DISCUS white paper:

Wavelength usage options in access networks

Dissemination level:

PU = Public

EXECUTIVE SUMMARY

DISCUS [1], [2], "The DIStributed Core for unlimited bandwidth supply for all Users and Services", is an EU-funded FP7 project whose goal is to exploit demonstrated technology and concepts needed to define and develop a new radical architectural concept that can enable an integrated wireless and FTTP future network which addresses the economic, energy consumption, capacity scaling, evolutionary, regulatory and service demand challenges arising from an FTTP enabled future.

In an earlier deliverable (D2.1) [3], which describes the proposed DISCUS architecture for future ubiquitous broadband provision it was stated that a major objective of the DISCUS project is to enable a future network that would tackle the three major problems facing today's network as it tries to respond to the huge growth required in network capacity that could arise over the next decade. These problems are:

- **the cost of network provision and financial viability of the telecoms sector**,
- **the huge growth in power used by the worlds telecommunications networks**
- **the need to avoid a "digital divide" being created between those customers in dense urban areas and those in the sparser rural communities, without the need for massive government subsidies**.

Solving such issues requires a radical change in the network architecture both from a technological perspective and from a regulatory and business model environment point of view. This has major implications for the regulatory policy, for the distribution and assignment of network resources at all layers and all users of the network, including the service providers, and for the nature of the ownership and business model structures that need to be supported.

The history of regulation in the wake of opening the incumbent dominated telecommunications network sector to competition was to focus on physical layer competition, particularly in the access network where the policy of Local Loop Unbundling (LLU) has been widely implemented. This was a very successful policy during that early era and because most of the network infrastructure, particularly the copper pair access network, was built from public funds, it was perfectly reasonable that other operators and service providers should get equal access to that existing infrastructure resource and avoid the need to build a parallel network at huge capital cost.

Despite the success of LLU in creating competition in the telecoms sector, from a customer or end user perspective the main benefit has been lower prices as the incumbents responded to the leaner competitors and became slimmer, leaner and much more commercial in their own operations and structure. However the ability to change provider, avoid contractual lock-in and select different services from multiple different providers at the same time has not occurred in the competitive market that has been created.

From a user perspective the ultimate solution should provide the ability to select, on the fly, any service provider for any service and have multiple service providers at the same time so that the users have the choice of avoiding contractual lock-in and can select the best offerings for their needs. They should have the option of only paying for what they use on a "pay as you go" basis" if this is desired. This would also enable a single network termination to provide multiple users in the same household, or office, the ability to have different service providers, even for the same services, if they wish to do so.

Another aspect of the DISCUS objectives is the "principle of equivalence" where the capability of the optical network termination is the same regardless of geographical location. The actual capability at the customer premises would depend only on the capability of the terminal equipment not the network serving the terminal. The network should be capable of delivering all services and capacities regardless of location of the customer. This would also allow service providers to locate and connect any where in the network and grow capability at that location, to 100Gb/s or greater capacity if they wish to. This would help stimulate service entrepreneurship, innovation and a much more competitive and dynamic service provision environment.

The aim of this white paper is to stimulate a discussion of wavelength usage options and models, as next generation access networks will allow multiple wavelength channels to coexist in the same PON. The paper analyses and discusses pros and cons of 4 wavelength usage scenarios: wavelengths assigned to Service Providers, wavelength assigned to service type, wavelength shared across service types and providers, and wavelengths assigned to users. Our conclusion is that sharing wavelengths across service types and providers is the favourite option, although this requires stronger and more effective regulations.

A companion white paper was also published [4], discussing "Ownership models for future broadband networks".

Copyright Notice

The DISCUS Consortium consists of:

Participant Number	Participant organization name	Participant org. short name	Country
Coordinator			
1	Trinity College Dublin	TCD	Ireland
Other Beneficiaries			
2	Alcatel-Lucent Deutschland AG	ALUD	Germany
3	Coriant GmbH	COR	Germany
4	Telefonica Investigacion Y Desarrollo SA	TID	Spain
5	Telecom Italia S.p.A	TI	Italy
6	Aston University	ASTON	United Kingdom
7	Interuniversitair Micro-Electronica Centrum VZW	IMEC	Belgium
8	III V Lab GIE	III-V	France
9	University College Cork, National University of Ireland, Cork	Tyndall & UCC	Ireland
10	Polatis Ltd	POLATIS	United Kingdom
11	atesio GMBH	ATESIO	Germany
12	Kungliga Tekniska Hoegskolan	KTH	Sweden

List of Authors:

Name	Affiliation
Marco Ruffini (editor and contributor)	Trinity College Dublin
David B. Payne (editor and contributor)	Trinity College Dublin
Thomas Pfeiffer	Alcatel-Lucent Germany
Werner Graudszus	Alcatel-Lucent Germany
Klaus Pulverer	Coriant
Julio Montalvo Garcia	Telefonica Investigacion Y Desarrollo
Andrea Di Giglio	Telecom Italia
Roland Wessaely	atesio
Giuseppe Talli	Tyndall institute

Publication date: 7.11.2013

TABLE OF CONTENTS

1 Introduction

Future networks will have to cope with a huge demand for growth in user bandwidths, maybe as much as three orders of magnitude or more compared to today. The use of wavelength division multiplexing (WDM) over fibre access networks will be one of the optical technologies to be exploited to meet this challenge. However the way wavelengths are used can affect the economic viability, the competitive environment and the regulatory framework required to ensure open and fair access to network resources by all customers and service providers. This white paper discusses wavelength usage models and the implications for regulation with the aim of fostering a wider debate that can help shape requirements for a future architecture.

Three major problems need to be tackled as networks try to grow to respond to this huge demand for network capacity. These problems are: the cost of network provision and the long term financial viability of the telecoms sector, the huge growth in electrical power used by the worlds telecommunications networks, and the need to avoid a "digital divide" being created between those customers in dense urban areas and those in the sparser rural communities, without the need for massive government subsidies for those areas.

The FP7 project DISCUS [1] is proposing a radical simplification of the network architecture with rebalancing of investment from core and metro towards the access, (by reducing the number of core nodes, reducing the opto-electronic ports required and the amount of electronic traffic processing switches and routers). This is combined with large-scale infrastructure and equipment sharing so that all three problems are addressed with a single general solution. However it is recognised that the DISCUS solution not only requires technical and design innovations but also a fresh look at the regulatory and business model environment that network providers, network operators and service providers need to operate within.

DISCUS considers the business model and regulatory environment from a customer/end user perspective so that the major benefits of a new network architecture would go to the customers and users of the network while at the same time giving a fair return on investment to the network and service providers to encourage network investment. One aspect of this is to provide much greater availability of competitive service provision to customers without the long period contractual lock-in that happens too often today.

DISCUS is aiming for an evolvable solution that can gracefully grow network capacity as it is expected that customer demands for bandwidth could grow by three orders of magnitude or more from today's values [2], [3]. To enable such large increases in capacity wavelength division multiplexing (WDM) will be exploited in the access network. WDM technologies in optical networks have been applied to the core network for many years, the major use being to increase the capacity of the installed fibre base. In the last few years there has also been increasing use of the ability to route traffic flows within the wavelength domain using reconfigurable optical add drop multiplexing technology.

When WDM is applied to the access network there are additional uses that could be applied to the wavelength domain, particularly when shared passive optical access networks are considered. Bandwidth expansion in a managed and graceful way becomes one of the major uses for wavelength multiplexing in access networks (cf. NGPON2 standard). However wavelengths could also be used to provide the equivalence of unbundled access to different network and service providers or could be used for different types or classes of services that could be handled differently in the terminating node.

Wavelength routing can also be used within the access network. Wavelengths can be routed through the access network in two ways: one is in a static or fixed way where a wavelength routing element such as a WDM device is placed within the access network infrastructure. This method assigns fixed wavelength paths between the network terminating node and the customer premises. The alternative method is fully flexible wavelength routing where the access network is wavelength transparent and wavelength routing is achieved by selecting the transmitter and receiver wavelengths at the customer premises and network terminating node.

The DISCUS architecture, which is based on long reach passive optical networks with large splitting ratio in the access and metro networks and a flat wavelength switched core network interconnecting a relatively small number of traffic processing and switching nodes, can exploit the wavelength domain in all the ways mentioned above. The DISCUS LR-PON architecture is based on power splitters and uses optical amplifiers to overcome the power budget limitations. The use of power splitters provides the greatest transparency of the optical path between the metro-node where the LR-PON terminates and the customer premises termination and will also provide the greatest flexibility when WDM is used over the optical distribution network (ODN). This is the case we consider in this white paper.

The wavelength usage options discussed in this paper are therefore:

- Wavelengths assigned to service and network providers (WpSP)
- Wavelengths assigned to the service type - Wavelength-per-Service-Type (WpST)
- Wavelengths for bandwidth management are shared across service providers and carry all service types - Shared Wavelengths (SW)
- Wavelength assigned to users - Wavelength per User (WpU)

The options are shown in Figure 1

These usage options will be compared against the following topics.

- Description of wavelength usage option
- Issues from business model perspective
- Technical and techno economic issues

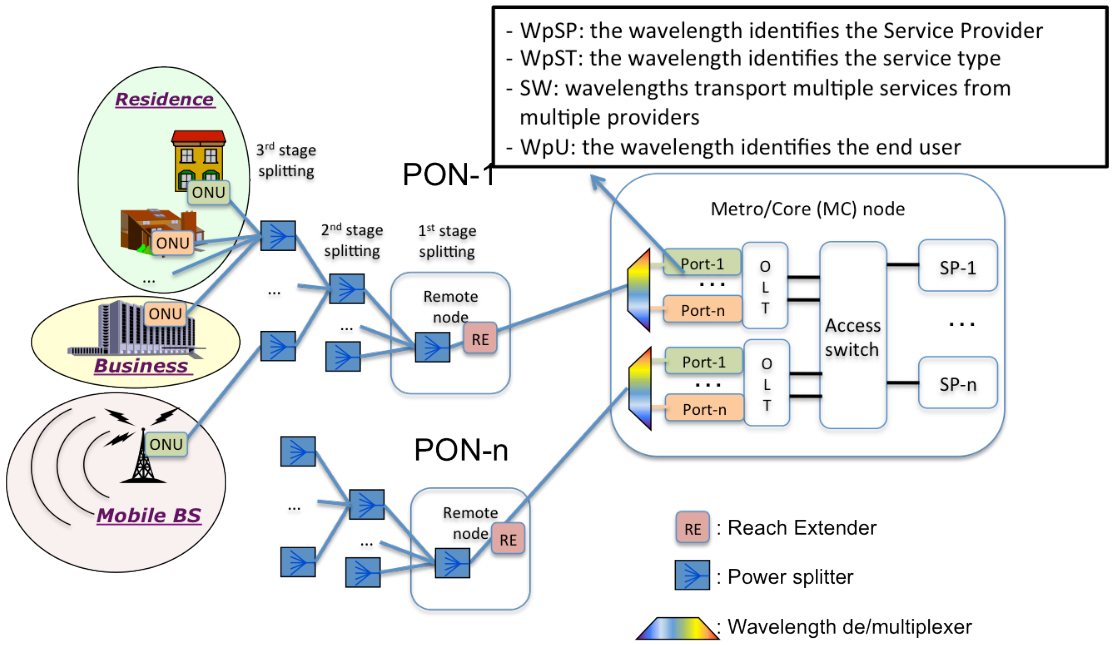

Figure 1 Wavelength Usage options over the DISCUS LR-PON architecture

2 Wavelength usage options

In this section we briefly describe the main features of the four wavelength usage options listed above. In this paper we use the term user to mean all types of user residential, business and even service providers. Where the different types of user need to be differentiated they will be mentioned specifically.

2.1 Wavelength assigned to Service Providers (Wavelength-per-SP – WpSP)

Assigning wavelengths passing over the PON infrastructure to individual SPs is equivalent to unbundling the PON infrastructure. In practice two wavelengths are assigned to each service provider, one for the upstream and one for the downstream direction. Any customer can connect to any SP by ensuring their ONU (the Optical Network Unit) selects the appropriate pair of wavelengths assigned to the SP for the up and down stream transmission paths. Because the ODN is based on a power splitter architecture all wavelengths channels are present at all ONUs and by using an appropriate wavelength selective filter and tuneable optical transmitter any SP can be selected by any customer. Typically it would be assumed that to keep the ONU low cost only one pair of wavelengths would be selected at any one time and the usual model would be that the customer will receive all services (i.e., telephone, broadband, Video-on-Demand etc.) from the same SP.

This model enables current local-loop unbundling regulations to be compatible and may be preferred by regulators if point to point fibre is not available.

2.2 Wavelengths assigned to service type – (WpST)

In this application of wavelength usage over the PON different services are assigned to different wavelengths, for example (VoIP, VoD, etc.). All SPs share access to customers on each wavelength or service using electrical multiplexing (usually TDM) via the PON protocol. This implies that each OLT delivers a particular service type, and the SPs access their portion of customers by sharing the PON channel capacity in a way that is proportional to the number of customers they service.

2.3 Wavelength for bandwidth management (Shared Wavelengths - SW)

An alternative option to both WpSP and WpST is to use wavelength purely for bandwidth management so that a wavelength is not assigned to a particular SP or service but will provide access to a number of SPs and all services from those SPs. Additional wavelengths are therefore only added to the system to expand capacity for increased service usage, and therefore the number of wavelengths is determined by the traffic requirements.

In this wavelength usage option there is no static association of wavelengths to a SP or a service type, but capacity is assigned to SPs as a form of bit-stream unbundling. There are two ways this capacity to SPs could be assigned: statically where each service provider has access to a fixed capacity bandwidth pipe within each wavelength (the usual way bit stream unbundling would be implemented today) or dynamically where the amount of bandwidth within each wavelength allocated to an SP will be proportional to their customer base and the use those customer make of the SP's services (in this case SPs only get capacity allocated if customers are actively using their services).

Wavelengths are added to the PON to increase capacity and to balance the traffic load across the wavelengths channels so that overloading is avoided. Customer ONUs would then be tuned to the appropriate wavelength/s.

For the majority of customers the ONU will only need a single transceiver. Initially this transceiver could be fixed-wavelength and will only require upgrading when the PON single wavelength capacity is exhausted and an additional wavelength is added. Even then, while the wavelength count is small, fixed-wavelength ONUs could be used to share customers across the wavelengths operating on any particular PON, increasing the average bandwidth per customer. Tuneable transceivers would be an upgrade option that would enable full dynamic traffic and capacity management but is not essential at day one.

Tuneable ONUs do have additional operational advantages compared to fixed-wavelength ONUs; there are no sparing/maintenance issues for ensuring the correct transceiver is in the correct customer ONU, and the network can be rebalanced/reconfigured remotely by the network operator without the need for changing out customer ONUs.

2.4 Wavelengths to individual users (Wavelength-per-User – WpU)

The original WDM PON replaced the passive power splitter with a wavelength multiplexer to route a specific wavelength to each user ONU connected to the PON. The advantage of this WDM-PON is that the WDM device has lower optical loss than the power splitter and enables lower power optical transmitters to be used. From a regulatory perspective this solution is a point-to-point topology with some of the advantages of the shared fibre solution of the TDM PON.

The point-to-point nature of the technology enables a carry over of LLU type unbundling into optical access networks. However there are a number of disadvantages with this solution the main one being the lack of flexible assignment of capacity to customers and the inefficient use of the PON capacity.

Wavelength per user can also be supported over power split PONs providing the same wavelength unbundled access but with the advantage of greater wavelength flexibility and the ability to randomly assign multiple wavelengths to those larger customers that may need multi-wavelength access.

3 Wavelength Usage options from a business model perspective

All the options have pros and cons from a regulatory and business model perspective and these issues will be discussed below under the headings of the four wavelength usage options being considered.

3.1 Wavelengths per SP (WpSP)

This use of wavelengths is at first sight very attractive, particularly as it gives a clear demarcation between service providers, but there are a number of issues that need to be considered.

One is scalability: the number of SPs available to customers is limited by the number of wavelengths that can be transmitted from the OLT and ONU over the PON infrastructure. The actual number is dependent on the PON architecture and the capabilities of the technology deployed. The DISCUS LR-PON architecture may use EDFA amplifiers within the PON, in which case the wavelength range would be the C-band (and maybe L-band). The maximum number of wavelengths for the C-band with current technology would be about 100, which could service 50 SPs (two wavelengths required per SP). SOA amplifiers could be an alternative technology which could increase the wavelength range; another possibility is coherent technology which could further increase the number of channels, however there will always be a limited number of wavelengths available.

For each pair of wavelengths used an opto-electronic terminating port is required at the head end of the PON (this is the metro-core node in the DISCUS architecture). The number of ports required at the metro-core nodes can therefore become quite large, being proportional to the number of PONs multiplied by the number of SPs (rather than being proportional to the overall access capacity required). Terminating port sharing is also reduced increasing the cost per customer of the head end equipment.

Another issue is the efficiency of wavelength usage. SPs will have a minimum of one wavelength allocated to them: depending on the number of customers and the popularity of their services some wavelengths will be under utilised because this spare capacity cannot be allocated to more popular or heavily used SPs. There is no statistical multiplexing gain from capacity sharing between SPs.

The same problem of SPs being locked to wavelengths also impedes end users from accessing services from different SPs simultaneously. This would be possible by adopting multi-channel ONUs, but it will incur higher cost for the user (at least due to a more complex and expensive ONU). From an SP perspective, physical channel separation is probably seen as an advantage, as each SP can easily separate their user base from other providers and directly control quality of service requirements on the PON. However from the end user perspective it will probably mean that SPs will lock their customers into 1-year term, or longer, contracts, similar to current DSL or cable contracts.

Another issue with wavelengths assigned to SPs is that in order to access a large number of customers an SP will need a wavelength pair on, possibly, all the LR-PONs connected to the metro-node. A large SP may be able to afford the cost associated with connection to many wavelengths via dedicated LR-PON OLT head ends, but this cost will be a barrier to a small start-up SPs that might want to connect via an ONU on one of the LR-PONs and try new and experimental services. Their customer base could initially be quite small and also scattered across many of the LR-PONs connected to the metro-node. These small SPs would prefer instead to use capacity on shared wavelengths that go to all LR-PONs and reach all potential customers on the metro-node, and quite possibly all customers on all metro-nodes in the network.

3.2 Wavelengths assigned to service type – (WpST)

This option where multiple SPs share the same wavelength for each service type provided would allow end users to dynamically switch between different SPs without tuning the ONU to different wavelengths. So within one channel an end user can choose among a large number of providers, thus increasing competition for each.

This approach also enables SPs to specialise in specific services: it could enable small SPs to enter specific service markets where they offer only one or a small number of service types. Small providers will not need to sustain the cost of providing entire wavelengths, but would share the cost of the channel with other providers, which could be in proportion to their usage of the channel. Larger, more popular SPs that use more of the channel capacity would pay proportionately more to the network provider.

Although it is still possible for SPs to offer multiple bundled services, the ONU would need to have multi-wavelength capability to gain access multiple service types simultaneously. Such a multi-wavelength ONU enables mixing services from multiple different providers including different bundles of services to the different users of the ONU terminal at the customers premises, but of course at the cost of a much more complex and expensive ONU.

The wavelength channels could be shared using the TDMA PON protocol and provide a form of bit-stream unbundling. As with the WpSP option, wavelength utilisation will not be high because spare bandwidth on wavelengths transporting services with relatively low traffic demand is not shared across wavelengths that carry popular high demand services.

3.3 Wavelength used for bandwidth management or shared wavelengths (SW)

This option does not assign wavelengths either to service providers or services but instead each wavelength is shared by service providers who would use the wavelength channel to deliver all their services to the customer. Because this is not wavelength or bit-stream unbundling in the commonly accepted sense, this mechanism requires changes to current regulatory and business model thinking, which are mainly predicated on physical separation of access infrastructure to provide access to different service providers.

With shared use of wavelength the physical infrastructure is necessarily also shared and access to SPs is either via static bit-stream separation or a dynamic assignment mechanism. The latter would provide greater usage efficiency of network resource, minimising the number of OLTs, access switch ports and energy requirements as well as cost, and also would be the best way to avoid bandwidth hogging by large wealthy SPs. In addition it would create a fairer environment for encouraging a greater entrepreneurial, innovative and competitive spirit for service provision.

Sharing wavelengths across services and service providers is only one of the many possibilities of using shared wavelength access. For example a new wavelength could be allocated to give a larger increase in capacity to a smaller number of heavy users or could even be assigned to one individual user, as a dedicated virtual point-to-point high-speed link across the PON. Indeed these high speed paths can be set up very quickly and dynamically, so users could have access on a “pay as you go” basis if desired.

Such capability leads to the ideas of capacity brokering for those users that need very high capacities for relatively short durations. It can also service a private circuit market at a granularity from Mb/s to 100Gb/s (possibly higher if flex-grid technologies can be applied in the future).

Capacity auctions could be employed, this however could lead to scenarios where some large SP could overbook their capacity, even bearing financial loss for a certain period of time, in order to eliminate its competition (as it indeed occurs in the allocation of mobile frequencies). In order to avoid this, such auctions may require regulation and policing so that anti-competitive behaviour can be curtailed while not stifling innovative use of dynamic resource allocation and new business opportunities.

3.4 Wavelengths per User – WpU

As mentioned previously there are two ways of assigning wavelengths to users; either statically with a WDM component within network or dynamically when the passive optical network uses wavelength transparent optical power splitters.

If the WDM components are in the network and provide the routing function to route the wavelength channels to the customers, then it is not possible to separate SPs or services by wavelength assignment because the customer ONUs can only receive one wavelength channel, while all others are blocked by the network embedded WDM component. Bit stream unbundling could be used to provide access to a number of service providers but this would be via layer-2 VLANs or VCs routed via the layer-2 access switch. Because the wavelength capacity cannot be shared over other users (by definition for this option – wavelength assigned per user) unused capacity is wasted and average efficiency will be low compared to the dynamically assigned capacity of the shared wavelength.

The scalability problems of WpSP also apply to WpU as the number of wavelengths available, dependent on the technology deployed, limits the degree of sharing on the passive optical network.

Because all SPs and all services need to be transmitted over a single wavelength to the customer using a bit-stream method, if the configuration of the bit stream pipes are via a slow management systems, it is more likely that service provision will be via longer term contracts. However if a fast flexible bandwidth assignment system is available, as described in the SW scenario, then a more flexible and dynamic service provision market is also possible.

Finally, the scenario where customers can obtain access to capacity via multiple wavelengths would only be possible if the network uses passive power splitters. This is the option proposed for the DISCUS architecture.

4 Technical and Techno-economic issues

The four wavelength usage options being considered also have technical and techno-economic advantages and disadvantages, which are discussed in this section.

4.1 Wavelengths per SP and wavelength per service options (WpSP & WpST)

Both the technical and economic challenges of these two wavelength usage options arise because of the need to change wavelength in order to change service provider or service type. To have flexible access to service providers and services will require the ONU to use tuneable components from day 1. There are technical challenges with the operation of the tuneable components and the interaction with the PON protocols and management systems. For example when a tuneable ONU cold starts it is not registered to any OLT and hence they cannot exchange information. The ONU needs to tune to the wavelength of an OLT and then start the ranging process and then finally register with the OLT. It is only after the ONU is correctly tuned, and the OLT has ranged and registered the ONU, that information about wavelength availability and assignment to SPs or services can be exchanged.

Therefore the well known problem for wavelength tuneable ONUs, to tune to an operating wavelength on the PON in order to identify itself and register and then be directed to the correct wavelength (in this case for the chosen SP), must be addressed. This problem also relates to the ownership of the wavelength: if the wavelength is wholly owned by an SP there may be no way to provide registration of ONUs not destined for that SP, that is, there may not be any management channel provided that can be used to direct the ONU to the correct wavelength for its service provider and service (Ownership models for future broadband networks are discussed in the companion white paper [4])

Alternatively the ONU would need to implement a mechanism that can tune it to the correct wavelength before it registers itself on the network. This would require implementing an absolute wavelength referencing inside both the tunable filter and tunable laser, which would impact considerably the cost of the ONU. Moreover, this implies that the customer has already decided to which SP to connect and that the ONU has knowledge of the assigned wavelengths. It is also quite likely that the customer using the ONU will not know the choices available for SPs before the ONU is registered and communicates with an OLT, only then can the SP options/choice information be passed to the customer.

Another related issue is the simultaneous access to multiple service providers and services. This could be provided by an ONU capable of multi-wavelength selection but that has significant cost and technical challenges associated with it. Multi-wavelength channel ONUs can be implemented in two ways: one is by fast-tuning the transceivers so that the ONU can time-division multiplex between the different wavelength channels. The other is by having multiple transceivers at the ONU, so that it can simultaneously operate over more than one wavelength channel. To use fast tuneable components would also require the protocols on the LR-PON wavelengths to be precisely synchronised and scheduled collectively. This would require either cooperation between SPs (or at least a well defined and enforced standard to ensure multi-wavelength TDM can be implemented), or ownership of the wavelengths by the network operator who would lease the wavelengths to the service providers but provide overall control and synchronisation.

Possible solutions to these issues:

For the WpSP case the ONU could be provided with a fixed wavelength transceiver. This would require a new ONU to be provided in order to change SP, or at least the ONU optical transceiver module would need to be changed, so that a different pair of wavelength channels is selected. This could be a cost barrier to changing providers and even if providers supply the ONUs there is greater cost and potential wasted resource as ONUs are changed out. Thus this mechanism would tend to lock customers to SPs. Fixed wavelength ONUs however cannot work for the WpST case as customers will generally want access to multiple services. Thus WpST requires random access to multiple wavelengths simultaneously. Of course if all wavelengths are demultiplexed and received at the ONU then multi-service access could be provided, but at considerable cost.

Another possible solution which could be applied to both WpSP and WpST would be for the ONU to have a tuneable optical transmitter and receiver module. With a tuneable transceiver the ONU can scan the LR-PON for active wavelength channels in a listen only mode. For this to work each wavelength must transmit an SP identification messages so that a map of SPs and corresponding wavelength can be built up by the ONU. The ONU would have a process of communicating to the customer the available SPs and the customer would be able inform the ONU of their SP selection. The ONU then tunes its transmitter and receiver to the appropriate wavelengths and ranges and registers under instruction of the OLT. An alternative method would be for the ONU to find any available wavelength and tune its receiver to it. Once the ONU can receive one of the wavelength channels it can receive information about all the wavelengths and SP assignments (assuming this is available on all wavelengths). At present it is uncertain what the additional cost of a tuneable transceiver over a fixed wavelength transceiver will be but it is likely there will be a cost penalty. An additional problem for the single tuneable transceiver ONU for the WpST option is that the ONU is required to be fast-tuning, so that one transceiver can be used in a TDM fashion to hop between different wavelengths to access the required services.

If transceivers are sufficiently low cost the ONU could be fitted with two transceivers, one at a fixed wavelength the other tuneable, however there will inevitably be a cost penalty compared to single channel ONUs. The fixed wavelength is always available and is used as a control channel, managed by the network operator. The other tuneable transceiver is used to connect to a service provider for services. ONU ranging and registration is initially done over the fixed wavelength channel and once established provides a permanent communication link for control and management of the ONU. Information about the available wavelengths and the assignments to SPs would be transferred to the ONU via this fixed wavelength channel. The SP selection process would then be the same as previously described.

The ONU could of course have multiple tuneable transceivers rather than one tuneable and one fixed wavelength transceiver. This solution would enable the simultaneous access to a number of SPs for the WpSP case, while for the WpST case it would enable simultaneous multi-service selection, an essential requirement for this option. However this is almost equivalent to multiple fixed wavelength ONUs where each wavelength will need to be terminated in an opto-electronic transceiver with electronic circuitry. Such functionality will almost certainly produce a significant cost penalty associated with this option. As a result it may be difficult for the WpST option to be an initial entry strategy as minimising upfront costs will be essential for high penetration and take-up of the fibre to the premises (FTTP) solution that will be required for a future ultra-fast and ubiquitous broadband network.

The main difference between the WpSP and WpST options is that for WpSP the number of different channels is proportional to the number of SPs used simultaneously, while for WpST it depends on the number of services used simultaneously. Thus the relative complexity of the ONU depends on whether the average user is more likely to use more SPs or more service types simultaneously. However, the economic challenges of WpST are more severe than WpSP as the former requires a multi-channel ONU to receive multiple services simultaneously.

4.2 Shared wavelengths used for bandwidth management (SW)

Since the shared wavelength option does not lock wavelengths to SP or services, it has the best statistical multiplexing gain, particularly for the dynamically assigned bandwidth case and therefore assures the highest PON utilization of all the scenarios discussed. The higher PON utilization also reduces the number of OLTs required at the metro-core node, reducing costs, power consumption and footprint of the node.

This scenario also reduces the cost of customer ONU equipment and also the initial cost of entry as low-cost single-wavelength non-tuneable ONTs could in fact be used at day 1, while leaving end users still free to switch between SPs and receive services from multiple SPs simultaneously using the capability of the TDMA PON protocol. However, tuneable ONUs would still remain a preferred option for future capacity upgrades, enabling the Network Operator to add wavelength channels to the PON without needing to change end user equipment, as well as manging bandwidth demands across all the available wavelengths. Certainly, an important advantage of SW over WpSP and WpST is that fast tuning or multi-channel ONUs is not required, as all the required flexibility can be achieved within any one channel. The only requirement for multi-wavelength ONUs will be for those large users requiring large amounts of bandwidth that cannot be accommodated on a single wavelength.

The disadvantage of the shared wavelength usage option is that conventional unbundling regulation cannot be carried over to this option. This is a sharing economy model where infrastructure and network resources are shared across users and service providers. Although bit stream unbundling could be applied to each wavelength operating over the optical network this would represent a less efficient use of capacity as unused capacity allocated to a bit-stream channel could not be used by other providers. What are needed are flexible bandwidth service and network products or bandwidth on demand products that only assign bandwidth to customers and service providers when customers request services from those providers. This may require new regulation to ensure full and fair open access for all service providers and customers.

4.3 Wavelength-per-User – WpU

For the original WDM PON, with the WDM component within the network, the ONU and OLT can be simpler than for the TWDM case, as both ends can use lower-cost and lower speed point-to-point transceivers (today these would be typically based on legacy 1GE technology). The main issues however is that the OLTs are not shared among different users, thus, although less expensive, their number is much larger. This also leads to increased overall energy consumption and equipment footprint. One additional issue is that, due to the large number of wavelengths in use it might not be practical to use fixed transceivers, mainly due to inventory issues (although from a CAPEX perspective this would be the ideal case, due to its lower cost). The limited number of wavelengths per PON also limits the maximum number of users able to share the feeder fibre of the PON so that typically more feeder fibres are required in the ODN compared to the SW TWDM solutions.

The use of coherent technology, when used with passive splitters in the ODN, allows for more flexibility in WpU, as a higher number of wavelength channels is available (in the order of 1000) which are broadcast to all users. Thus for example a business user with high capacity requirement could be assigned more than one wavelength channel on-demand. The main drawback of coherent transmission is that it is still too expensive as a large-scale start-up solution but could be a future upgrade for all wavelength usage options.

From a capacity efficiency perspective, WpU is probably the least efficient mechanism for providing broadband as it locks capacity to users independently of their actual usage or needs. In addition, in principle, it allows a peak rate that is the same as the average sustained rate, which basic traffic theory shows is highly inefficient.

5 Summary

Future optical access networks will need to use the multi-wavelength capabilities of optical fibre technology to grow capacity. However how wavelengths are used and what they are used for can have a significant impact not only on the costs and efficiency of the future network but also on the opportunities for competition and the service creation environment.

In this white paper four wavelength usage options have been discussed: wavelengths assigned to service providers, wavelengths assigned to services, wavelength used flexibly for bandwidth management and wavelengths assigned to users. The FP7 DISCUS project is proposing a new flexible network architecture for future networks which could support all four options. Indeed because of the flexibility of the architecture the options need not be mutually exclusive.

However the favoured option is the fully flexible bandwidth management option (SW) which provides the potential for lowest upfront costs, the most efficient usage of network resources and the greatest opportunity for creating a fairer competitive environment while encouraging a greater entrepreneurial, innovative and competitive spirit for service provision.

The wavelength for bandwidth management option does not exclude other uses of wavelengths but would be the most economical solution for mass market FTTP provision as it can start with a single wavelength using fixed wavelength technology and then gracefully evolve to the fully flexible solution as demand for bandwidth grows.

One of the driving philosophies of the DISCUS architecture is to use sharing of network resources as much as possible as a way of reducing cost per user. The dynamic sharing of bandwidth across wavelengths and within wavelength channels (i.e., when using the wavelengths for managing bandwidth option) maximises the resource sharing potential and minimises cost per user. To enable this vision regulations for competition would need to be reconsidered from a shared network perspective rather than the simple unbundling strategies currently employed. However it is recognised that the current regulatory environment may only slowly change and therefore the DISCUS architecture is designed to also support wavelength and bit-stream unbundling within the different wavelength usage options discussed in this white paper.

References

[1] DISCUS FP7 project: 'The DIStributed Core for unlimited bandwidth supply for all Users and Services '. http://www.discus-fp7.eu/

[2] M. Ruffini, N. Doran, M. Achouche, N. Parsons, T. Pfeiffer, X. Yin, H. Rohde, M. Schiano, P. Ossieur, B. O'Sullivan, R. Wessaly, L. Wosinska, J. Montalvo and D.B. Payne, DISCUS: End-to-end network design for ubiquitous high speed broadband services **(Invited)**. ICTON conference, 2013.

[3] DISCUS deliverable D2.1: 'Initial reference achitecture'. http://www.discus-fp7.eu/activities/deliverables

[4] DISCUS white paper: 'Ownership models for future broadband networks '. http://www.discus-fp7.eu/white-papers

Abbreviations

CAPEX	Capital Expenditures
EDFA	Erbium-Doped Fibre Amplifier
FP7	Framework Program 7
FTTP	Fibre-To-The-Premises
LLU	Local Loop Unbundling
LR-PON	Long-Reach Passive Optical Network
NGPON2	Next Generation PON 2
ODN	Optical Distribution Network
OLT	Optical Line Terminal
ONU	Optical Network Unit
PON	Passive Optical Network
SOA	Semiconductor Optical Amplifier
SP	Service Provider
SW	Shared Wavelengths
TDM	Time Division Multiplexing
TDMA	Time Division Multiple Access
TWDM	Time-Wavelength Division Multiplexing
VC	Virtual Circuit
VLAN	Virtual Local Area Network
VoD	Video on Demand
VoIP	Voice over IP
WDM	Wavelength Division Multiplexing
WpSP	Wavelength per Service Provider
WpST	Wavelength per Service Type
WpU	Wavelength per User