system house, Siemens Networks and an SME, Kailight.

The work described above is planned to be performed within the framework of 6 different workpackages that are closely linked. One additional workpackage was dedicated to project management.

- WP2: One of the main objectives of this workpackage is to define the network architecture that the project will focus on. It will also provide the network and system level requirements and specifications. Comparative studies among various technology options together with value analysis studies and benchmarking will be also performed.
- WP3: The main activity of this workpackage is the development of a fully functional optical switching node that includes the design, the implementation and the performance evaluation of the optical switching node at data rates between 10 Gbit/s and 160 Gbit/s.
- WP4: This workpackage focuses on the design, fabrication and characterization of devices suitable for 2R multi-wavelength regeneration. The technologies that will be used are active involving quantum-dot semiconductor optical amplifiers and passive involving highly nonlinear fibres.

- WP5: This workpackage will focus on the development of linear and nonlinear optical modules suitable to perform transparent grooming and aggregation involving also bit-rate adaptation. These modules will offer mapping of WDM channels to OTDM signals and vice versa.
- WP6: This workpackage will concentrate on the demonstration of the developed sub-systems in a network environment based on a lab testbed, consisting of optical nodes and emulated transmission impairments as well as in a demo together with a commercially available system.
- WP7: This work package will focus on drawing a manufacturability plan for the commercialization of the TRIUMPH platform. It will generate intellectual property and disseminate the project results.

2.5- Conclusions

Metropolitan Area Networks will need a strong upgrade in order to cope with future traffic demands. MANs are being pressured by technological advances both in the access networks and in the regional/long-haul networks. In fact, the improvement of access technologies is now at a level that the delivery of high-bandwidth to the end user is enough to satisfy the demand growth brought by new applications. At the same time, in the regional/long-haul network, several technologies are mature enough to guarantee high connectivity and supply the high bandwidth requirements of lower network levels. This leaves today's MANs, mostly based on SDH/SONET, as the bottleneck of the network chain and, therefore, in need for a huge change.

The innovations introduced by the TRIUMPH project aim at establishing a breakthrough in the implementation and deployment of advanced optical communications across an interdisciplinary array of both industrial and research stakeholders. It is expected to bring a significant impact in a number of areas including: network architectures, system implementation and technologies suitable for future broadband networks: access, metro-access and core-metro. More specifically it will:

- Provide improvement of the signal quality and the overall network performance through optical multi-wavelength 2R regeneration, thus enabling the transparency requirements.
- Provide all optical grooming/aggregation, i.e. conversion of lower rate WDM signals into higher rate single channel OTDM streams and vice versa, further enhancing the transparent functionality of the proposed system, offering an additional feature required in metro and access network environments.
- Offer reduced-power consumption and compact size

Through these advanced functionalities and features the TRIUMPH will support:

- improved network infrastructures with very high capacity and increased scalability
- transparency to data-rates, format and protocols
- interoperability of existing network infrastructures and smooth migration to future network solutions
- end-to-end intelligent optical networking
- flexibility in bandwidth provisioning

reduced capital and operational expenditure

3- Manufacturability Plan

3.1- Introduction

The TRIUMPH project's sub-systems under development include 2R all-optical multi-wavelength regenerators and devices for all-optical traffic aggregation (WDM-to-OTDM converter and OTDM-to-WDM converter). Thinking of a manufacturability plan for these components, which are still under scientific investigation and development, is a challenging task which can only be done in rough at this moment. A manufacturability plan for the TRIUMPH router should be split it into three distinguishable steps:

- Step 1 – The TRIUMPH project
- Step 2 – From prototypes to commercial devices
- Step 3 – System integration

In the first step, the TRIUMPH project itself, is where the basic ideas are developed and the fundamental research is performed. This step is expected to end with the validation of prototypes in a network environment. In this phase the responsibility is shared between the partners that build up the consortium of the project.

The second step will probably be made by either an SME or a Spin-off company coming out of the project. Their function is to take the prototypes developed in the previous step and turn them into commercial devices taking into account all the requirements imposed in a real network system. This is a very demanding task and involves many risks.

The third step has to be made by a systems vendor company. The work here is to integrate the new devices in a complete network system. This will either generate a completely new network system product or an upgraded version of an existing one.

Although these three steps can be identified, they are not independent from each other.

The prototypes developed during the TRIUMPH project must have a clear potential to be translated into commercial devices. The two industrial partners of the project will have an important role presenting their expertise to the rest of the partners and giving their industrial perspective.

In step 2, although the responsibility lies on the company that develops the commercial devices, this company will have to work based in a close interaction with a system vendor company which will impose its requirements for the new devices.

Finally, in step 3, the new system product or upgrade will certainly be influenced by the actual needs of the service providers or any other company that might be a potential buyer of the system.

In the next sections a more detailed perspective of each one of the steps presented above will be given. In step 1 the objectives, deliverables and milestones of the TRIUMPH project are already defined so a rigorous plan can be presented in this case. For steps 2 and 3 a more general perspective will be given, a detailed manufacturability plan is one of the tasks that will be performed in the last months of the TRIUMPH project.

3.2- Step 1 – The TRIUMPH project

This project proposes the development of network architectures and system solutions suitable for future broadband access networks. The main objective is to provide Transparent Ring Interconnection Using Multi-wavelength PHotonic switches to significantly increase the network functionality and capacity. The scenario proposed refers to a large bandwidth network supporting transparent connectivity between core/regional-metro rings, metro-access rings and access networks. The required functionality in such architecture will be provided through an optical switching node located at the interconnection points between rings. The design and development of this node will be the main focus of the project with the aim to provide a cost effective solution that can transparently offer inter-domain connectivity. It also aims to support a variety of data rates, protocols and formats that are present in the metro and access network environments and are associated with the requirements of new and emerging services and applications that are rapidly becoming available to the end-users. This will be performed using novel technologies offering reduced cost, future-proof solutions able to replace existing complicated and expensive equipment. The proposed solution will support a variety of data rates ranging between 10Gbit/s and 160Gbit/s and apart from transparent optical switching will support functionalities currently unavailable in the optical layer such as transparent grooming/aggregation through the use of WDM to OTDM conversion and vice versa as well as optical regeneration. The optical 2R regenerator will provide multi-wavelength operation i.e. a single regenerator device will support 2R regeneration of a number of individual wavelength channels following the concept of optical amplifiers used to simultaneously amplify a number of WDM signals. These functionalities will be achieved through technological breakthroughs based on novel passive and active technologies. These technologies will be developed and deployed in the system context by the project consortium that has a unique combination and complementarity of the required technical expertise and know-how. The proposed solution is expected to support the requirement of future networks offering broadband access for all. It is important to note that such an approach will be able to interoperate with existing infrastructures and provide a smooth migration path from existing to future infrastructures supporting a variety of new services and applications. The functionality and performance of the optical switching node will be demonstrated through a network trial in which it will be used to interconnect two collectors and one core-metro ring.

The work described above is planned to be performed within the framework of 7 different workpackages that will be closely linked as shown in Figure 11.

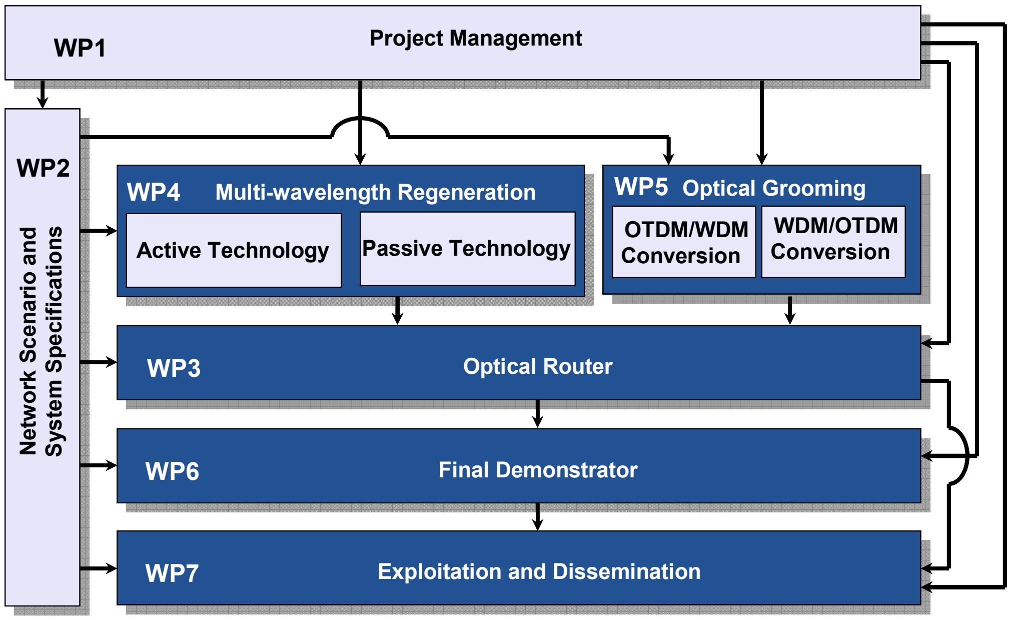

Figure 11 - WP structure and activities

More specifically the project management will be carried out within the framework of WP1, while WP2 will focus on defining the Network Architecture and System Requirements the optical switching node should satisfy. WP3 will work on the design and the implementation of the optical switching node integrating the 2R regenerator, the OADM/λ-switch as well as the WDM/OTDM and the OTDM/WDM converter and optional asynchronous retiming units. This work includes the system implementation as well as system characterization and optimization. WP4 will focus on the design and implementation of the optical 2R-regenerator based on active technology. This includes the development of suitable technology based on QD SOAs able to achieve multi-wavelength operation. In addition to the development work on QD SOAs an alternative approach based on commercially available bulk SOAs suitable for single wavelength operation will be pursued to provide a reference point for bench marking purposes as well as offer a contingency plan. This work will include both design through modelling, simulations and experiments as well as development. WP4 will apart from active multi-wavelength optical regenerators also focuses on the optical 2R regenerator based on an alternative approach i.e. passive technology. This is also development work aiming to produce the appropriate technology to support multi-wavelength operation of these sub-systems. The technology to be developed includes dispersion flattened fibre, dispersion managed fibre, super-structured gratings and the work involves design through modelling, simulations and experiments that will be used to drive the development activity. WP6 focuses on the WDM/OTDM and OTDM/WDM converter, retiming units as well as grating based OADM/λ-switch. This work involves also design and development of the suitable technologies including highly nonlinear fibre and gratings that will be based on modelling, simulations and experiments. WP6 will provide the lab validation of the optical switching node in a realistic network scenario and the final project demonstrator. WP7 will concentrate on the exploitation of the project outcome and results and dissemination activities.

The duration of the project is 36 months (M1- M36). In Figure 12 the time scale of the work plan of the TRIUMPH project is presented. Here it is possible to understand the evolution of the work in each WP that will culminate in the lab test validation performed in WP6.

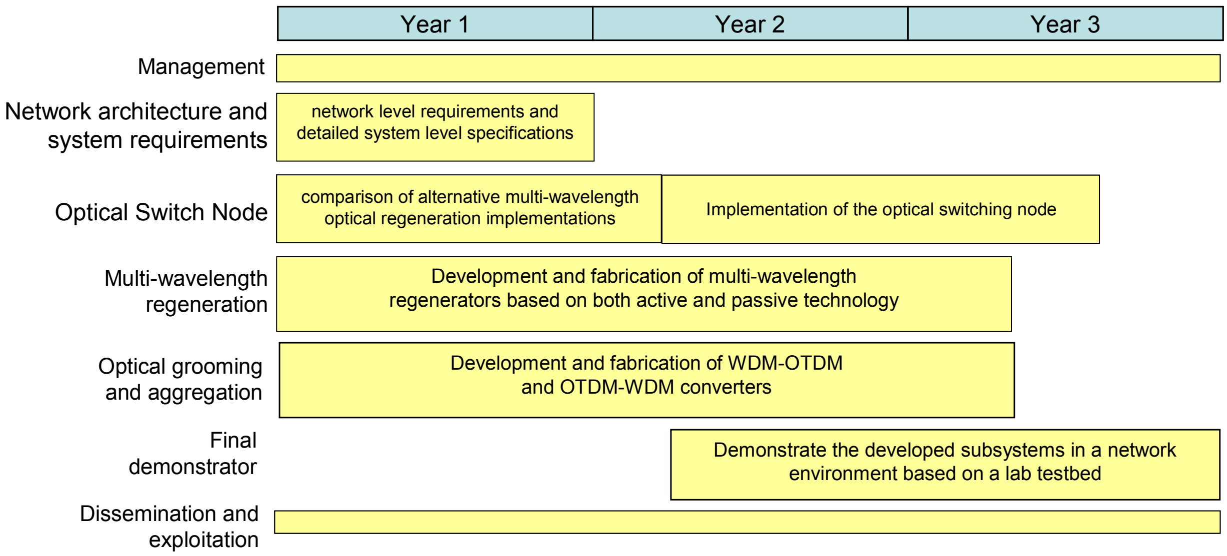

Figure 12 – Work planning of the TRIUMPH project, showing the timing of different WPs

It is expected that in the end of the TRIUMPH project fully functional and validated prototypes of the 2R Multi-wavelength regenerator, the OTDM to WDM and the WDM to OTDM converters will be available. At this stage, if the market conditions are favourable, the conditions to pass to Step 2 will be gathered.

3.3- Step 2 – From prototypes to commercial devices

3.3.1- General

This section will describe the process planned for taking components relevant to the TRIUMPH router from a prototype level to a commercial grade level and to production stage in high volume.
The process is based on a practical and common approach that is used by SMEs to bring new products to the market, in an efficient and time consuming manner.
All the information below will relate to 3 main components that are included in the TRIUMPH router design:

- Multi wavelength 2R regenerator
- WDM to OTDM converter
- OTDM to WDM converter.

3.3.2- Process Steps

The following chart summarizes the flow of the planned development process:

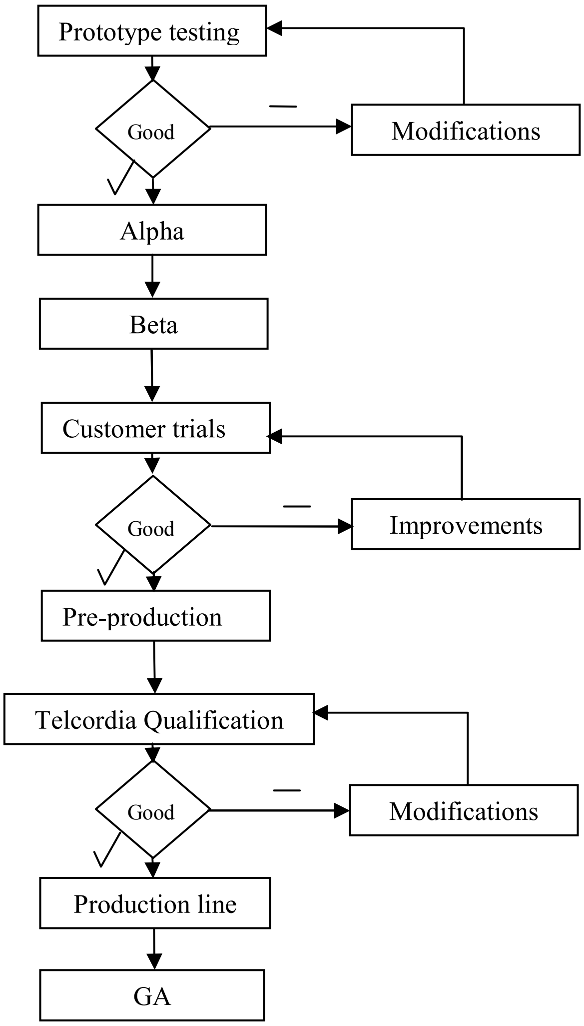

Figure 13 - Chart summarizing the flow of the planned development process

Prototype testing – In this phase it is planned to perform characterization of the devices that were developed including back to back testing, electrical and optical characteristics measurements, Loop test measurements for cascading of components and DWDM performance of multiple wavelengths running in parallel in the device (including SPM, XPM, non-linearities in high power transmission). The results of this phase will set the basis for the product development that is described in the following sections.

Alpha design, build and testing – this phase includes usually redesign of the prototype, where unlike in the prototype level, a use is being made of commercial grade sub-components and not one of a kind components. Special fibres and or materials will be replaced by fibres or materials from known vendors using reproducible techniques and procedures, preferably by more than one supplier. Testing in this phase will be similar to prototype testing level and will lead to enable customer validation done in a latter stage. In general Preliminary Design Review and Critical Design Review will be performed during this phase in order to allow control over the development process and in order to allow for the R&D team to allocate and pinpoint crucial failure points in the design of the product. A market requirements document will be compiled, that will set the required parameters for the device based on customers needs and market expectations.

Beta design build and testing – this phase includes generally small redesign phase of the Alpha product regarding to the expected performance. However, a major effort is done in this phase to define the packaging and sealing structure of the suggested device, and also to define the environmental conditions that the device will withstand. Preliminary environmental testing is done in this phase, mainly temperature cycles (0^0C to 70^0C cycles, with low relative humidity) to make sure the device has good chance to pass the Telcordia testing in a later stage. An effort is being done in this phase to reduce the size of the device and lower the power consumption as well as the cost of the main sub-components.

Customer preliminary trials – Multiple Beta samples (usually 5 or more) are produced in this phase and are being supplied to selected customers for market validation. Important features and parameters are being measured and validated by the customers and applications are being reviewed in order to make sure the device answer a specific need in the market. Usually the R&D team will accompany closely this phase and will dedicate resources of engineering staff to support the trials and modifications to follow.

Modifications and improvements – a step to follow the Beta phase testing, that is targeted at incorporating corrections, improvements and problem solving in the product, mainly discovered by the customers trials.

Pre-production and line assembly –This step is designed to fulfil several main tasks:

1. Perform major cost reduction step for the device and its manufacturing and testing process.
2. Select components and vendors for highest reliability, shortest lead time and most cost efficient solution.
3. Identify second source for every major sub-component.
4. Negotiate supply chain agreements and frame orders.
5. Define production method, calibration, testing and qualification methods

It is also here where assemble is done for a preliminary, low volume production line, using mainly manual process and man based control. The line usually is set for production of several 10s of units per month with close proximity to the R&D and engineering team that support the transfer of the product to manufacturing.

Telcordia qualification – The key Telcordia standard for optical-communication applications is GR-468-CORE, which sets out the reliability requirements for most of the optoelectronic devices used in telecom equipment. The document covers, for example, the lasers, LEDs, photodiodes and optical modulators used to create equipment such as digital cross-connects, optical amplifiers, and terminal and add-drop multiplexers. The basic aim of GR-468 is to ensure sound reliability practices throughout a product's life cycle. The qualification program - a table of test procedures - forms the heart of the Telcordia standard. But the document also describes the whole range of high-level reliability practices, including: lot-to-lot control; corrective actions for failures; environmental, health and safety considerations; and documentation processes. GR-468 is updated now also to reflect advances in optical technology and to incorporate new product developments such as tuneable lasers. The scope of the standard was extended to include higher-level devices like optical transmitters, receivers and transponders below the circuit-package level. The new version doesn't change the number of tests listed, the test conditions or other basic requirements for qualification, but in some cases alters the test durations. The cost and time needed to perform a complete qualification program are now often marginally reduced. Crucially, components qualified to the previous version are considered compliant with the new issue, although some systems vendors refer back to the old GR-468 to meet its more stringent conditions.
The majority of the GR-468 document comprises a detailed description of the test procedures that optical-component makers must employ to assess device reliability. The program requires vendors to characterize the basic performance parameters of their devices, as well as examine environmental effects and accelerated aging. The program can be split into three stages:

Stage one enables full characterization of product performance under nominal operating conditions. Manufacturers need to examine a representative selection of devices to investigate optical and electrical parameters (optical power, spectral characteristics and laser-drive voltage, for example), perform operational shock and vibration analysis, and examine physical parameters such as electrostatic discharge and hermetical sealing. The exact parameter set employed depends largely on the product's application, which may vary between customers.

The second stage lets vendors demonstrate that their products survive under normal mechanical and environmental stresses, such as those experienced during transportation, storage, installation or over an operating lifetime of around 20 years. Mechanical tests included at this stage include shock, vibration and thermal shock, plus fiber and connector integrity tests. Environmental tests include powered and non-powered storage at high temperatures and humidity, plus temperature cycling. The standard calls for test durations of up to 2000 hours, or even 5000 hours for some specific cases.

The final stage of the program comprises the accelerated-aging tests, which focus on the physics of failure mechanisms. Such tests are conducted at different stress levels until failures occur. The proposed program is a continuation of the above environmental-stress tests, but extended to up to 10,000 hours and applied to a smaller number of samples.

To summarize: In this phase a full Telcordia qualification test according to GR 468-CORE will be performed to the optical modules under development. Number of units to be built is usually in the range 10 to 50 units (depends on the level of integration of the product). At the end of the process (3 months expected for most modules) correction actions will be taken to improve the device and make sure it withstands the requirements.

Production unit development and Production line assembly – At this stage all modifications are inserted into the final, general availability product, and it is expected that this product could be manufactured in volume. The current development phase will focus on increasing and improving the yield of production of the device, by improving production procedures and/or replacing production schemes and parts. This phase will also be dedicated to build the production line, with sufficient qualification control means and tools. Usually, the production assembly line will include automatic handling of sub-components and some semi-automatic processes that can reduce the time needed for manufacturing. Supply chain management tools will be adopted to make sure the line can operate flawless over time and in volume.

Once a fully developed and certified device is available, conditions for system integration are assembled.

3.4- Step 3 – System Integration

Once the devices like the 2R Multi-wavelength regenerator and the WDM to OTDM and OTDM to WDM converters are commercially available, the market analysis should be updated and a deep study on the system to be developed is elaborated. If all conditions are met, a new product can start being produced or if it fits in the already existing portfolio of the company, a new release of an existing line of products can be developed.

To develop a network system based on the TRIUMPH router, a network unit based on each functional block represented in Figure 2, the R-OADMs, the space switch, the 2R regenerators and the WDM to OTDM and OTDM to WDM converters, has to be developed. Different manufacturers have to be identified for each component and then a decision for each one of them as to be made. Figure 14 shows a picture with an example of different interconnected network units.

Figure 14 – Example of Several Installed Network Units

The process to develop the whole system formed by the different network units is summarized in Figure 15.

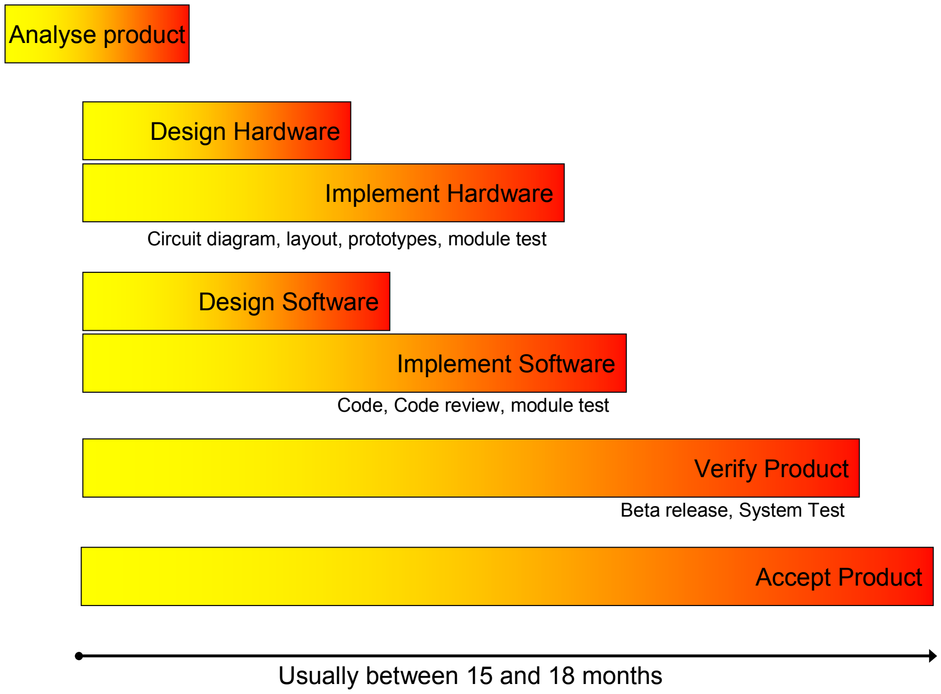

Figure 15 – Typical evolution of the development of a new product.

After a first study of the product, the system engineering group will define the specifications that the product will have to meet. Issues like the number of WDM channels, the type and number of network units needed for the system to work, the preferred technology in each one of them, etc… will be defined in this phase. This information is then passed to both the hardware and software team. Each team will then start creating the specifications for the product in their own areas in close collaboration with both the system engineering group and the component suppliers. The implementation of the hardware includes issues like the development of the circuit diagram, the product layout, the development of several prototype releases and final module test validation. In the software case the code to control the system is developed, revised and tested in the modules developed by the hardware team.

After the releases of the hardware and software teams, the system is tested in every possible configuration, as a whole and in each network unit individually. If all tests have a positive result, a beta release of the product can be delivered. This beta release is subjected to a new round of validation tests.

When the system test team finishes their work, the product can be delivered to the costumer. Then the costumer makes its own tests and validation of the product and will make the decision of whether accept it or turn it over for further developments.

3.5- Conclusions

A general manufacturability plan for the TRIUMPH router was drawn. The plan was divided in three steps: Step 1 - The TRIUMPH project; Step 2 - From prototypes to commercial devices; Step 3 – System integration.

For the first step a detailed picture was presented showing how the work within the TRIUMPH project is planned. In the end of the project prototypes of the 2R regenerator, the WDM to OTDM and the OTDM to WDM converters will be available and tested.

After the project, assuming that the market conditions are favourable, a general plan should be drawn of how to transform prototypes into commercial devices and then taking them to the production stage in high volume. This is the general procedure that an SME usually has to go through when developing a new product.

Finally a general idea of how to develop a complete network system based on the new devices is presented. The details of this implementation are far beyond the scope of this short deliverable and will be the subject of future studies.

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