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## D D2.3 – Optical Access Solutions

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<i>Abstract (for dissemination)</i>	This document presents the prototypes of the different Optical Access technologies developed in MUSE SPD, and the first results that have been obtained. Developed prototypes were applied in a lab trial conducted in Berlin.

**DOCUMENT HISTORY**

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## EXECUTIVE SUMMARY

In the MUSE project, various deployment scenarios, Access Platforms and First-Mile technologies are subjected to a number of studies. Subproject D focuses on high-speed access technologies that apply to FttX scenarios, where the available bandwidth per subscriber ranges from VDSL speeds (10 Mb/s and up) to Fast Ethernet speeds (100 Mb/s).

In deliverable D2.1: "Options for fibre Access", an extensive overview was given of available and emerging technologies that to a smaller or larger extent meet these requirements. Some approaches that can provide promising features were introduced in that deliverable as well. These technologies are studied further in detail in SPD, and prototypes are developed for individual testing, as well as in integrated trials.

The first versions of these prototypes have become available, and in order to report on the results of the developments, MUSE deliverables DD2.2 through MD2.4 present the results of

- The CWDM Double Ring Architecture, which not only provides FttH connectivity, but can also function as a feeder network for other First Mile Access technologies, as will be demonstrated during a lab trial.
- The CWDM feeder for VDSL over Optics (VDSL<sub>o</sub>O). DSL specific issues are addressed in deliverable D2.2. This document will focus on the optical feeder technique involved in this solution.
- Subcarrier Multiplexing over Multimode Fibre (SCMoMMF), which envisages cheap broadband access for short-range scenarios such as dense urban and multi-tenant building units.
- The development of the Asymmetric PON (AsPON) Access Multiplexer has been delayed. In order to allow timely reporting of the available results, the prototype of this particular technology will be reported later.

This document presents the prototypes of the different technologies, and the first results that have been obtained. Apart from the SCMoMMF prototype, which is yet still too premature for interoperability testing, the developed prototypes are fit for application in the lab trial conducted in Berlin. Evaluation of this lab trial (DD4.3) involving the prototypes presented here will become available at the end of Phase I of the project.

To capture the main outcome of these studies, the following conclusions can be drawn.

With **VDSL over Optics** prototype, real time audio and video were successfully transmitted using multimedia desktops. This successful transmission of combined spectra consisting of two subcarrier-modulated VDSL channels shows that the system is capable of transmitting multiple channels of VDSL signals using subcarrier multiplexing. For demonstrating purposes, 4 VDSL channel system will be available using local clock sources and transmission will be performed through the ring network HHI has built.

The **CWDM access** network has been successfully set-up. Its feasibility has been proven using GbE channels throughout the entire CWDM band by means of commercially available components, which have potential to be low-cost in a volume market. The target feeder ring circumference of 20 km can be met using SSMF and/ or ZWPF (worst-case parameters) with

suitable assignment of wavelength channels to the remote nodes. The next step is to prove the system using different wavelength clients. This will be performed in a joint lab-trial using VDSL<sub>o</sub>O described here, and the Fixed Wireless Access system that is also developed in SPD.

The electronics of the **Subcarrier Multiplexing** prototype is working correctly. The carriers in the transmitter can be adapted dynamically over 500MHz, which was one of the objectives. A system with 2 subcarriers, both modulated with 1Gb/s of data was experimentally proven to be feasible. Both for 750m and 4.4 km a BER < 10<sup>-9</sup> could be obtained. There are however a few improvements possible. The dynamic range of the PLL is currently limited while also the sensitivity can still be improved. The feasibility of the broadband receiver has been shown. The next step is to include the optical path in the setup.

**TABLE OF CONTENTS**

**EXECUTIVE SUMMARY .....4**

**LIST OF FIGURES.....8**

**LIST OF TABLES .....9**

**ABBREVIATIONS.....10**

**1. INTRODUCTION.....12**

**2. CWDM RING.....13**

2.1 OVERVIEW.....13

2.2 COMPONENTS .....14

2.2.1 *Fibres*.....14

2.2.2 *Connectors* .....15

2.2.3 *Transceivers* .....15

2.2.4 *Multiplexer and Demultiplexer* .....16

2.2.5 *Add-Drop Multiplexer* .....17

2.3 BUILDING BLOCKS .....18

2.3.1 *Hub design*.....18

2.3.2 *Remote node design*.....19

2.3.3 *ONU design* .....19

2.4 SYSTEM CONSIDERATIONS .....21

2.4.1 *Power budget*.....21

2.4.2 *Sharing of distribution ring bandwidth*.....22

2.4.3 *Protection switching*.....22

2.5 CONCLUSIONS .....24

**3. CWDM VDSLOO .....26**

3.1 DP ACCESS CONCENTRATION USING SUB CARRIER MULTIPLEXING.....26

3.2 SUB-CARRIER MULTIPLEXING THROUGH CONCATENATED DISCRETE MULTITONE MODULATION (SUPER DMT) .....27

3.3 EVOLUTION OF THE VDSLOO SOLUTION TO P2MP ARCHITECTURES .....28

3.4 ECONOMIC EVALUATION .....31

3.5 LATEST RESULTS .....31

3.5.1 *AWG based network architecture* .....31

3.5.2 *AWG-based network performance* .....33

3.6 CONCLUSIONS .....34

3.7 REFERENCES .....34

**4. SUB-CARRIER MULTIPLEXING .....36**

4.1 INTRODUCTION .....36

4.2 DESIGN OF SCM PROTOTYPE .....37

4.2.1 *Transmitter*.....37

4.2.2 *Receiver*.....37

4.3 TESTING OF SCM PROTOTYPE .....39

4.3.1 *Testing of electronics*.....39

4.3.2 *Testing SCM prototype with optical path included*.....40

4.3.3	Testing of the broadband receiver .....	44
4.4	CONCLUSION AND RECOMMENDATIONS .....	45
<b>5.</b>	<b>CONCLUSIONS.....</b>	<b>46</b>
<b>6.</b>	<b>REFERENCES.....</b>	<b>47</b>

## LIST OF FIGURES

Figure 1: Scheme of ring-based CDWM access network .....	13
Figure 2: CWDM grid (centre wavelengths) and corresponding fibre attenuation of zero water peak fibre (ZWPF). .....	14
Figure 3: Channel by channel profile of transceiver power characteristics.....	15
Figure 4: Dependencies on ambient temperature: Examples of Tx optical output power (left) and Rx sensitivity at 1.25 Gb/s (right) .....	16
Figure 5: Spectral characteristics of an 18:1 DeMultiplexer. The 13 nm CWDM passband ranges compliant to ITU- T rec. G.694.2 are marked by hatched areas.....	17
Figure 6: 2-channel OADM .....	17
Figure 7: Transmittance of OADMs with standard filters (left) and ultrablocking filters (right) .....	18
Figure 8: Hub node architecture .....	19
Figure 9: Remote node (RN) architecture .....	19
Figure 10: ONU architecture .....	20
Figure 11: ONU software block diagram .....	20
Figure 23: General schematic of the SuDMT transmission scheme.....	27
Figure 24: Point-to-multipoint access network architecture .....	28
Figure 25: CWDM tree structure.....	29
Figure 26: Hybrid D/CWDM architecture .....	30
Figure 27: Hybrid C/DWDM ring network architecture featuring 8 CWDM channels, M DWDM channels in every CWDM channel and 24 VDSL channels in every DWDM channel .....	31
Figure 28: Block diagram for baseline optical transmission.....	32
Figure 29: Subcarrier China bandplan VDSL upstream-downstream at 50MHz &120MHz, for a single wavelength .....	33
Figure 30: Bit-loading curve for 12 MHz bandplan 998.....	34
Figure 31: Upconverted VDSL spectrum for 12 MHz bandplan 998.....	34
Figure 41 : SCM point to point architecture .....	36
Figure 42: basic schematic of transmitter .....	37
Figure 43: basic schematic of the receiver .....	38
Figure 44: creation of VCO with large tuning range .....	38
Figure 45: SCM prototype electronic part.....	39
Figure 46: SCM prototype with optical path included.....	41
Figure 47: 450Mb/s measurements with optical path included (single carrier).....	42
Figure 48: 1Gb/s measurements with optical path included (single carrier) .....	42
Figure 49: 450Mb/s measurements with optical path included and load carrier at 1 Ghz.....	43
Figure 50: 1Gb/s measurements with optical path included and load carrier at 1Ghz .....	43
Figure 51: BER comparison with and without load carrier for 750m fibre and 1Gb/s data.....	44
Figure 52: broadband receiver.....	45

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## LIST OF TABLES

<b>Table 1: Key parameters for calculation of the power budget .....</b>	<b>21</b>
Table 2: Loss budget calculation using SSMF and ZWPF for a total FR length of 20 km and nine equidistant RNs in it, each with 2 add-drop ports.....	22
Table 3: Comparison of options for Layer 2 ring protection with Ethernet on the Link layer .....	24
Table 7: measurements on 1Ghz carrier for 450Mb/s and 1 Gb/s.....	40
Table 8: measurements on 2.5 Ghz carrier for 450Mb/s and 1 Gb/s.....	40

**ABBREVIATIONS**

ADSL	Asymmetric DSL
AGN	Aggregation Node
AM	Amplitude Modulation
AON	Active Optical Network
P/A-ON	Asymmetric Optical Network
ATM	Asynchronous Transfer Mode
AWG	Arrayed Waveguide Grating
CAP	Carrierless AM/PM
CATV	Cable Access TV
CO	Central Office
CP(E)	Customer Premises (Equipment)
CWDM	Coarse Wavelength Division Multiplexing
DBS	Digital Broadcast Satellite
DMT	Discrete Multi-Tone
DP	Distribution Point
DSL	Digital Subscriber Line
DSM	Dynamic Spectral Management
DSLAM	Digital Subscriber Line Access Multiplexer
DVB	Digital Video Broadcast
DVD	Digital Video Disk
DWDM	Dense Wavelength Division Multiplexing
FDM	Frequency Division Modulation
FSAN	Full-Service Access Network
FttB	Fibre to the Building
FttC	Fibre to the Curb
FttCab	Fibre to the Cabinet
FttH	Fibre to the Home
FttN	Fibre to the Neighbourhood
FttP	Fibre to the Premises
HFC	Hybrid Fibre Coax
HDTV	High Definition TV
HDSL	High-Data-Rate Digital Subscriber Line
MAC	Medium Access Controller
MM	Multi-mode (fibre)
NT	Network Terminator
OADM	Optical Add-Drop Multiplexer

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OLT	Optical Line Terminal
ONU	Optical Network Unit
PC	Personal Computer
P2P	Point-to-Point
PDH	Plesiochronous Digital Hierarchy
PM	Pulse Modulation
PON	Passive Optical Network
POTS	Plain Old Telephone Service
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RSTP	Rapid Spanning Tree Protocol
SCM	Sub-Carrier Modulation
SDH	Synchronous Digital Hierarchy
SDSL	Symmetric Digital Subscriber Line
SM	Single-mode (fibre)
SONET	Synchronous Optical Network
TFF	Thin Film Filter
VCSEL	Vertical Cavity Surface Emitting Laser
VDSL	Very-High-Data-Rate Digital Subscriber Line
VDSL <sub>o</sub> O	VDSL over Optics
WDM	Wavelength Division Multiplexing

## 1. INTRODUCTION

In the MUSE project, various deployment scenarios, Access Platforms and First-Mile technologies are subjected to a number of studies. Subproject D focuses on high-speed access technologies that apply to FttX scenarios, where the available bandwidth per subscriber ranges from VDSL speeds (10 Mb/s and up) to Fast Ethernet speeds (100 Mb/s).

In deliverable D2.1: "Options for fibre Access", an extensive overview was given of available and emerging technologies that to a smaller or larger extent meet these requirements. Some approaches that can provide promising features were introduced in that deliverable as well. These technologies are studied further in detail in SPD, and prototypes are developed for individual testing, as well as in integrated trials.

The first versions of these prototypes have become available, and in order to report on the results of the developments, MUSE deliverables DD2.2 through MD2.4 present the results of the different prototypes.

This milestone, DD2.3 presents the designs of the FttX solutions that were proposed in SPD:

- The CWDM Double Ring Architecture
- The CWDM feeder for VDSL over Optics (VDSL<sub>o</sub>O)
- Subcarrier Multiplexing over Multimode Fibre (SCMoMMF).

The development of the Asymmetric PON (AsPON) Access Multiplexer has been delayed. In order to allow timely reporting of the available results, the prototype of this particular technology will be reported later.

This document presents the prototypes of the different technologies, and the first results that have been obtained. Evaluations of the lab trials (DD4.3) involving the prototypes presented here will become available at the end of Phase I of the project.

## 2. CWDM RING

In search of a potentially low-cost solution for optical access networks a concept using fibre rings was developed. WDM ring networks can cover large distribution areas with few optical fibres and provide large bandwidth. Additionally, they render the benefit of inherent protection without much additional effort. A detailed description of concept and features of the proposed solution using CWDM technology is covered by deliverable D2.1 [i, ch. 4.5].

### 2.1 Overview

An Ethernet-based optical access network is considered to be able to deliver bandwidths of 25 Mb/s (typical) to 100 Mb/s (peak) to an average end-user. The basic network architecture is shown in . In accordance with the reference model of MUSE Subproject A, it is assumed that the access network area consists of two major parts: the feeder and the distribution area. The feeder part covers the section between a central office (CO) and several remote nodes (RN) placed in the field for passive signal distribution/ aggregation, whereas the distribution area links customer's premises to the feeder. Both parts of the network consist of ring structures. In the feeder area, a hubbed network is considered with a dual-fibre bidirectional CWDM ring carrying a maximum of 18 wavelength channels, each running at the Gb-Ethernet (GbE) data rate of 1.25 Gb/s. In a configuration where assigned wavelengths are fixed, each channel addresses a dedicated optical add-drop multiplexer (OADM) located in one of the RNs. All connections between RNs are established via the hub, which is set up as managed Ethernet switch located in the CO. Optical GbE ports throughout the entire CWDM wavelength grid and related multiplexers/ demultiplexers form the optical line terminal (OLT). The hub processes the whole traffic in the access network and acts as gateway towards the metro domain. At the RNs, passive OADMs drop a given wavelength downstream onto the distribution ring (DR), and add the same wavelength upstream onto the feeder ring (FR).

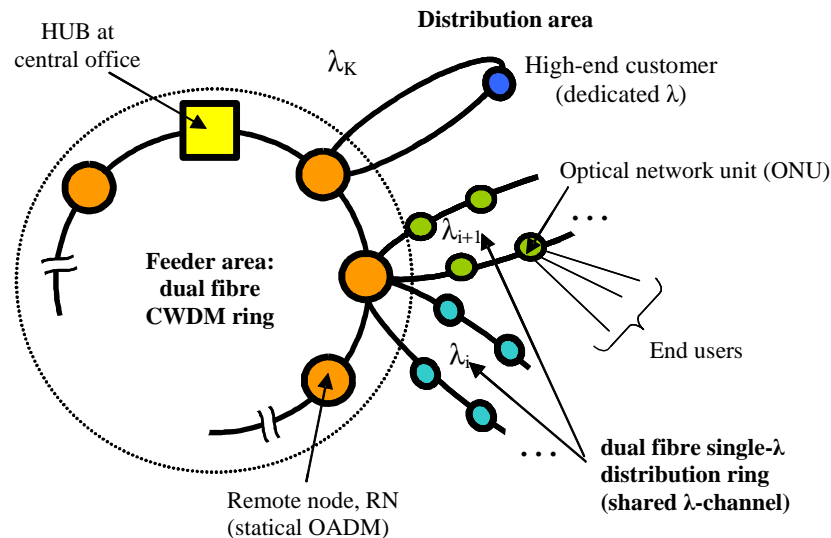
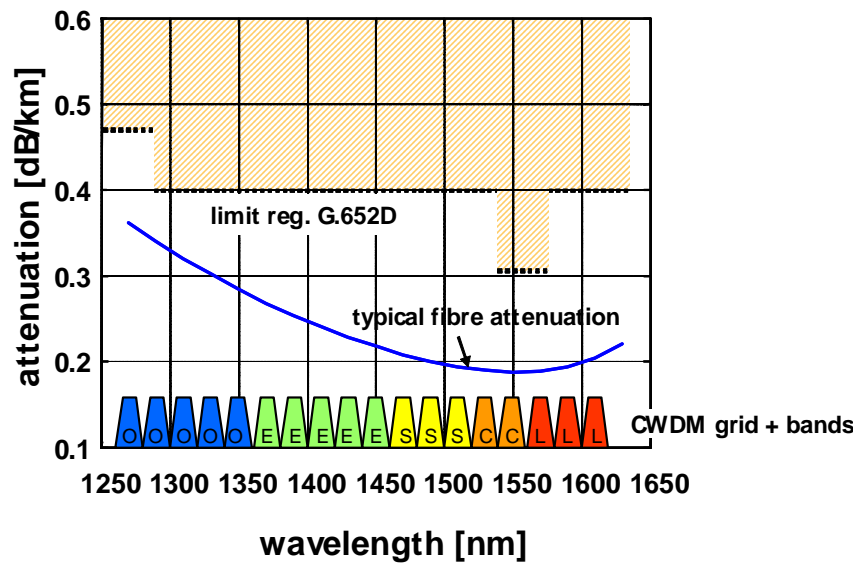


Figure 1: Scheme of ring-based CDWM access network

Each DR is a dual-fibre bidirectional ring with point-to-point interconnections between its nodes, which are the optical network units (ONUs) equipped with active opto-electronic hardware. These nodes usually represent traffic aggregation points for their vicinity and are placed at the customers premises (e.g. in the cellar of buildings, FttB) or in cabinets at the street (FttCab). For ring-like interconnection of several ONUs within a DR, their interfaces are coloured (CWDM) or grey depending on the ONU location. In one DR, all users share the bandwidth of the same wavelength channel by means of protocol driven media access. Thus, individual customers can be linked to an ONU using all options of “last meter”, LAN and indoor backbone transmission media including appropriate media conversion. The access network is designed for fully equipped CWDM FRs with an extent of up to 20 km using commercially available components. The CWDM grid is used according to ITU-T [ii], as illustrated in . In the following, the performance of the optical CWDM path is investigated, since this is the crucial part of the network concept.



The CWDM band is usually structured in subbands O = Original, E = Extended, S = Short, C = Conventional, L = Long

Figure 2: CWDM grid (centre wavelengths) and corresponding fibre attenuation of zero water peak fibre (ZWPF).

## 2.2 Components

### 2.2.1 Fibres

The maximum aggregated distance within the 18 channel CWDM ring network is assumed to be in the order of 20 km. As a result, there is a preference to use ZWPF enabling full spectrum operation at a maximum fibre insertion loss of 0.47 dB, as recommended in ITU G.652 D [iii] even in the water peak region around 1383 nm. ZWPF provides full backward compatibility with the legacy SSMF plant. Moreover, it should be noted that commercially available fibres might exhibit substantially improved loss specifications. Legacy SSMF featuring same dispersion but merely comparable loss characteristics might also be used in CWDM transport systems. However, due the inferior insertion loss characteristic in the water peak region their deployment may be restricted to shorter transmission distances typically found e.g. in the DR

network area. Moreover, fibres with a reduced bending radius less than 10 mm can be applied advantageously to cut space requirements in modules and cabinets.

### 2.2.2 Connectors

Besides splices, connectors can be reliably deployed in the fibre infrastructure of access networks. Suitable connectors may increase the network flexibility. Standard size connectors as well as small form factor connectors with a smaller footprint may be deployed to meet the rigorous demands resulting from installation and operational conditions at non-weather-protected locations such as RNs. To avoid corrosion effects there is a preference for connectors with full ceramic ferrules and sleeves. For power budget calculations, connectors with a maximum insertion loss of 0.25 dB (0.5 dB for plug and socket) are considered.

### 2.2.3 Transceivers

Throughout the ring network, hot pluggable SFP (small form-factor pluggable) transceivers may be deployed to terminate the optical paths. Different types of transceivers will be used. Coloured CWDM type transmitters are necessary in the FR fabric. Due to the shortcomings of alternative laser types (e.g. VCSEL or FP), DFB lasers have to be used to meet the system demands with respect to optical output power and spectral characteristics such as line width and thermal wavelength stability. Typical specifications of commercially available transceivers for medium reach include 0 dBm launched optical power, 0.1 nm/K thermally induced drift and 0 °C – 70 °C operating temperature range, which is sufficient for environmentally controlled operation within buildings. The corresponding range of the wavelength drift amounts to < 7 nm and fits well into the typical CWDM channel passband of 13 nm. Due to the marginal demands associated with shorter point-to-point links between ONUs, colourless (grey) type transmitters will be deployed within DRs, allowing the use of cost-efficient VCSEL or FP lasers. As far as possible, PIN photo diodes should be deployed at the receiver side. However, depending on the power budget needs, transceivers with APD may also be used.

In order to calculate the power budget realistically, CWDM transceivers have been characterised at 1.25 Gb/s over all 18 channels. Output powers of > 0 dBm and PIN based receiver sensitivities < -27 dBm @ BER 10<sup>-9</sup> have been measured at 25 °C ( ).

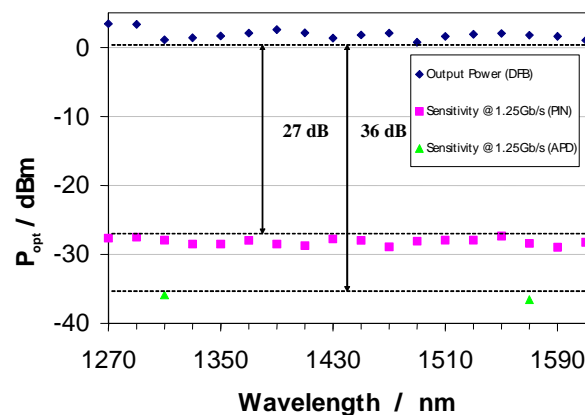


Figure 3: Channel by channel profile of transceiver power characteristics

However, the transceiver power characteristics also vary with ambient temperature changes (). Despite automatic bias-control, the transmitter output power decreases considerably with increasing temperatures whereas sensitivity changes of PIN based receivers remain constant to a great extent. Moreover, SFP receivers are broadband. Their wavelength dependency over all CWDM channels is below 0.5 dB.

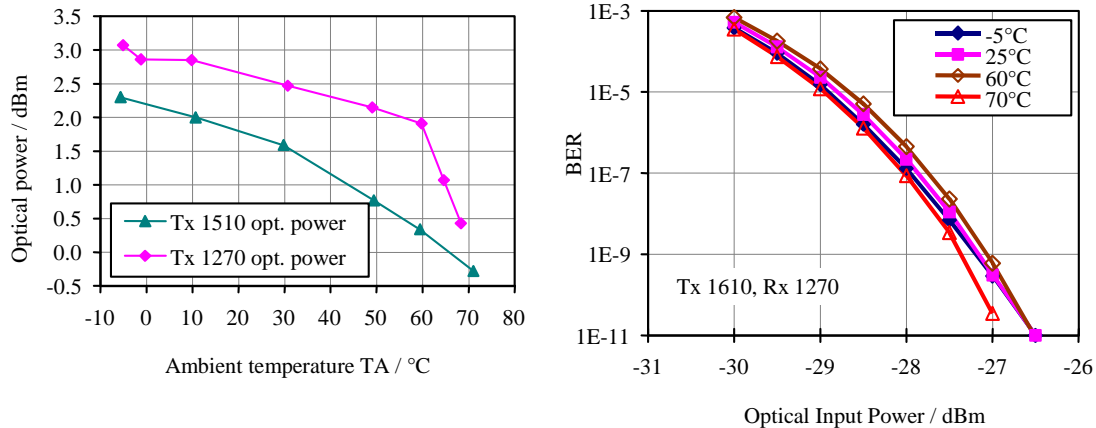


Figure 4: Dependencies on ambient temperature: Examples of Tx optical output power (left) and Rx sensitivity at 1.25 Gb/s (right)

## 2.2.4 Multiplexer and Demultiplexer

In [xii, p. 71] it was established that thin-film based filters (TFF) should be favoured for constructing CWDM networks, due to their wide availability and excellent filter characteristics. TFF based multiplexers and demultiplexers are located at the CO site to combine and separate CWDM signals transported via the outside plant infrastructure. For an 18-channel standard TFF DeMultiplexer, insertion loss and crosstalk behaviour have been measured (here, crosstalk is defined as the signal portions stemming from adjacent channels that can be observed in the passband region of the investigated channel). Results are shown in . For the measured channels, the insertion loss is below 1.6 dB. The highest crosstalk in the order of -35 dB was found in channel #3 at 1311 nm. However, due to manufacturing tolerances maximum crosstalk values may be in the order of -30 dB. For system applications this crosstalk figure is quite sufficient but could be improved by a more complex filter design if necessary. (Note that in the range 1380-1440 nm data are not yet available due to the restricted tuning range of light sources used for testing. However, it is expected that the remaining channels have similar characteristics). Since the CO is assumed to be air-conditioned, operating temperature dependencies of the filter specifications are not an issue.

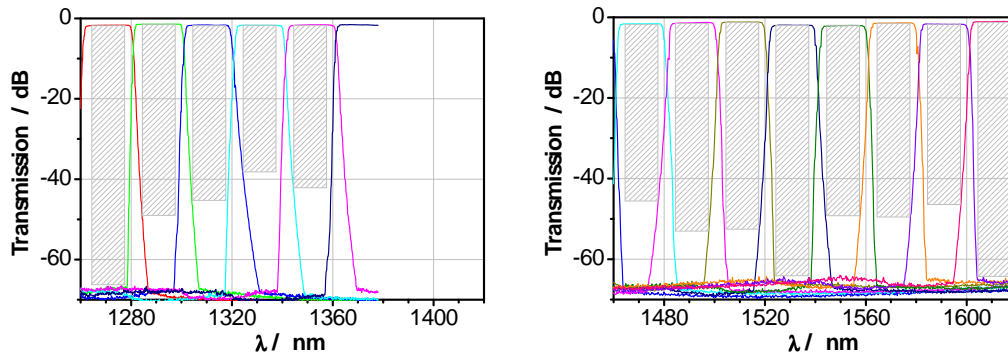


Figure 5: Spectral characteristics of an 18:1 DeMultiplexer. The 13 nm CWDM passband ranges compliant to ITU-T rec. G.694.2 are marked by hatched areas.

### 2.2.5 Add-Drop Multiplexer

Since OADMs at the remote nodes carry different user signals at the same nominal wavelength through the *add* and *drop* ports, it is important to evaluate inherent crosstalk properties. For a fixed-wavelength OADM with 2 add-drop ports operating at  $\lambda_1$  and  $\lambda_2$  (), insufficiently dropped signals that are passed to the out port have been measured.

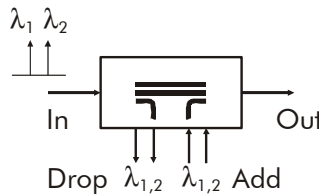
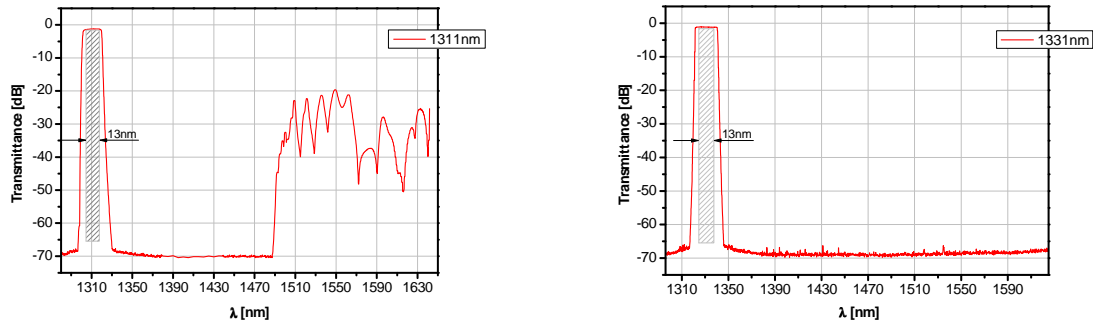


Figure 6: 2-channel OADM

As a result, the maximum crosstalk that could potentially interfere within the passband of the observed channels is 29 dB below the added signal level. Again, for system applications such crosstalk figures are sufficient but could be improved by a more complex filter design if necessary. The crosstalk between the *add* and the *drop* port is negligible and well below -60 dB. The insertion loss of add/drop and in/out ports is not higher than 1.6 dB. Notice that this value is quite favourable for designs of OADM chains, since the typical insertion loss of single channel add/drop devices is above 1 dB.

Standard type CWDM filters tend to generate unwanted passbands typically 150 - 200 nm beyond their specified bandpass centre. Hence, for full spectrum OADM operation, ultra-blocking filters will be needed featuring low transmittance outside their passbands ().



**Figure 7: Transmittance of OADMs with standard filters (left) and ultrablocking filters (right)**

Currently available TFF based filter modules are specified mostly for operating temperatures between 0 °C to 70 °C. In order to apply these filters at non-weather protected locations such as RNs, extended operating temperature ranges will be required, which is primarily an issue for packaging. Filter modules that were tested were highly stable with wavelength drifts of < 2pm/K and a slight increase in terms of insertion loss at negative temperatures. It is expected that, in case of growing demand, advanced filter modules will be increasingly available for the extended temperature range between -33 °C and +85 °C.

## 2.3 Building Blocks

The building blocks of the proposed CWDM access network are:

- the *hub* at the central office, which handles all traffic between RNs and provides a gateway to the metro domain,
- the *RN* at the outside plant, which interconnects feeder and distribution area by means of fixed passive OADMs,
- the *ONU* at or close to the customer site, which connects several users per unit to a distribution ring.

These building blocks are described in detail in the following sections.

### 2.3.1 Hub design

The hub is located at the CO and processes all the traffic from the access rings. In addition, it presents a gateway towards the metro network domain. As shown in , the core element of the hub is a managed GbE switch with optical interfaces by means of CWDM SFPs. All CWDM channels are de/multiplexed by means of TFF MUX devices with up to 18 channels, where each CWDM channel addresses a dedicated remote node/ distribution ring. Each protected CWDM channel is terminated using a second SFP at the switch. To enable protection switching at Layer 2, the switch must support the respective protocol (see also section 1.1.1).

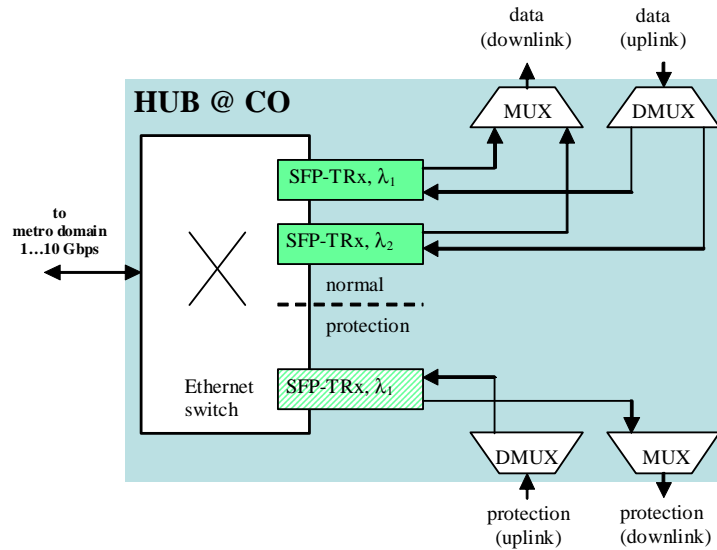


Figure 8: Hub node architecture

### 2.3.2 Remote node design

The RN connects the CWDM feeder ring and the single channel distribution rings. They consist of passive OADMs, which drop a defined wavelength onto the distribution ring in downstream direction and add the same wavelength to the feeder ring in upstream direction for data and protection path (see ).

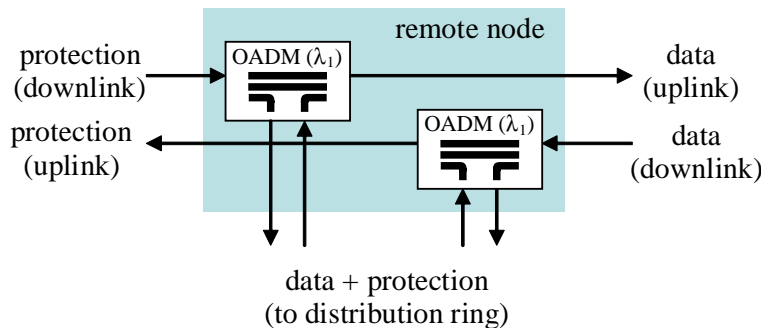


Figure 9: Remote node (RN) architecture

The add/drop function is achieved by means of two OADMs with fixed wavelength channels. Another option is to add/drop two or more wavelength channels onto several distribution rings at the same OADM. Compared to a single-channel OADM the insertion loss is only marginally increased. Consequently, the available power budget can be used more efficiently.

### 2.3.3 ONU design

The ONUs are located at or close to the customer premises (FttH, FttB, FttCab). They have two optical interfaces for the ring-like interconnection of several ONUs in a distribution ring.

Further Ethernet interfaces connect the users either directly or via other technologies (xDSL, Fixed Wireless) to the ONU.

The software development platform is based on Linux driven standard PC with 64bit PCI-X interfaces, hosting two GbE network interface cards with SFP slots for the distribution ring connections. Depending on the ONU location in the ring, the interface cards can be equipped either with coloured (CWDM) or grey transceivers. An onboard Ethernet interface (Fast Ethernet, GbE) is used to connect end users to the ONU, ().

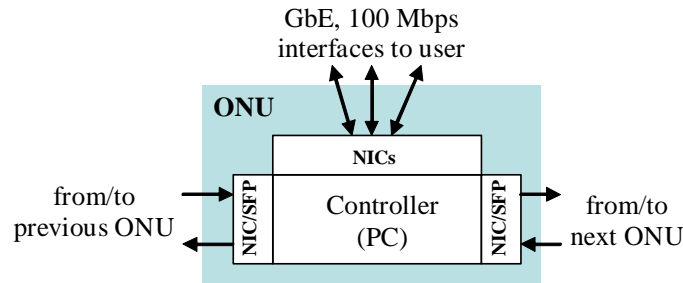


Figure 10: ONU architecture

To implement ONU functions like protection switching and user policing, a “click router” platform has been chosen. shows the block diagram of the implemented ONU software using the rapid spanning tree protocol (RSTP). Software modules for RSTP implementation have been provided by courtesy of Ghent University - IMEC.

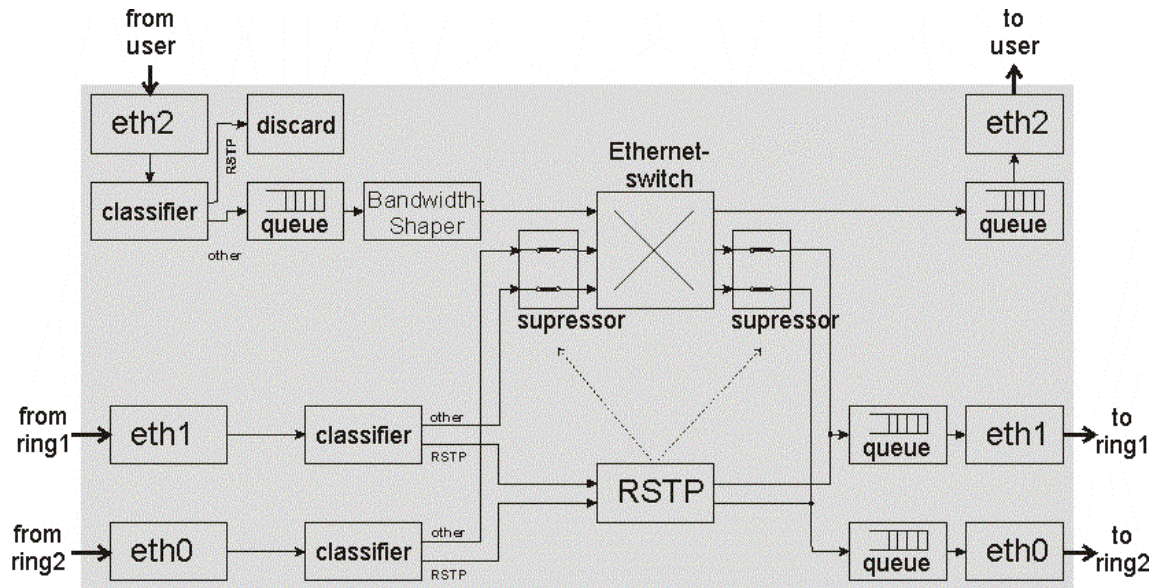


Figure 11: ONU software block diagram

The incoming packets are classified in two categories: RSTP and others. The *RSTP* packets are forwarded to the RSTP module, which implements a RSTP finite state machine. The

other packets go to the Ethernet Switch module. At the ingress and egress of the Switch modules so-called Suppressor-modules are passed through. These modules block certain paths depending on the RSTP status. Based on the RSTP configuration, packets for transit are passed to their corresponding queued output ports. At the user-input, two policing functions have been implemented. First, incoming packets are filtered with respect to RSTP BPDUs. These are filtered out to prevent a user-initiated reconfiguration of the ring. Second, users are connected to their ONU at a line rate of 100 Mb/s or even 1 Gb/s. To allow for an arbitrary maximum user bandwidth from zero to line rate, a BandwidthShaper module is used.

## 2.4 System considerations

### 2.4.1 Power budget

Transceivers to be used for the entire CWDM grid according to ITU-T [ii] as illustrated in are specified with an optical output power of  $> 0$  dBm ( $> 1$  mW). The maximum launched optical powers depend on the operating temperature but they are well below the limits defined in [iv] for laser class 1M in the FR (18 CWDM channels per fibre) and laser class 1 in the DRs (1 CWDM channel per fibre). Consequently, there is no need for safety measures like automatic power shutdown etc.

As shown in [v], the influence of chromatic dispersion is negligible at line rates  $< 2.5$  Gb/s and at fibre lengths  $< 40$  km. Thus, for target distances of 20 km, the CWDM system can be designed to be oriented solely to the power budget and the insertion loss of the components in the optical path. Key parameters are summarised in . It is assumed that each RN adds/drops two adjacent channels onto two DRs. To achieve an adequate ratio of insertion loss to coupling loss per device, RNs have to be inserted into the FR by splicing. The receiver sensitivity of  $< -27$  dBm @1.25 Gb/s results in an available loss budget of 27 dB.

Tx minimum launched optical power	0 dBm
OLT insertion loss (Mux, connectors)	2.6 dB
RN transit insertion loss (OADM, splices)	1.6 dB
RN add/drop insertion loss (OADM, splices)	1.2 dB
ONU insertion loss (connector)	0.5 dB
Receiver sensitivity @ 1.25 Gb/s, BER $10^{-9}$	-27 dBm

**Table 1: Key parameters for calculation of the power budget**

For a network scenario with 9 equally spaced RNs in a FR with 20 km circumference based on SSMF and ZWPF, the power margins are given in . Since a short working path implies a long protection path, the margins refer to the worst-case situation.

# of RNs to pass (working/ protection path)	1/9	2/8	3/7	4/6	5/5
Length of working/ protection path (km)	2/18	4/16	6/14	8/12	10/10
Used CWDM band (notation see )	C/L	S/C	O/L	E	E*
Max. SSMF attenuation (dB/km)	0.4	0.4	0.5	0.6**	1.0**
Max. ZWPF attenuation (dB/km)	0.3	0.4	0.47	0.4	0.4
Fibre independent insertion loss (dB)					
OLT (in CO)	2.6	2.6	2.6	2.6	2.6
RNs (in worst case path)	14.0	12.4	10.8	9.2	7.6
ONU (FR interface)	0.5	0.5	0.5	0.5	0.5
SSMF case					
Fibre loss of worst case path (dB)	7.2	6.4	7.0	7.2	8.0
Margin (@ loss budget 27 dB)	2.7	5.1	6.1	7.5	8.3
ZWPF case					
Fibre loss of worst case path (dB)	5.4	6.4	6.6	4.8	4.0
Margin (@ loss budget 27 dB)	4.5	5.1	6.5	9.9	12.3

\* Centre channels of E-band

\*\* Assumption, since not specified for SSMF; real value depends on manufacturer and date of production

**Table 2: Loss budget calculation using SSMF and ZWPF for a total FR length of 20 km and nine equidistant RNs in it, each with 2 add-drop ports**

As is also shown in [vi], margins of about 3 dB or more can be expected for the use of either SSMF or ZWPF. However, it is necessary to assign certain wavelength channels properly according to the RN position in the FR. In any case, the short wavelength channels should not be assigned to the longest path (first/ last node of the RN chain). In addition, channels in the OH-peak region of SSMF must be assigned to the shortest path, i.e. to the node in the centre position of the RN chain. More relaxed situations can be expected with smaller sized FRs: This is also the case when taking into account the real fibre attenuation since it is well below the measures given in the ITU-T Recommendations.

#### 2.4.2 Sharing of distribution ring bandwidth

The maximum number of users in a fully equipped network depends on the number of wavelength channels and users per wavelength channel. The developed solution uses 18  $\lambda$ -channels, where each CWDM channel carries a GbE signal. Assuming a 10% activity (ratio of simultaneously active users to total number of users) of average customers, up to 100 users can share a single DR for peak bit rates of 100 Mb/s. In such case, up to 1800 users (with average requirements) can be connected to the system. Moreover, a wide range of different customer demands can be satisfied, up to a dedicated wavelength channel e.g. for high-end application.

#### 2.4.3 Protection switching

Given that the network is structured with rings, each ONU can be reached by two disjoint paths. Therefore, a protection mechanism against link failure can be implemented by means of a Layer 2 protocol [vii]. There are several options, which can be divided into two groups.

The first one is based on the spanning tree approach and includes Spanning Tree Protocol (STP) [viii], Rapid Spanning Tree Protocol (RSTP) [ix] and proprietary vendor-specific solutions, e.g. [x]. Alternatively, the Resilient Packet Ring (RPR) can be used. A comparison of advantages and shortcomings is given in .

The RPR Standard [xi] is a new ring topology network architecture. It mandates a restoration time below 50 ms and supports different physical layers for point-to-point connections (like Ethernet or SONET/SDH). Since special chip-sets are necessary, an implementation in the framework of MUSE is too ambitious. In order to enable multi-vendor solutions, a standards compliant option is preferred, in which case RSTP is currently the fastest one.

It is expected that RSTP will allow for restoration times below two seconds, which seems to be acceptable for this purpose. Thus, the RSTP solution has been chosen for implementation. However, if real time media applications need to be perceived uninterrupted by the user, shorter restoration times in the order of 50 ms are desired. This issue will be addressed in the second phase of MUSE.

Tech nology	Restore Time	Node Limit	Com- plexity	Characteristics	Inter- opera- bility	Standard
RSTP	~1 - 3 s	31	Medium	Well-known Standard Root-centered spanning tree Designed for generic bridged networks	+	IEEE 802.1d (2004)
RPR	< 50 ms	255	High	Packet priority classes Fairness algorithm Multiple frame formats	+	IEEE 802.17
RFER	< 50ms	None	Not available	Builds on low cost Layer 2 Ethernet Optimal data and voice traffic multiplexing Designed for small-to-medium applications	-	Proprietary
Extreme Networks EAPS	50 - 1000 ms	None	Medium	Single-Master-Many-Slaves configuration Protects a group of data-carrying VLANs Uses a control VLAN for network management	0	Proprietary
Garrett S-Ring	200 – 2000 ms	50+	Medium	Optimizes STP for ring topologies Provides for ring auto-learning mechanism	+	Proprietary
Weed R208W	30 ms	200	Not available	Designed for Industrial Ethernets Resilient construction	-	Proprietary
Telco T-Metro	< 50 ms	50+	Not available	Designed for Triple Play over GbE	+	Proprietary

Table 3: Comparison of options for Layer 2 ring protection with Ethernet on the Link layer

## 2.5 Conclusions

The CWDM access network has been successfully set-up. Its feasibility has been proven using GbE channels throughout the entire CWDM band by means of commercially available components, which have potential to be low-cost in a volume market. The target feeder ring circumference of 20 km can be met using SSMF and/ or ZWPF (worst-case parameters) with suitable assignment of wavelength channels to the remote nodes. Considering typical fibre attenuation relaxes the needs for wavelength assignment, or significantly increases the power margin. Protection switching on Layer 2 is achieved by means of the standardized RSTP protocol. Initial tests show restoration delays of few seconds, and improvements are expected to some extent. Since real-time media applications may be more sophisticated, faster restoration will be addressed in MUSE II.

The next step is to prove the system using different wavelength clients. This will be performed in a joint lab-trial using VDSL<sub>o</sub> and Fixed Wireless Access systems, also developed in SPD.

### 3. CWDM VDSL00

VDSL is a technology designed to make optimum use of legacy access network architecture through reuse of the existing copper infrastructure, however in practice the useable bandwidth is heavily constrained by the copper loop length. Optical fibre is fully expected to penetrate into the access network and replace much of the access 'backbone' and ultimately achieve full penetration to the customer premises. This project aims to study the feasibility of carrying VDSL over a hybrid fibre/copper access network architecture that makes optimal reuse of the legacy network. By carrying VDSL directly over optics the technique forgoes the requirement to concentrate the subscriber lines on to a higher level carrier protocol such as ATM or SDH with the inevitable advantages in terms of capex, power consumption and heat dissipation in the access concentrators/distribution points.

The study will start with a P2P upgrade solution that considers FttC architecture and extend this to examine the impact of this technology on the full access network by also considering a CWDM solution both in a P2MP tree architecture and the deployment of fully protected and possibly optically switched ring architectures.

The work has a clear overlap with that described in deliverable DD2.2 covering the VDSL aspects, as such the reader is here referred to this document for further elaboration on some aspects of this work.

#### 3.1 DP Access concentration using sub carrier multiplexing

The first stage of the study examines the use of analogue sub carrier multiplexing of multiple VDSL signals for direct modulation of an inexpensive laser transmitter. The scheme applies identically in both upstream and downstream directions, whereby the VDSL signals for each of the downstream (i.e. from the CO OLT) and upstream (i.e. from the FttC DP ONU) directions are sub-carrier multiplexed onto their respective optical carriers.

The DP houses an access concentrator based on the up-shifting of the carrier frequency and subsequent multiplexing of each of the VDSL signals. The multiplex is used to directly modulate a VCSEL or similar low cost uncooled transmitter. The received signals are split and downshifted to re-generate the original VDSL signals, so providing a transparent optical path between the CPE modem and the CO DSLAM. As an additional consequence of this scheme, the VDSL modems will treat the optical path and all components as parts of the electronic link and will therefore automatically account for and accommodate any spectral deformations and modulation nonlinearities within its usual DMT handshaking process (i.e. the bit loading algorithm).

The signal bandwidth of a VDSL signal is less than 25MHz (depending on the bandwidth plan specified) and so, assuming 100% guard bands, 24 channels will occupy a maximum bandwidth of 1.25GHz. Typical modulation bandwidths available in VCSELs are in excess of 1GHz and some exceeding 2GHz.

The advantages of this technique are: readily deployable solution to FttX (not FttH) scenario using legacy type network architectures without the requirement for wide scale deployment of higher level packet/circuit switched network equipment. Also, the scheme employs low-cost and low powered equipment and simple electronics that are readily deployable in curb side distribution points. The scheme is also compatible with ATM switched optical access

networks as it provides a low capex means of delivering high bandwidth services between the DSLAM and the distribution point. Although VDSL has been mentioned throughout, there is no protocol dependence of the hardware and intelligent bandwidth allocation would enable the provision of multiple protocols over the optical links.

### 3.2 Sub-carrier multiplexing through concatenated discrete multitone modulation (super DMT)

Analogue sub-carrier multiplexing on to an optical carrier was described in the previous section and more extensively in deliverable DD2.2. This section extends this idea by introducing the concept we define as super DMT. Super DMT is essentially a DSP technique for combining the DMT signals from xDSL modems in a manner that uses many of the same DMT techniques. This allows for dynamic bit loading and bandwidth allocation to optimise the transmission of the signals over an impaired optical link.

shows the general schematic of the scheme. In particular it depicts the CPE modems each connected to the DP over a UTP connection. The SuDMT processor takes each signal, converts it to a digital signal stream suitable for input to the DSP processor. This Fourier transforms the signal and concatenates them prior to the IFFT and retransmission process. The output signal is then spectrally flat, even in the presence of prior bandwidth limitations such as those in the UTP. This output signal is used as a direct modulation signal to the semiconductor laser transmitter. The diagram shows the upstream path, but the downstream path operates in an identical manner and the scheme is fully capable of duplex transmission.

Some early models of the processes required for this technique have produced favourable results. In particular the models have demonstrated that the processing rates required for multiple xDSL signals are within the bounds of current technology and that the concatenated signal can be transmitted over very long distances of a non-bandwidth constrained link such as an optical fibre.

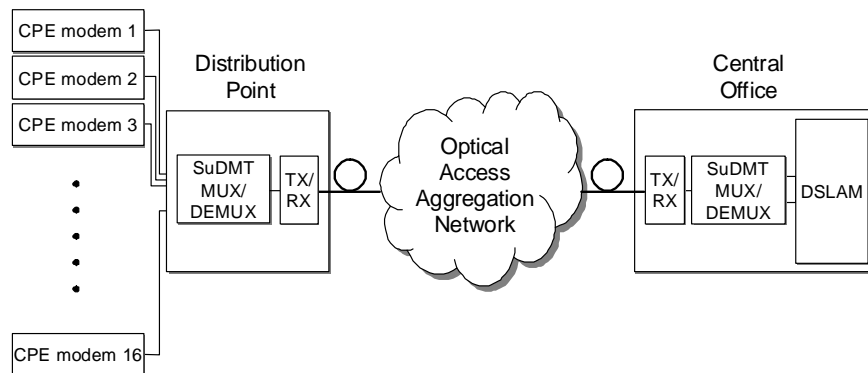


Figure 23: General schematic of the SuDMT transmission scheme

### 3.3 Evolution of the VDSL<sub>o</sub> solution to P2MP architectures

The generic definitions of the above schemes apply to the P2P architectures currently in existence. Evolution of the scheme depends on the upgrade strategies of the network operators and whether the deployment of fiber is a staged process. The bandwidth capabilities of VDSL and its' upgrades (VDSL2 etc.) are strictly limited to the length of the copper plant. In an FttC scenario, this may be only ~20m rendering upstream and downstream bandwidths of >100Mbps possible. An FttN approach may require copper lengths of several hundred meters, restricting the useable bandwidth to lower levels. The key issue of the VDSL<sub>o</sub> schemes described is their scalability in the optical domain, or how to extend the P2P legacy architecture to a P2MP approach.

#### CWDM Architectures

The CWDM standards were designed to provide an inexpensive solution to multichannel optical transmission; this is highly conducive to the general concept of optical access networks. depicts the typical structure of an optical access network with FttC optical penetration. The primary Feeder needs to accommodate typically 7000-10000 end users, this reduces to 200-500 for the secondary Feeder and 16 to 25 for the Feeder to the distribution point. After this, the architecture is assumed to be a mixture of UTP copper, coaxial cable, wireless and FttH.

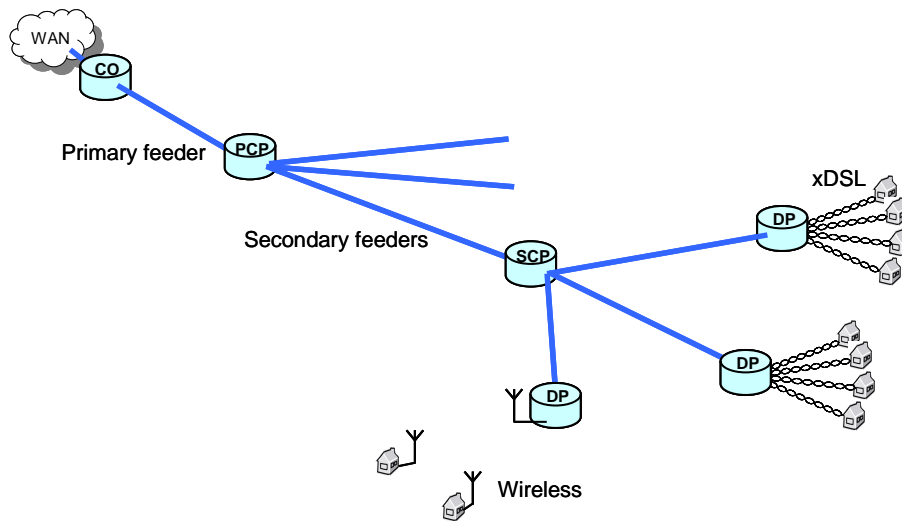


Figure 24: Point-to-multipoint access network architecture

The use of CWDM provides around 16-18 useable channels within the ~1300-1600nm optical window. Each channel being separated by 20nm being bracketed by 8nm guard bands to provide a useable 12-13nm optical window. This allows for the use of poor spectral quality optical sources (large linewidth, multiple mode, high chirp, etc.) so the use of inexpensive directly modulated uncooled VCSEL and FP lasers is now permitted.

One scenario is the tree structure depicted in . This shows the use of CWDM multiplexing for concentration in the secondary feeder part of the network with spatial division multiplexing in the primary feeder. CWDM mux/demuxes will be required in the secondary connection points. This architecture is highly efficient in terms of fibre and is suitable for optical duplex

as the upstream and downstream paths are passively identical. Loss will also be greatly reduced relative to the analogous passively split PON architectures.

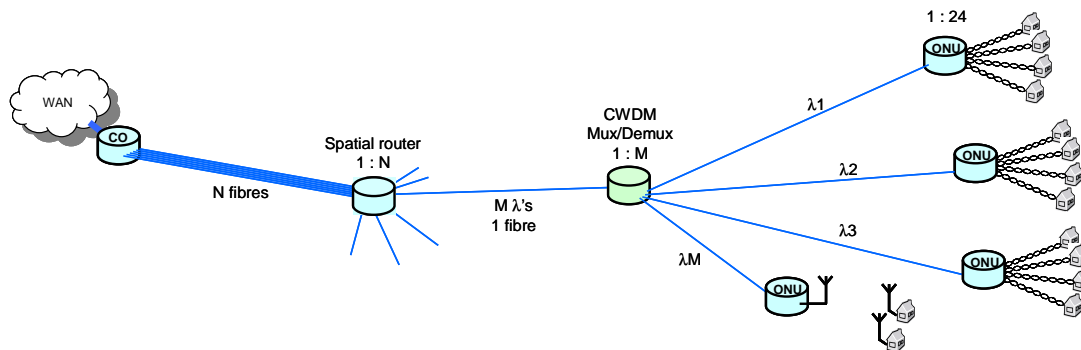


Figure 25: CWDM tree structure

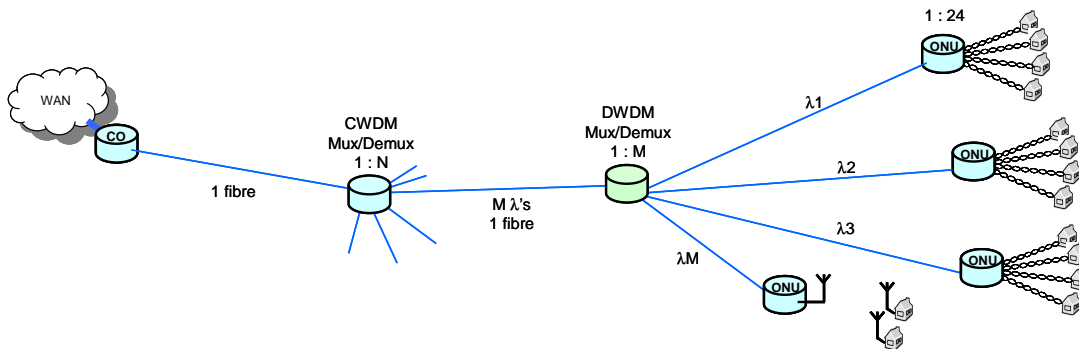
The scenario above permits a total of  $24 \times M \times N$  end users from the head office. If we assume 18 CWDM wavelengths and a 24 fibre bundle in the primary feeder this equates to a total of 10,368 VDSLs from the central office. At the central office, we expect 18 CWDM channels per access multiplexer card which, with the expected high packing density of VCSELs, is a feasible solution. To re-iterate on an earlier statement, the PHY layer assumed here is not protocol dependent so non xDSL signals can be packed with equal efficacy.

We anticipate the expected impairments of CWDM and VDSL<sub>o</sub>O, particularly the water peak loss at  $\sim 1400\text{nm}$ , the availability of transmitters across the full CWDM spectrum, the spectrally dependent impairments such as group velocity dispersion and the component performance impairments such as spectral deformations and modulation nonlinearity.

#### Hybrid C/DWDM

A further architecture that has received some interest is the combination of the Dense and Coarse WDM architectures as a method or further extending the capacity of the available fibre.

The available 12 nm bandwidth of each CWDM channel allocation can, using suitable transmitters, be sub-divided into smaller channel frequency allocations, say with a 100 or 200GHz channel separation. This enables a potential 10 to 20 fold increase in the number of channels that can be transmitted over a single fibre, see .



**Figure 26: Hybrid D/CWDM architecture**

The generic architecture uses a CWDM mux/demux in the primary connection point and a DWDM mux/demux in the secondary connection point, providing a total of (see diagram)  $N \times M \times 24$  SLs with a single fibre in the primary feeder. Considerations of particular importance in this scenario are transmitter stability requirements leading to increased transponder expense and potentially higher power requirements if cooling is necessary. Also of consideration is the effect of the large optical power delivered from/to the central office leading to stimulated Raman scattering crosstalk (SRS). Other nonlinear penalties are not expected to be significant due to the relatively low per-channel power and broad spectral spacing.

#### *Ring architectures*

The above architectures are based on a linear star approach, but the general philosophy behind their design is equally applicable to ring network architectures. Rings offer the potential of protection and intelligent routing at the expense of increased capacity redundancy. Again, the use of rings can be applied to DWDM, CWDM and even hybrid C/DWDM. The structure shown in depicts ring-equivalent architecture to the tree structure of .

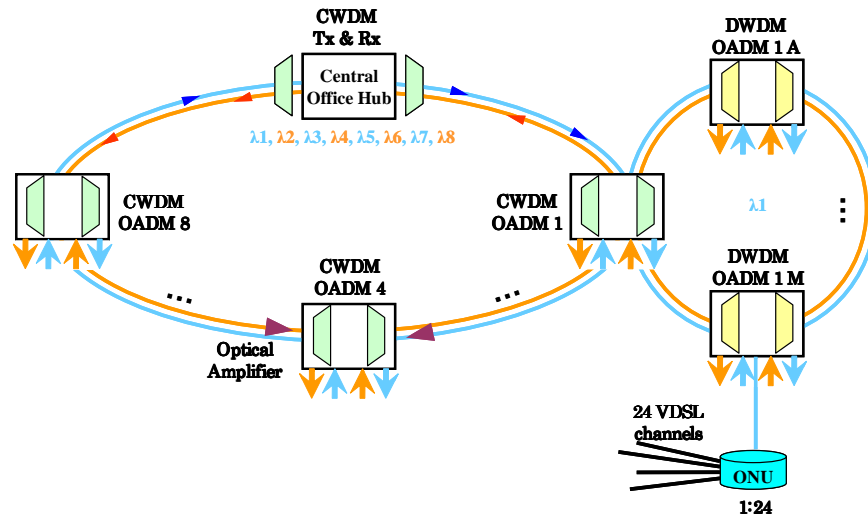


Figure 27: Hybrid C/DWDM ring network architecture featuring 8 CWDM channels, M DWDM channels in every CWDM channel and 24 VDSL channels in every DWDM channel

### 3.4 Economic evaluation

Cost considerations are paramount for successful access network evolution and future wide scale broadband rollout. As such this is one of the key drivers to the technology we have proposed in this document. The philosophy of the approach is to minimise the cost and complexity of the network (AGN and CO) equipment, to reuse as much legacy infrastructure as possible (UTPs etc), whilst maintaining a viable upgrade evolution path, and to comply with the requirements for a fully passive optical PHY layer. The advantages of VDSL with reuse of existing copper infrastructures were demonstrated in section 3. Apart from minimising the AGN and CO costs, also the remote power requirements can be lowered with this solution.

### 3.5 Latest results

#### 3.5.1 AWG based network architecture

Extended investigation was carried out to study the optical transmission characteristics of the sub-carrier multiplexed VDSL channel over an AWG-based access network, as shown in Figure 28. Two different VDSL bandplans, a China band-plan that offers 37/30Mbps downstream/upstream and a 998 bandplan that offers 67/40Mbps transmission rates [1], were investigated on the test-bed.

The core network of the system was based in a cascaded format of AWGs, consisting of both NxN and 1xN passive devices interconnected with single mode fibre. Two ITU-standard wavelengths (1545.39 and 1545.7 nm) were used at the central office for downstream transmission, while the same were used at the ONUs for the upstream transmission.

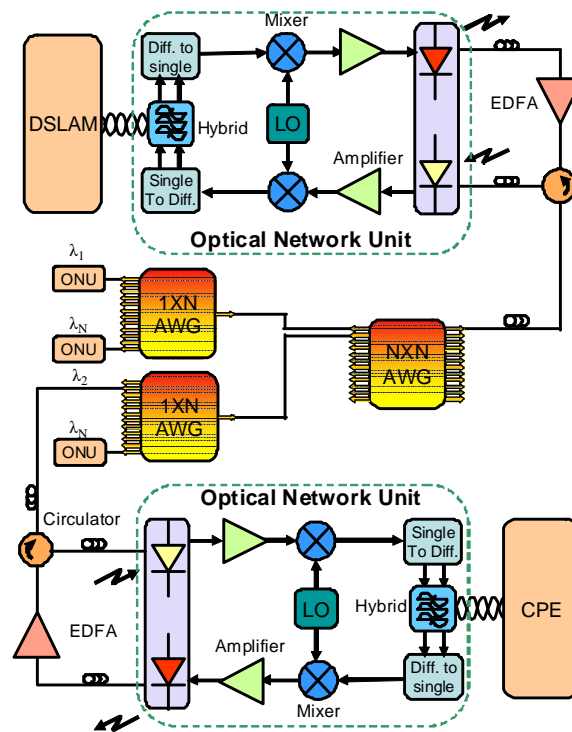


Figure 28: Block diagram for baseline optical transmission

A 16x16 AWG, with 100GHz channel spacing and 9dB insertion loss was used in the central office. Different passive 1x16 AWGs with identical channel spacing and 4.5dB insertion loss were placed at the distribution points. All AWGs had channel isolation greater than 25dB. 32 wavelengths could be simultaneously transmitted from the CO exploiting the free-spectral range (FSR) of all the AWGs. Thus an overall of 12,288 users (24 VDSL channels, 32 wavelengths, and 16 distribution points) can be simultaneously addressed.

Two sets of CO and CPE VDSL modems (both QAM and DMT based) were used to achieve two different sets of upstream and downstream signals, for two different wavelength ports utilization at the input of the 16x16 AWG. The OLT at the CO consists of the low-power sub-carrier multiplexer, CO modem and the 16x16 AWG. Each distribution point consisted of one 1x16 AWG, which in turn was connected to an ONU. The ONU is identical to the OLT except for the CPE modem. Multiple modems can be used depending on the guard band allocation, filter characteristic and the bandwidth available with each laser-photodiode pair.

In any chosen bandplan, the peak-to-peak voltage of the baseband VDSL signal was just under 3V. The baseband electrical spectral bandwidth of the China bandplan was 8.5 MHz; deployed as 138 kHz-3.75 MHz downstream and 3.75-8.5MHz upstream. For the 998 bandplan, the bandwidth was 12 MHz, where downstream occupied the 138 kHz-3.75 MHz and 5.2-8.5 MHz windows, whilst the upstream occupied 3.75-5.2 MHz and 8.5-12.0 MHz. Directly-modulated DFB lasers were used with the sub-carrier multiplexed VDSL channels. Bidirectional optical transmission was achieved using the same wavelength for upstream and downstream channels and three-port circulators. Previous experiments have demonstrated loss of ~0.3dB due to crosstalk for simultaneous downstream and upstream transmission [2].

This setup offered the opportunity to establish a point-to-point optical link to each ONU on a different wavelength on each DP AWG. As the total usable bandwidth of each ONU was 1.5 GHz, the total number of double sideband upconverted VDSL channels that can be transmitted is 24 with each allocated with 50MHz of space. For VDSL2 standard 30 MHz bandwidth signal, 15 channels can be transmitted. The up-converted China bandplan VDSL signal was transmitted with both the side-bands, having a bandwidth of 17 MHz for the upstream and 8.5 MHz for the downstream channel. In this experiment, the VDSL signals were up-converted with carrier signals of frequencies 50MHz and 120 MHz on both optical channels. The third harmonic levels were at least 15 dB below the signal spectrum, as shown in . More than 15dB signal-to-noise ratio was achieved for both VDSL channels in electrical domain measurements, for simultaneous downstream and upstream transmissions. The total penalty in the AWG network was approximately 1.2dB [2], which proved to be acceptable for VDSL transmission.

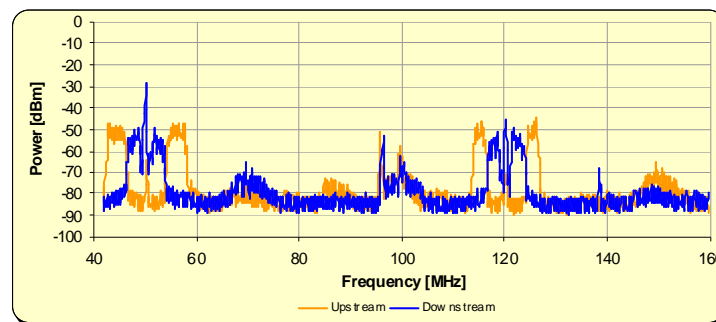


Figure 29: Subcarrier China bandplan VDSL upstream-downstream at 50MHz & 120MHz, for a single wavelength

### 3.5.2 AWG-based network performance

Real time audio and video were successfully transmitted using multimedia desktops. This successful transmission of combined spectra consisting of two subcarrier-modulated VDSL channels shows that the system is capable of transmitting multiple channels of VDSL signals using subcarrier multiplexing. The compensation action of VDSL modem mitigates the impairments introduced by non-linear optoelectronic components additional to cable characteristics. Data rates were measured at the connected end computers and there were no packet or frame losses (TCP/IP) in the bidirectional link. The total SNR degradation is 16dB for both up/downstream signals. It can be seen that the SNR is >15dB. In , showing the China bandplan, the third harmonic, present at 150MHz, was found to be 25dB below the signal. It has been shown [3, 4] that composite triple beat (CTB) products on optical link are not an issue and with optimum optical transmission power for different wavelengths this system can be scaled for multiple VDSL channels.

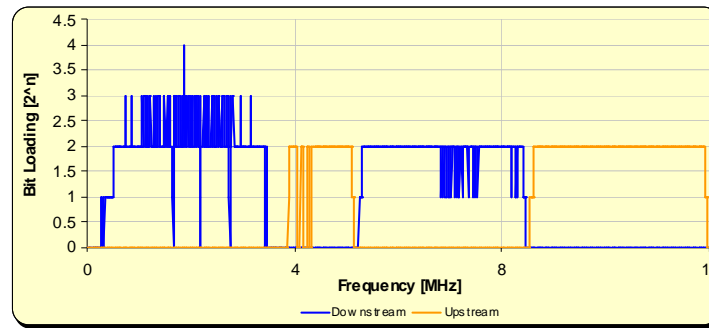


Figure 30: Bit-loading curve for 12 MHz bandplan 998

The SNR required for optical transmission of DMT-based VDSL signal was found to be 10-15dB more than that required for direct transmission on UTP [5]. Data rates achieved for China and 998 band plans were 15.7/13.8Mbps and 36.2/22Mbps respectively, for one VDSL channel. Thus, the efficiency of one VDSL channel was ~42/46% and ~54/55% for China and 998 bandplans, respectively. The bit-loading curve for the hybrid copper/optical network can be seen in . Maximum bits allocated to the DMT tones were 4 (compared to 12 which can be achieved on a back-to-back connected modem link). Also in , an up-converted double sideband plan 998 VDSL channel is shown. The SNR is >30dB at 250MHz. Due to the non-linear mixer, the SNR degrades as the subcarrier frequency approaches 800MHz.

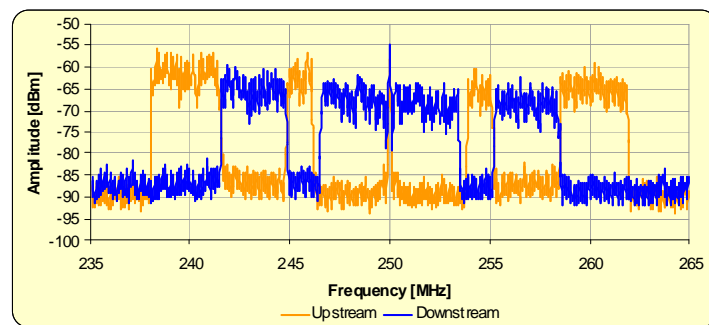


Figure 31: Upconverted VDSL spectrum for 12 MHz bandplan 998

### 3.6 Conclusions

The reader is referred also to deliverable DD2.2 where, due to the considerable VDSL content of this work, many aspects of the system have been described. Lab trials of the system are running in Q4 2005 and results of physical layer measurements as well as interoperability measurements with other projects within the SPD framework will be presented.

### 3.7 References

- [1] R. Sekar, "VDSL2: Single worldwide VDSL standard for delivery of triple-play services over copper," Ikanos Communications, Inc (2005)

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## 4. SUB-CARRIER MULTIPLEXING

### 4.1 Introduction

In Deliverable D2.1 the SCM technology has been described. In MD2.2 the first designs and considerations were presented. In this Deliverable the first designs and first measurement results of the prototype are described.

Multimode optical fibre provides a cost-reducing alternative for the commonly used single-mode fibre. Multimode fibre is easier to install than single-mode fibre with its tiny core: due to its larger core diameter, the coupling of light from a light source into the fibre and the (fixed or demountable) splicing of fibres together is easier. In particular in the access network, this may yield considerable reduction of installation costs.

The subcarrier multiplexing (SCM) technology is specifically aimed at the last mile of FttH. It is a technology to bypass the bandwidth limitation of MMF. The baseband-bandwidth of MMF fibre is rather limited; conventional MMF has a bandwidth times distance bandwidth of only 500Mhz\*km. However, there are also other parts of the fibre, beyond baseband suitable for transmission. The transfer characteristic of MMF does not steadily decay to zero, but there are relative flat parts of the fibre with an additional loss compared to baseband of maximum 3dB, which are very suitable for transmission by means of SCM. In Phase I the emphasis will be on a point-to-point architecture, where the subcarriers can be used for different services e.g. one for data, one for video etc. The subcarriers could also be used for fibre unbundling, e.g. a different subcarrier for every operator. Another possibility is to increase the capacity of the fibre. The proposed architecture is displayed in Figure 41. In Phase II of MUSE the system will be upgraded to a point to Multipoint architecture.

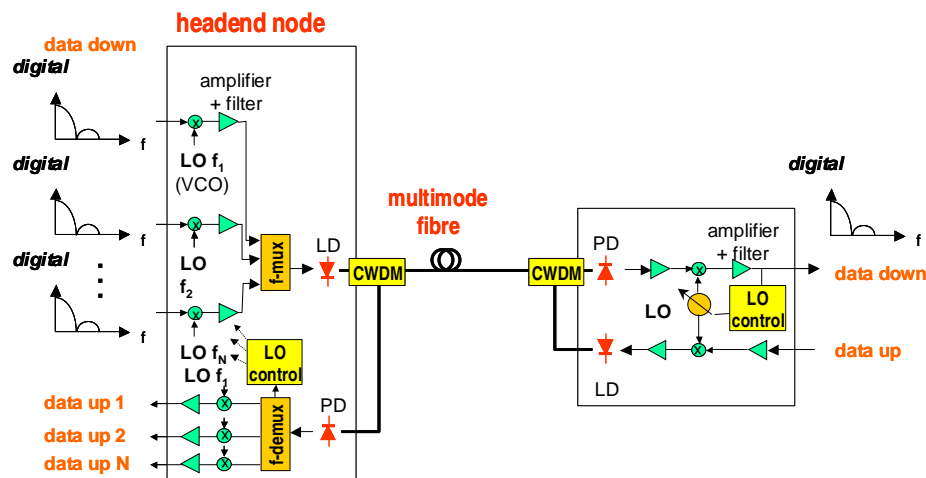


Figure 41 : SCM point to point architecture

The aim is to prove the technical feasibility of SCM and to develop a system that is ready for integrated tests at the beginning of Phase II. The emphasis will be on the design of the electronics. A major objective of the system design is to implement adaptive channel allocation. This puts special requirements on the transmitter (i.e. carriers should be dynamically adjustable, no filtering possible) and on the receiver (i.e. tuning of the receiver, channel selection).

## 4.2 Design of SCM prototype

### 4.2.1 Transmitter

In order to prove that the system is capable of handling several carriers, the transmitter should have at least 2 carriers. The basic schematic of the transmitter with 2 carriers is displayed in Figure 42. For the transmitter every component can be dedicated, i.e. the components can be relative narrowband. These components are commercially available. The transmitter is fed with a bit stream in BPSK format (aim: 1GbE). A local oscillator up converts this bit stream. The VCO should be tuneable over at least 500MHz for dynamic frequency allocation, in order to avoid (possible) large dips in the bandpass characteristics. The carrier frequency will be reinjected in order to ease the carrier recovery in the receiver for downconversion and to monitor the passband characteristic while operating the system. After suitable amplification the resulting signal will directly modulate a laser source.

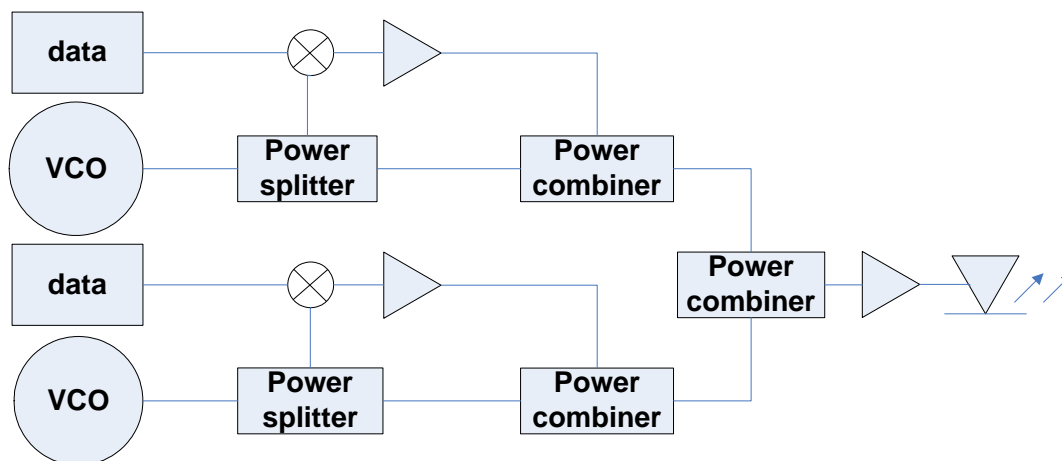


Figure 42: basic schematic of transmitter

### 4.2.2 Receiver

The basic receiver scheme is displayed in Figure 43. The receiver consists of a photodiode, some suitable amplification, a recovery circuit for the carrier (PLL), a downconversion stage and a baseband receiver. The receiver should preferably be able to receive all carrier frequencies. This means that all components should be capable of operating over the entire frequency range. A VCO with a tuning range of more than 1Ghz in the 1-5 Ghz range is unavailable. There are several options to bypass this limitation. The first and easiest solution is to design a receiver with several dedicated VCO's for every subcarrier. For a system with two carriers this is realisable, but if there are more carriers included this becomes quite costly. Therefore a solution as proposed in Figure 44 will be investigated.

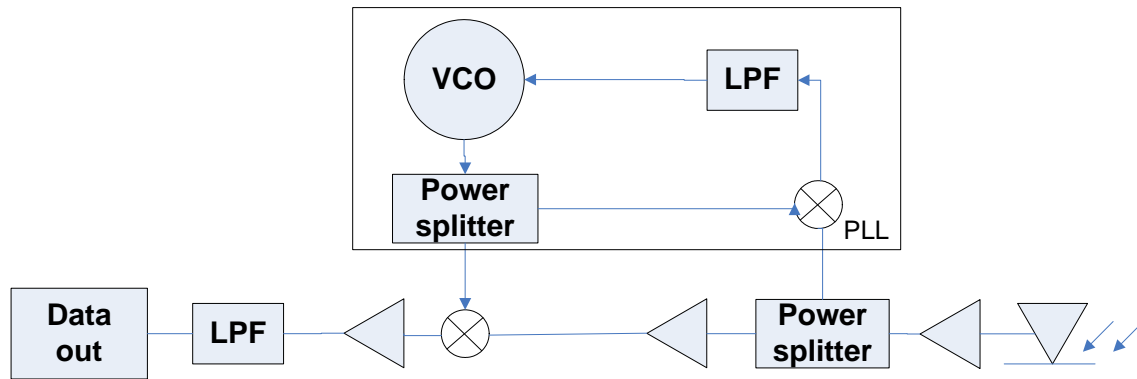


Figure 43: basic schematic of the receiver

In the setup displayed in Figure 44 a VCO with large tuning range is created by mixing the signals from 2 VCO's. One VCO is running at a fixed frequency, in this setup at 8 Ghz (VCO2). The other VCO can be tuned from 4-8Ghz (VCO1). By filtering the sum frequencies this results in a frequency range of 0-4Ghz, which is required to receive both carriers in our setup. This setup requires further study. The feasibility of this setup still has to be shown.

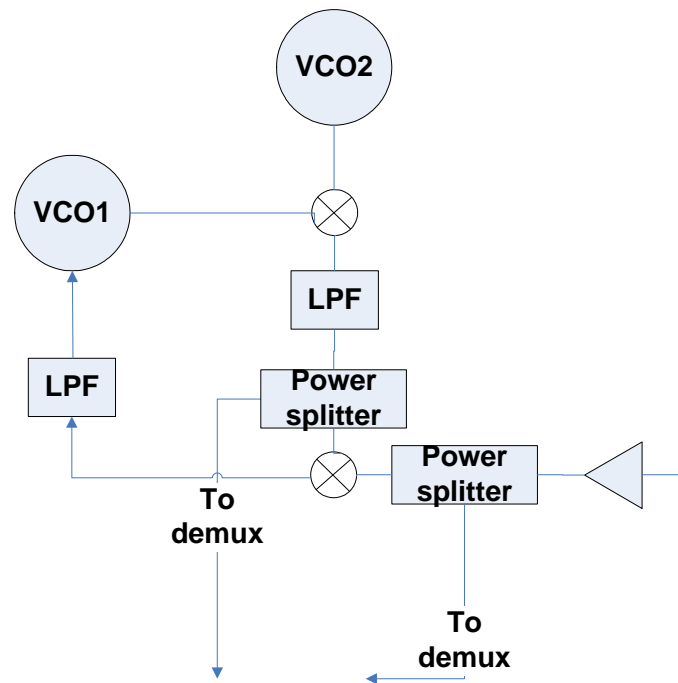


Figure 44: creation of VCO with large tuning range

### 4.3 Testing of SCM prototype

#### 4.3.1 Testing of electronics

In Figure 45 the test setup of the electronic part is displayed. VCO1 can be tuned from 900-1500Mhz. VCO2 can be tuned from 2.2-2.8Ghz. In the transmitter it appeared to be very important to match the cable length between the data signal and the reinjected carrier, otherwise the power level of the reinjected carrier varied with frequency (due to phase difference). The carrier was attenuated by 23dB before combining the signal with the data stream. A  $2^7-1$  PRBS bitstream was used for the experiments. The setup was built up with discrete components.

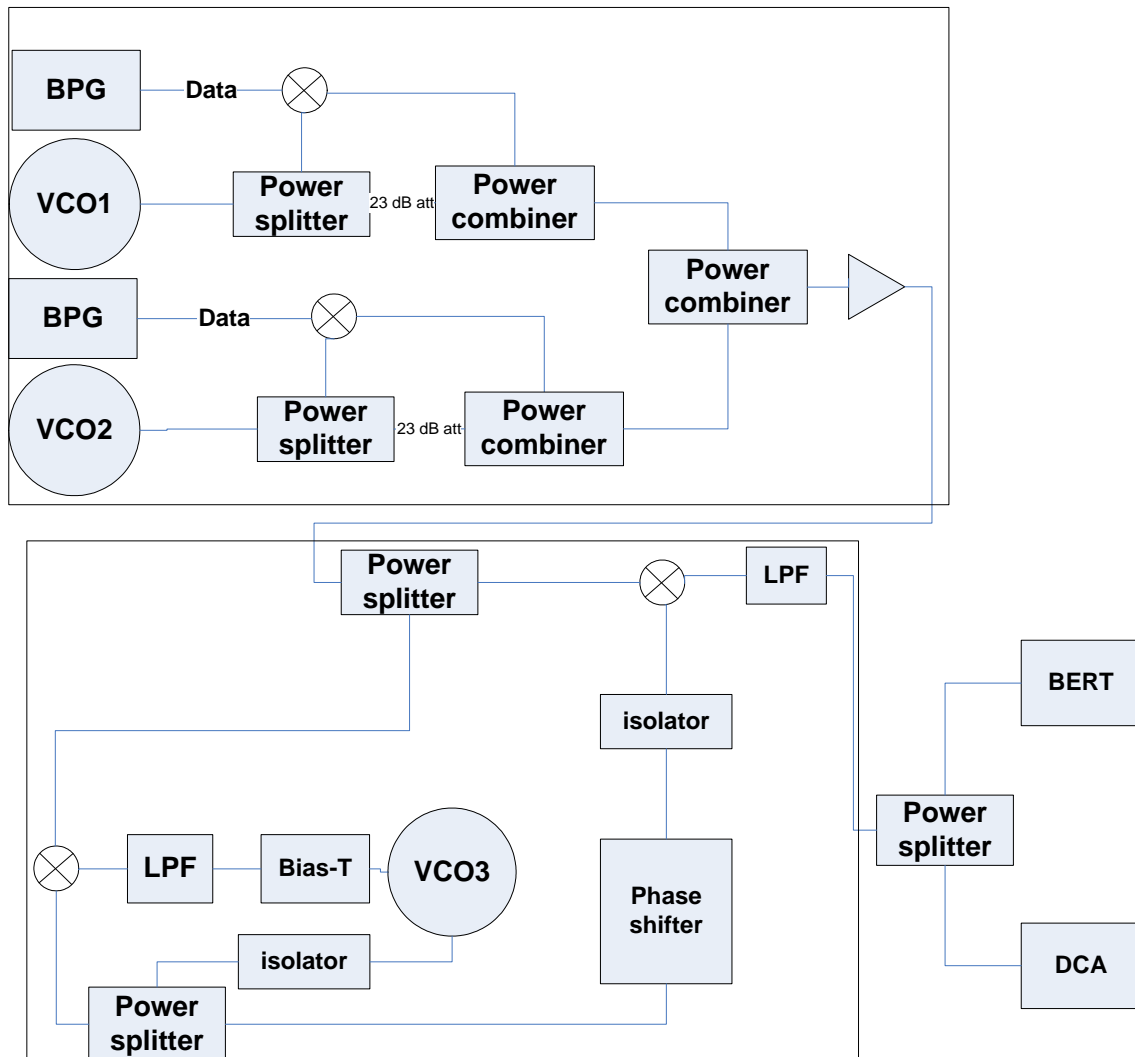


Figure 45: SCM prototype electronic part

The receiver has two major differences compared to the original design. The most important difference is the introduction of a phase shifter. Early tests showed that it was mandatory to include a phase shifter. Although the phase is well known at the output of the PLL, the cable

length between the output of the PLL and the mixer for the downconversion introduces a difference in phase for different frequencies. Since the phase is very important for correct downconversion the phase shifter was introduced. The second difference compared to the early design is the introduction of 2 isolators. The VCO in the PLL became sometimes unstable when it almost locked. By including 2 isolators this problem was solved. The receiver as displayed in Figure 45 is only capable of receiving one of the carriers. In order to receive the other carrier the VCO in the receiver has to be replaced. In Table 7 and Table 8 The measurements of the electronics part are given. The system was both tested for 450Mb/s and for 1Gb/s. Since the performance for 450Mb/s and for 1Gb/s was the same, they are combined in one table. From these measurements it can be observed that the electronics parts operates error free. When the carriers were spaced closest to each other, for the 1Gb/s measurements a very small eye penalty could be observed. It was also observed that the dynamic range of the PLL was limited to 8-13dB (depending on frequency used). This means that for the measurements with the optical part (with large dynamic range) the signal into the PLL has to be controlled, otherwise the PLL goes out of lock, resulting in poor performance.

Load carrier	2.2Ghz	2.5Ghz	2.8Ghz
Test carrier			
1.00Ghz	<10 <sup>-12</sup>	<10 <sup>-12</sup>	<10 <sup>-12</sup>
1.25Ghz	<10 <sup>-12</sup>	<10 <sup>-12</sup>	<10 <sup>-12</sup>
1.50Ghz	<10 <sup>-12</sup>	<10 <sup>-12</sup>	<10 <sup>-12</sup>

Table 7: measurements on 1Ghz carrier for 450Mb/s and 1 Gb/s

Load carrier	2.2Ghz	2.5Ghz	2.8Ghz
Test carrier			
1.00Ghz	<10 <sup>-12</sup>	<10 <sup>-12</sup>	<10 <sup>-12</sup>
1.25Ghz	<10 <sup>-12</sup>	<10 <sup>-12</sup>	<10 <sup>-12</sup>
1.50Ghz	<10 <sup>-12</sup>	<10 <sup>-12</sup>	<10 <sup>-12</sup>

Table 8: measurements on 2.5 Ghz carrier for 450Mb/s and 1 Gb/s

#### 4.3.2 Testing SCM prototype with optical path included

In Figure 46 the test setup for the SCM prototype with the optical path included is displayed. The electronic part is exactly the same as displayed in Figure 45. As laser transmitter an already available DFB laser diode was used. The 3dB bandwidth of this laser was 3Ghz, which is actually too small for our application. The output power of the laser is 3dBm. A new DFB laser diode with 3dB bandwidth of 8Ghz has been ordered, but delivery is not expected before mid October. The photodiode used in this setup is a New-focus laboratory measurement photo-diode. The fiber included in the measurements is GI-MMF.

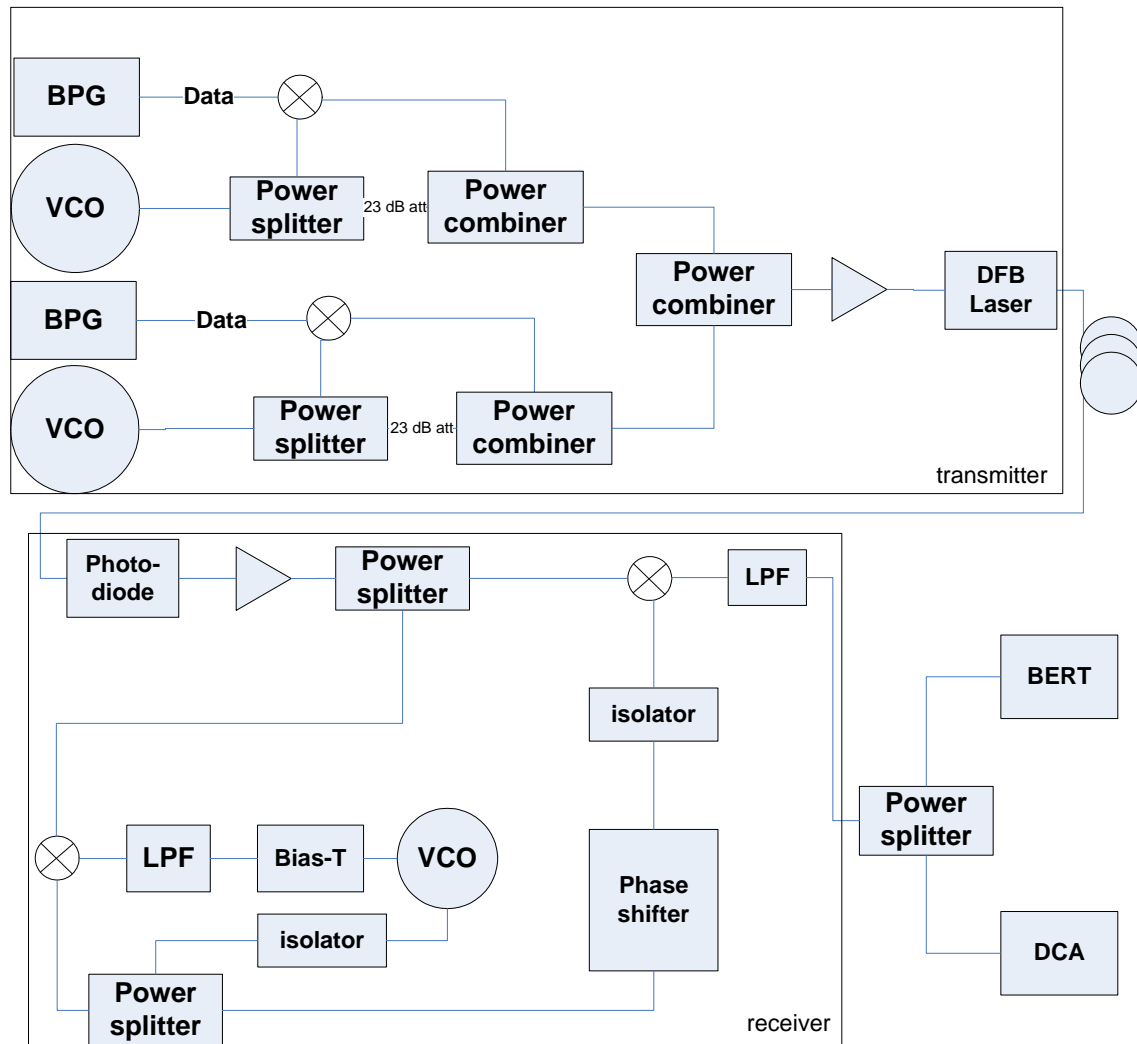


Figure 46: SCM prototype with optical path included

In Figure 47 and Figure 48 single carrier measurements with the optical path included for 450Mb/s and 1Gb/s datarate are displayed. Measurements are executed with no fiber included, 750m of fibre included and 4.4km of fibre included. The measurements are executed for a 2.2Ghz carrier and a 2.8Ghz carrier. As can be observed from the measurements, the degradation due to the fiber in the system is less than 1dB. It was also observed that for higher power levels, the performance degraded. This was due to the fact that the power level into the receiver became too large. By introducing electrical attenuation, error free transmission could be obtained for higher optical power levels.

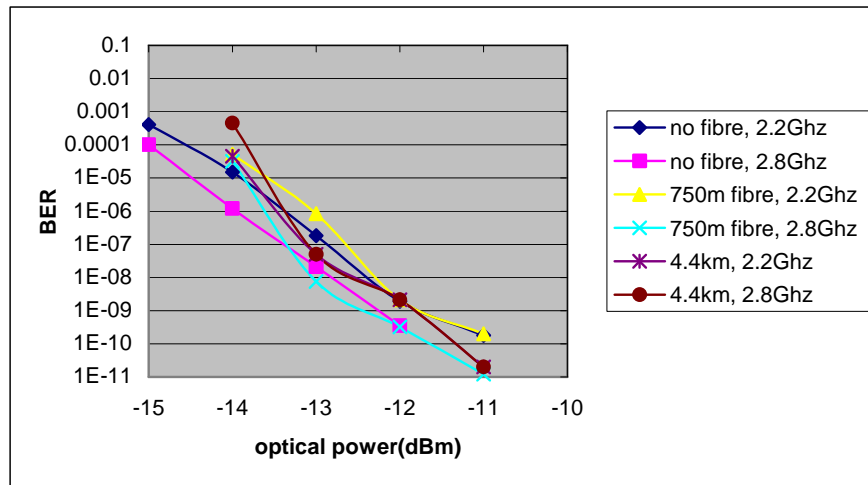


Figure 47: 450Mb/s measurements with optical path included (single carrier)

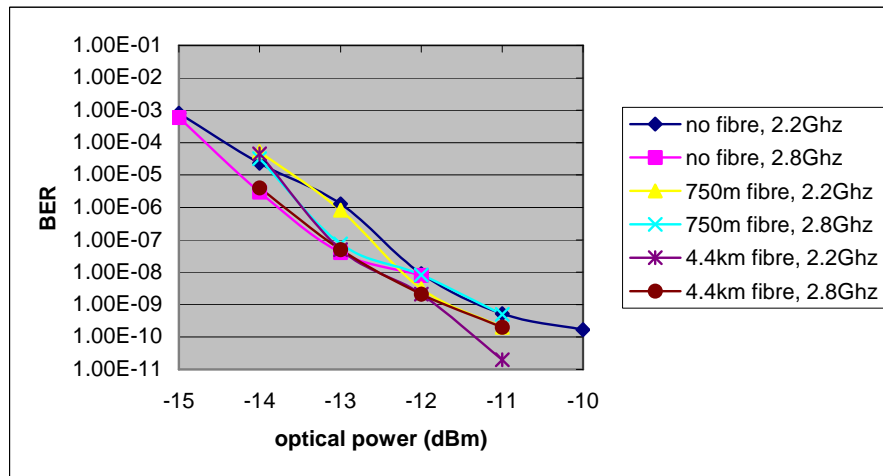


Figure 48: 1Gb/s measurements with optical path included (single carrier)

In Figure 49 and Figure 50 the measurements with 2 carriers present are given with the optical path included for 450Mb/s and 1Gb/s datarate are displayed. Measurements are executed with no fiber included, 750m of fibre included and 4.4km of fibre included. The measurements are executed for a 2.2Ghz carrier and a 2.8Ghz carrier. As can be observed from the measurements, the degradation due to the fiber in the system is less than 1dB

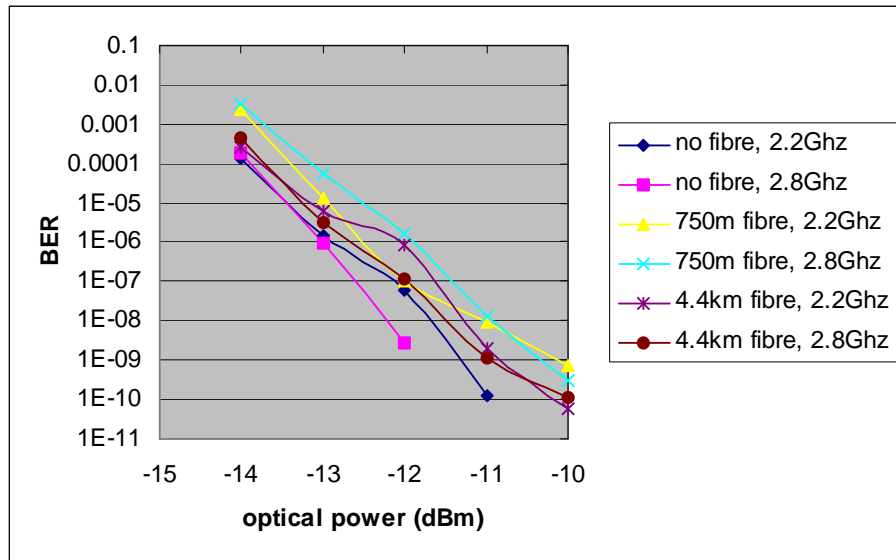


Figure 49: 450Mb/s measurements with optical path included and load carrier at 1 GHz

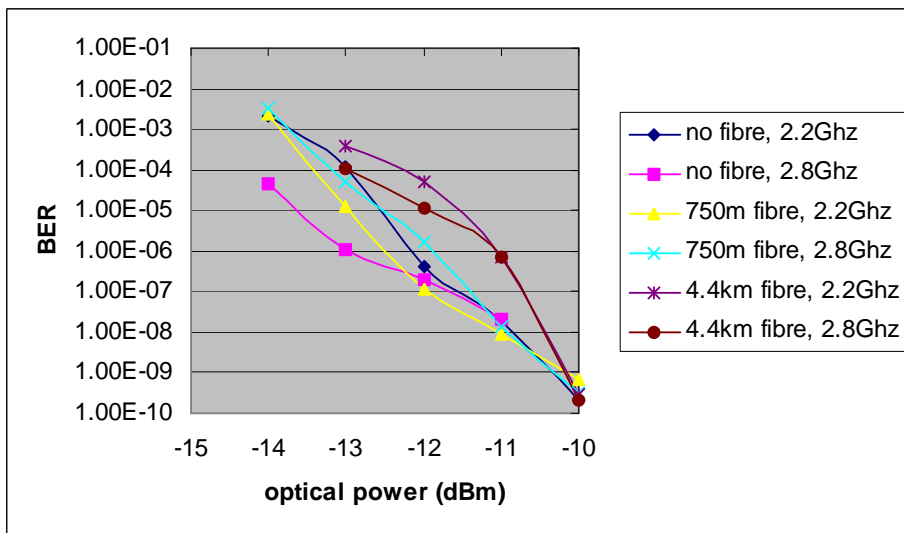


Figure 50: 1Gb/s measurements with optical path included and load carrier at 1 GHz

In Figure 51 a comparison is made between the measurements with and without a load carrier in the case of 750m of fibre and 1Gb/s datastream. It can be observed that there is about 1 dB penalty introduced by introducing a load carrier.

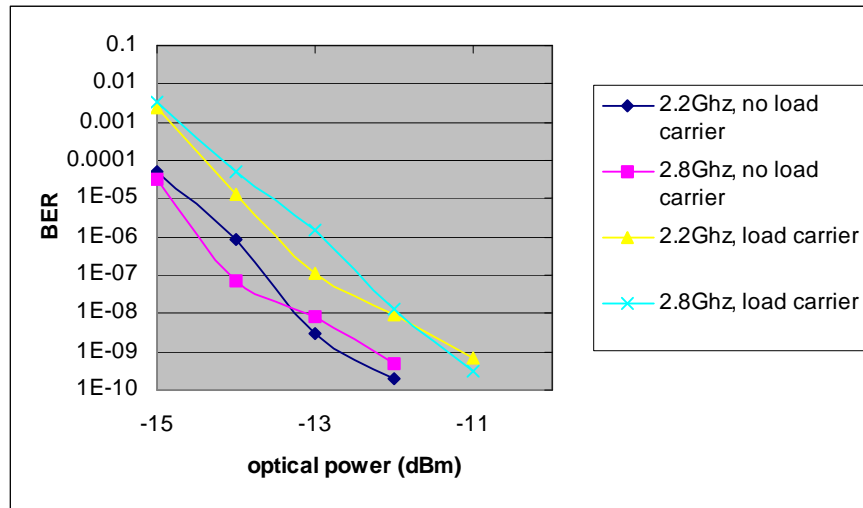


Figure 51: BER comparison with and without load carrier for 750m fibre and 1Gb/s data

#### 4.3.3 Testing of the broadband receiver

The receiver required to receive both carriers is displayed in Figure 52. First measurements on this receiver showed that the principal operation works, i.e. the receiver can lock both carriers, but that the stability of this receiver at this moment is insufficient. The two main issues with this setup are the reduced tuning sensitivity of the VCO's compared to the previous setup and temperature stability. In the previous setup the tuning range was 600Mhz/10V or 60Mhz/V. The VCO1 in this setup has a tuning range of 4Ghz/15V or 266Mhz/V. This makes it more difficult to correctly set the frequency in the PLL. The second issue is the temperature drift of the VCO's, which has a maximum value of 150Mhz (compared to 10Mhz of the VCO's in the previous setup. In order to solve this problem, the VCO1 was replaced by the VCO used in the previous experiments, and set to a frequency 2.8GHz. Since this VCO has a better tuning sensitivity and a better temperature stability this will improve the performance. VCO2 was replaced by the VCO tunable over 4-8Ghz. This results in a possible frequency range of 1.2-5.2Ghz. VCO2 is now used to set the frequency. This resulted in a stable setup.. It was possible to do system measurements on the electronics. It was possible to receive both carrier frequencies error free ( $BER < 10^{-12}$ ). The feasibility of the broadband receiver was shown. The next step is to include the optical path.

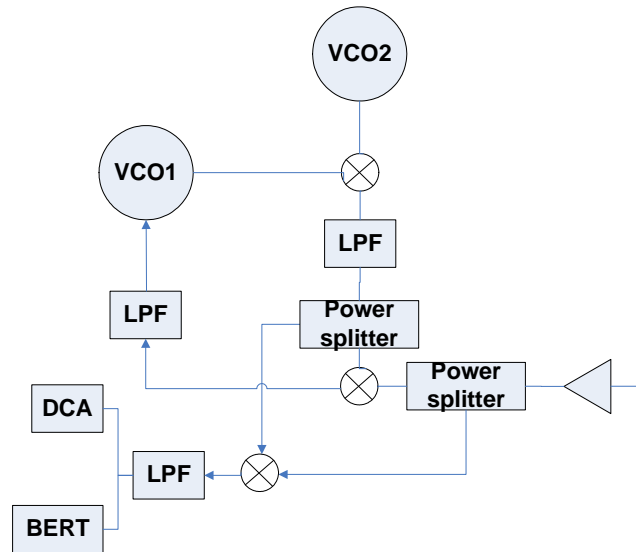


Figure 52: broadband receiver

#### 4.4 Conclusion and recommendations

The electronics of the SCM prototype is working correctly. The carriers in the transmitter can be adapted dynamically over 500Mhz, which was one of the objectives. A system with 2 subcarriers, both modulated with 1Gb/s of data was experimentally proven to be feasible. One major issue identified in the experimental setup was the influence of phase variation due too cable length for different frequencies. It was hence required to insert a phase shifter in the receiver. It is therefore recommended to Implement the transmitter and receiver on a PCB so no cables are used anymore and the phase shifter is no longer required. Phase should be one of the major design parameters.

Including the optical part in the system did not cause serious issues. Both for 750m and 4.4 km a BER < 10<sup>-9</sup> could be obtained. So it can be concluded that the technical feasibility of the system was proven. There are however a few improvements possible. The dynamic range of the PLL is currently limited. This means only a limited optical power range can be handled without inserting electrical attenuation / amplification in the receiver. Also the sensitivity can still be improved. The amplifiers used in the receiver are general propose, broadband amplifiers (18Ghz bandwidth). Moreover, the photodiode currently used has a bandwidth of 18Ghz. Since the bandwidth of the amplifier and photodiode is very large, unnecessary noise is introduced in the system. The bandwidth of the laser used in the experiments is too small. A newly order laser with a wider bandwidth should improve the performance of the system.

The broadband receiver is stable enough to include in system experiments. Error free measurements on the electronics were performed on both carriers. The feasibility of the broadband receiver was shown. The next step is to include the optical path in the setup.

## 5. CONCLUSIONS

MUSE subproject D addresses new high-speed technologies for future broadband access services. In this deliverable, the results of the different studies on optical access technologies were addressed. To capture the main outcome of these studies, the following conclusions can be drawn.

The **VDSL over Optics** lab trials in cooperation with HHI and Tue will take place in Berlin in late October. The final results will be added to the document in mid November. Currently, the system incorporating a single VDSL channel has been working perfectly. For demonstrating purposes, 4 VDSL channel system will be available using local clock sources and transmission will be performed through the ring network HHI has built.

The **CWDM access** network has been successfully set-up. Its feasibility has been proven using GbE channels throughout the entire CWDM band by means of commercially available components, which have potential to be low-cost in a volume market. The target feeder ring circumference of 20 km can be met using SSMF and/ or ZWPF (worst-case parameters) with suitable assignment of wavelength channels to the remote nodes. The next step is to prove the system using different wavelength clients. This will be performed in a joint lab-trial using VDSL<sub>o</sub> described here, and the Fixed Wireless Access system that is also developed in SPD.

The electronics of the **Subcarrier Multiplexing** prototype is working correctly. The carriers in the transmitter can be adapted dynamically over 500Mhz, which was one of the objectives. A system with 2 subcarriers, both modulated with 1Gb/s of data was experimentally proven to be feasible. Both for 750m and 4.4 km a BER < 10<sup>-9</sup> could be obtained. There are however a few improvements possible. The dynamic range of the PLL is currently limited while also the sensitivity can still be improved. The feasibility of the broadband receiver has been shown. The next step is to include the optical path in the setup.

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