The photonics based KM3NeT readout and data transmission system

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On behalf of the KM3NeT Collaboration

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- **Next Steps**
- **Summary**

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KM3NeT Optical Networks

- **KM3NeT Prototype Detection Unit: ‘PPM-DU’**
  - 3 DOMs (Digital Optical Modules)
  - To be deployed in KM3NeT-It (100 Km main cable)
- **KM3NeT Detection Unit (DU)**
  - 18 DOMs (Digital Optical Modules)
  - 2x backbone cable with 12 fibers
- **Phase-1 of KM3NeT-It (Italy)**
  - Main cable already deployed
    - Length ~100 Km
    - 20 fibers
    - maximum of 24 KM3NeT DUs (number limited by power)
- **Phase-1 of KM3NeT-Fr (France)**
  - Main cable delivered and ready for deployment
    - Length ~40 Km
    - 36 fibers
    - 1 Node with maximum of 20 KM3NeT DUs

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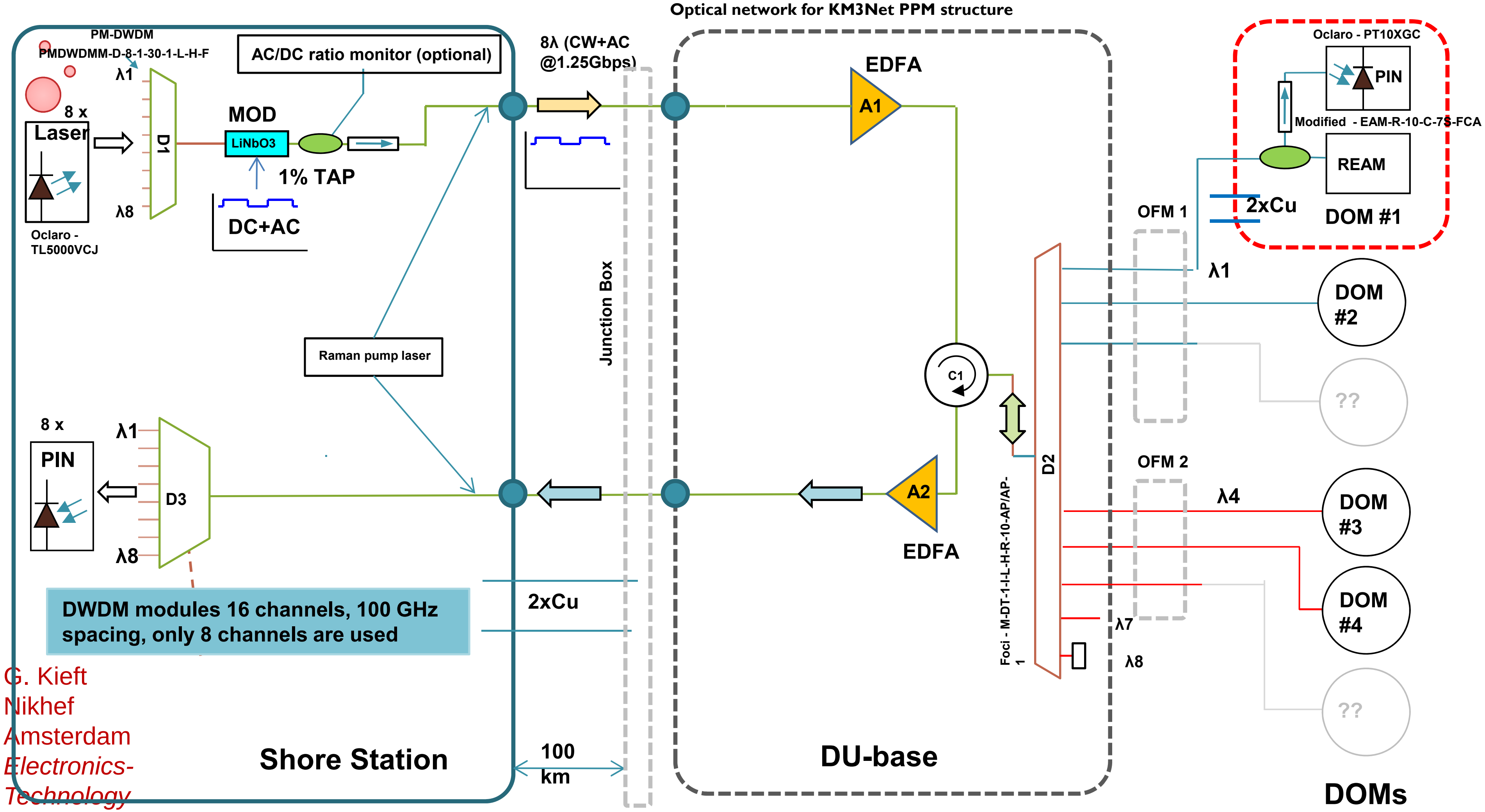
Optical Test Bench using REAM and Low-ER signals

(as presented at VLVnT11)



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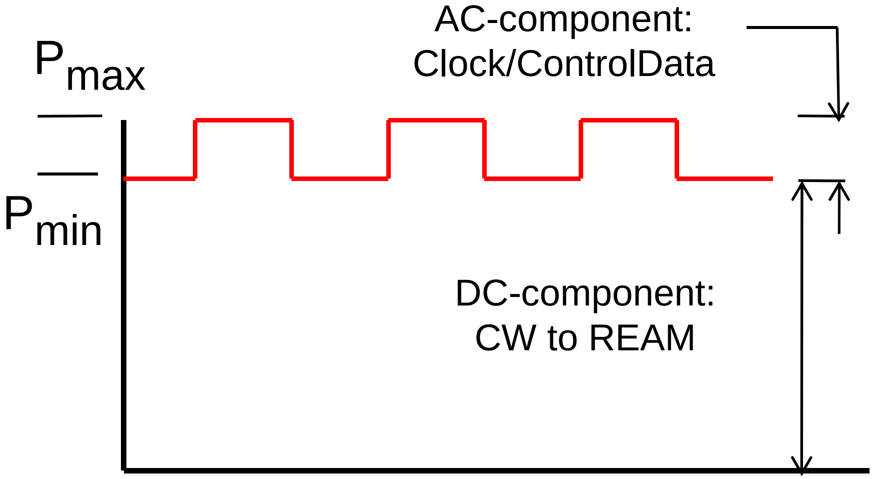
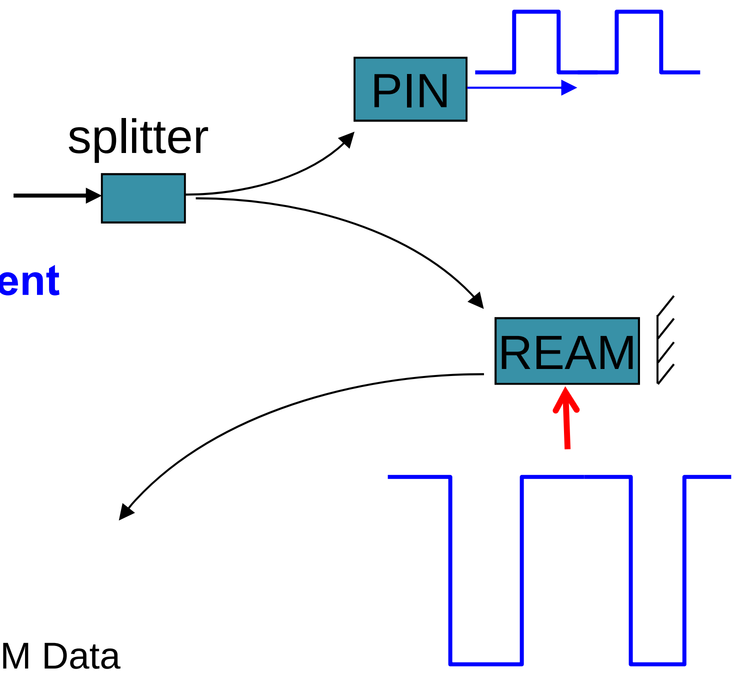
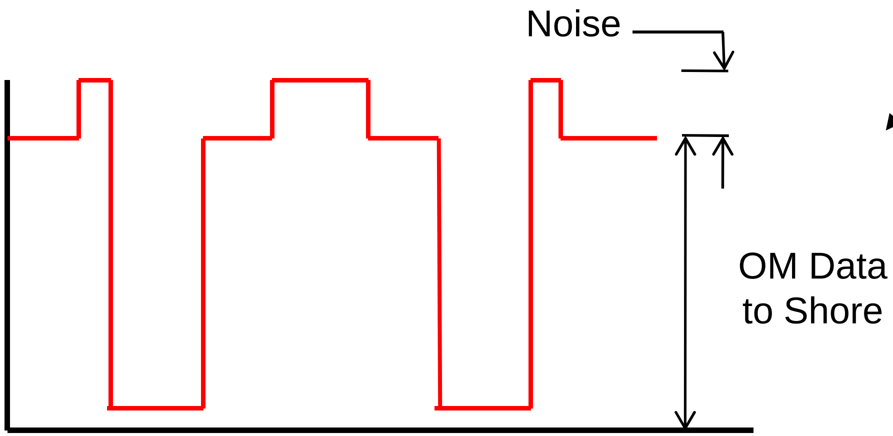
Low Extinction Ratio Approach



Extinction ratio (ER) = P_{max}/P_{min}
For KM3NeT:
ER as close as possible to 1



Same wavelength for AC- and DC-component



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Characteristics of low-ER signal for downstream data

- In the low-ER approach, downstream data to a specific DOM is broadcasted at the same wavelength as the CW signal to the REAM in that DOM.
- The low-ER approach eliminates wavelength-selective components for combining the downstream data signal and the CW signal. This greatly simplifies the network and reduces the number of wavelength-selective components.
- In the low-ER approach, the incoming (downstream) signal in each DOM is distributed over the PIN receiver and the R-EAM, using an optical power splitter.

The DOM is fully colorless in the low-ER approach -> all DOM's are identical!

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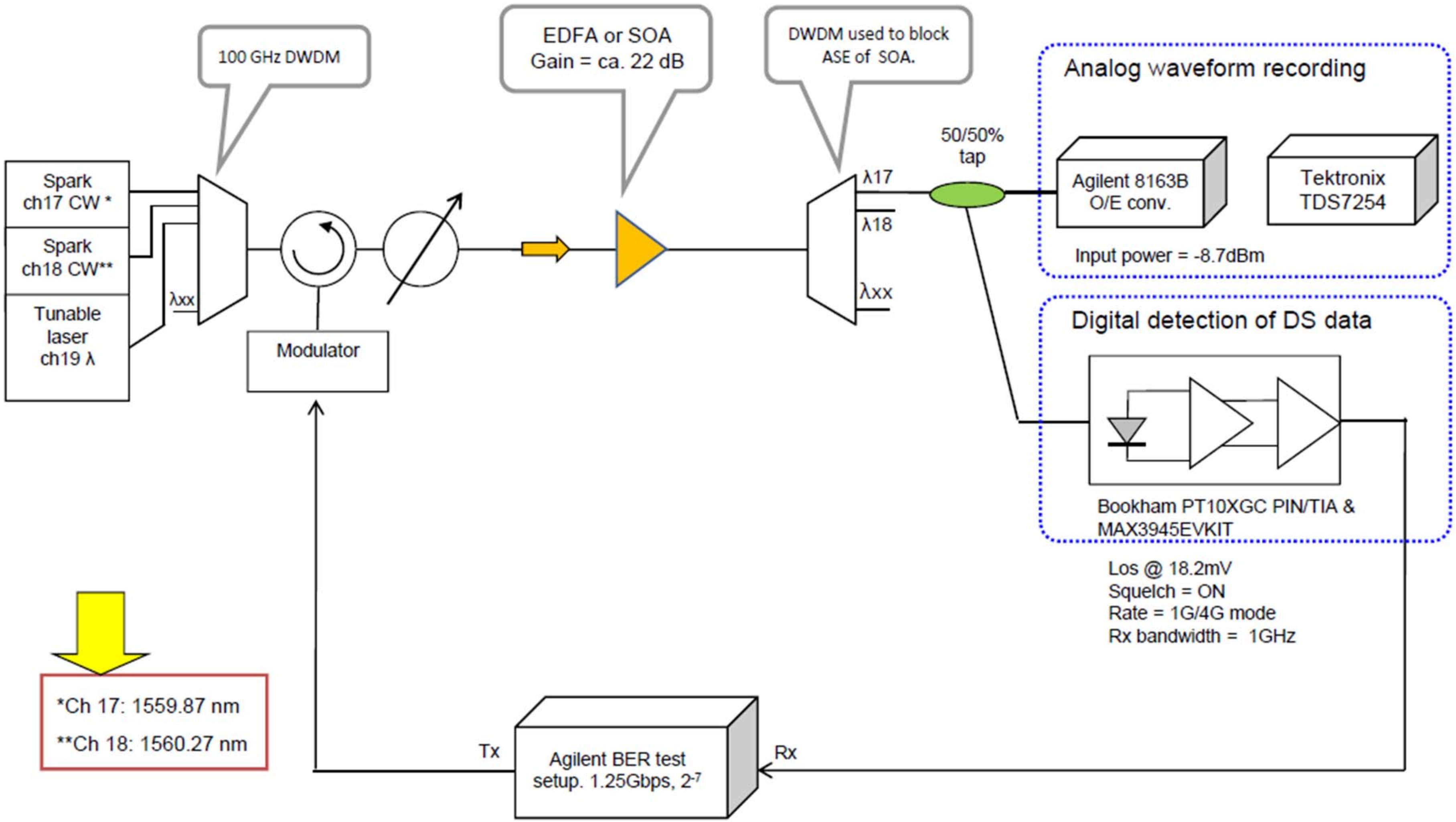
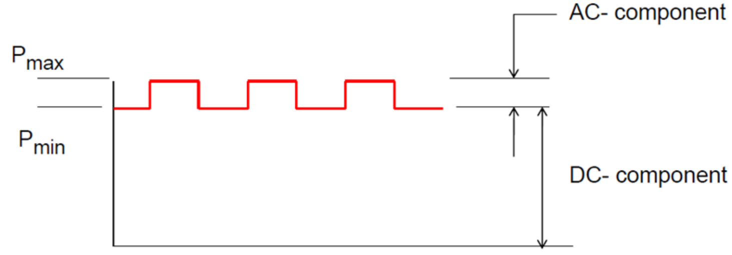
Test configuration for downstream Low-ER data
(up to 3 channels)



Effect of ER-variations on detection of low-ER signals

When using low-ER signals the optical power at the PIN diode in each DOM need a relative high CW power, in order to achieve a stable BER of e.g.10-7.



Extinction ratio (ER) = P_{max}/P_{min}

Example for an ER of 1.2:
- the AC-component power is ~5 times lower (7 dB) than the CW power
- for a PIN/TIA receiver sensitivity of -20 dBm @1.25 Gb/s the CW optical power on the receiver in the DOM must be -13 dBm to achieve an AC level of at least -20 dBm.

Example for an ER of 1.1:
- the AC-component power is ~10 times lower (10 dB) than the CW power
- for the same CW power of -13 dBm, the AC power will be only -23 dBm, which is well below the detection sensitivity of -20 dBm the PIN/TIA receiver

A ~10 % change in the ER has a strong influence on the detection of the low-ER signal.

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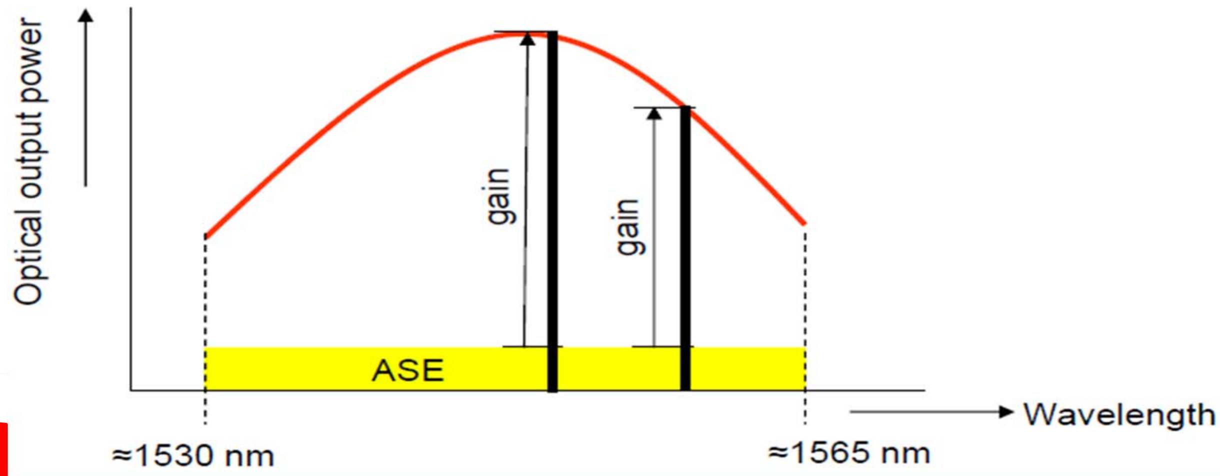
The effects of optical amplification on low-ER signals

-The CW power in one channel influences the AC-power in another channel, due to effects in the amplification process of the EDFA or SOA. Signals with high optical power are amplified more then signals with low power

- Gain of the EDFA is wavelength dependent

- Due to ASE (Amplified Spontaneous Emission) ER-degradation occurs for EDFA gain settings as required for loss compensation over 50 km up- and downstream fiber

- When using up to 3 optical channels, accurate fine-tuning of the EDFA gain setting was needed for conservation of the ER of the individual channels



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Main results of the low-ER experiments

Experiments on optical amplification of a set of low-ER signals showed distortion of the individual wavelengths due to:

- Wavelength- and power-dependent competition in optical gain for the low-ER signals
- Addition of ASE (Amplified Spontaneous Emission) from the gain medium
- Addition of noise from the optical amplification process

Due to the above effects maximal 3 optical channels / wavelengths could be used for transmission over 50 km downstream fiber.

For simultaneous transmission of more optical channels, even a BER of (10^{-7}) could not be achieved

This indicates a poor scalability of the low-ER downstream concept towards the full number of 80 wavelengths as foreseen in the final KM3NeT architecture.

Decision: Use 1 high-ER wavelength for downstream data (instead of 80 low-ER wavelengths)!

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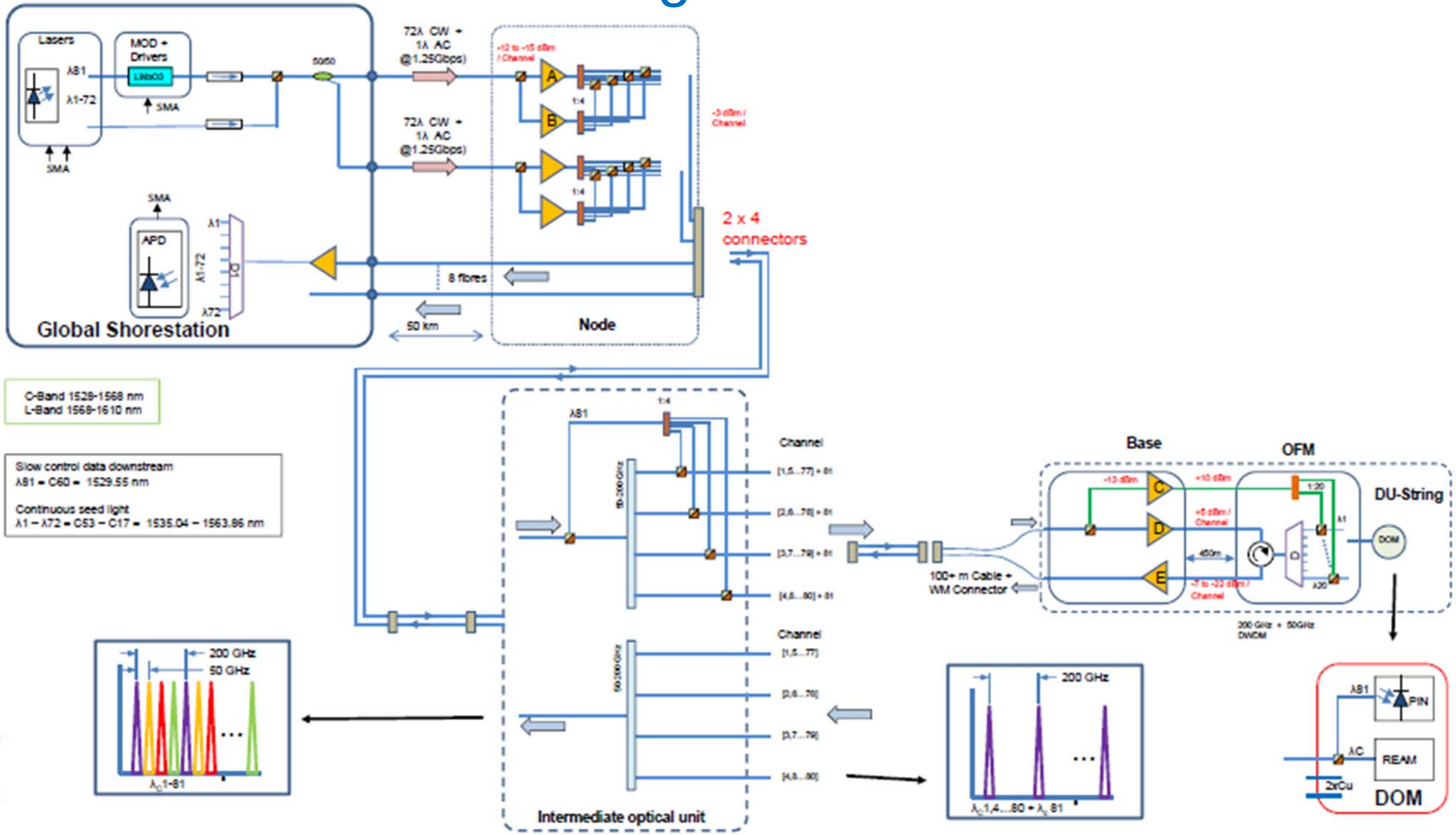
Concept Optical Network with 1 high-ER wavelength downstream



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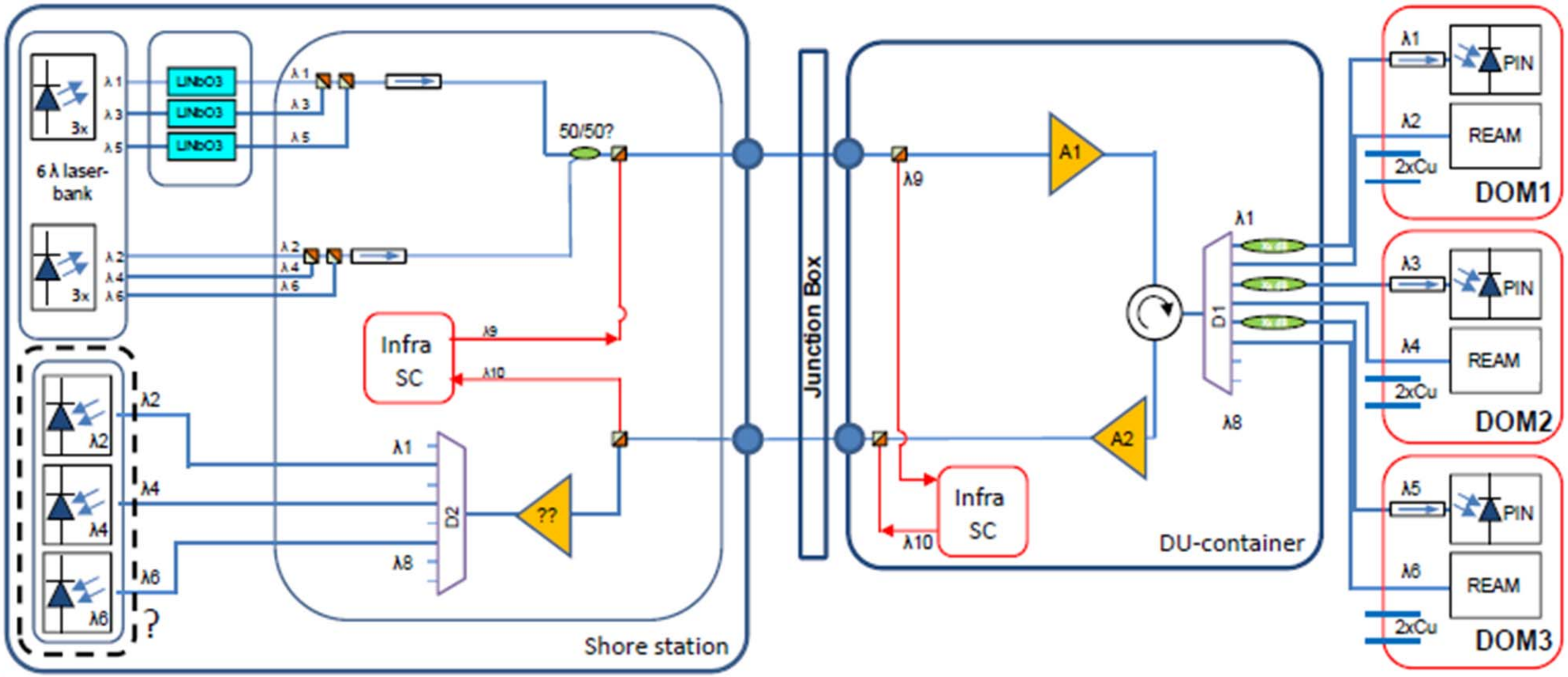
Optical Network PPM-DU using REAM and high-ER

- Similar to the PPM-DOM that is successfully working in Antares
- Three DOMs use a REAM as modulator for data to shore
- Test bench is build and successfully tested



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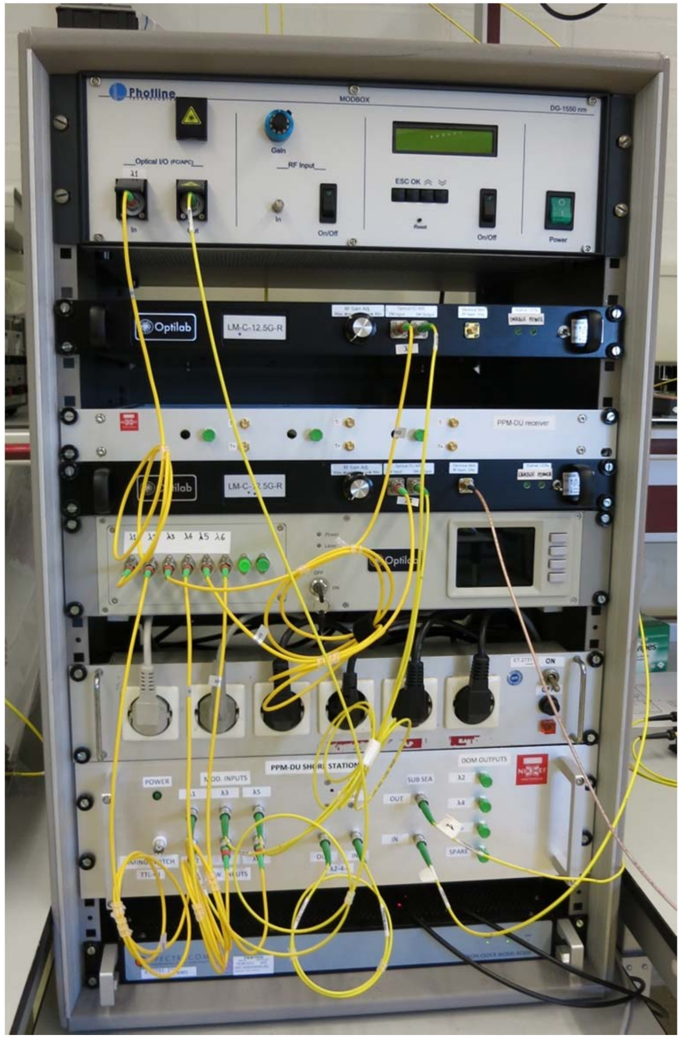
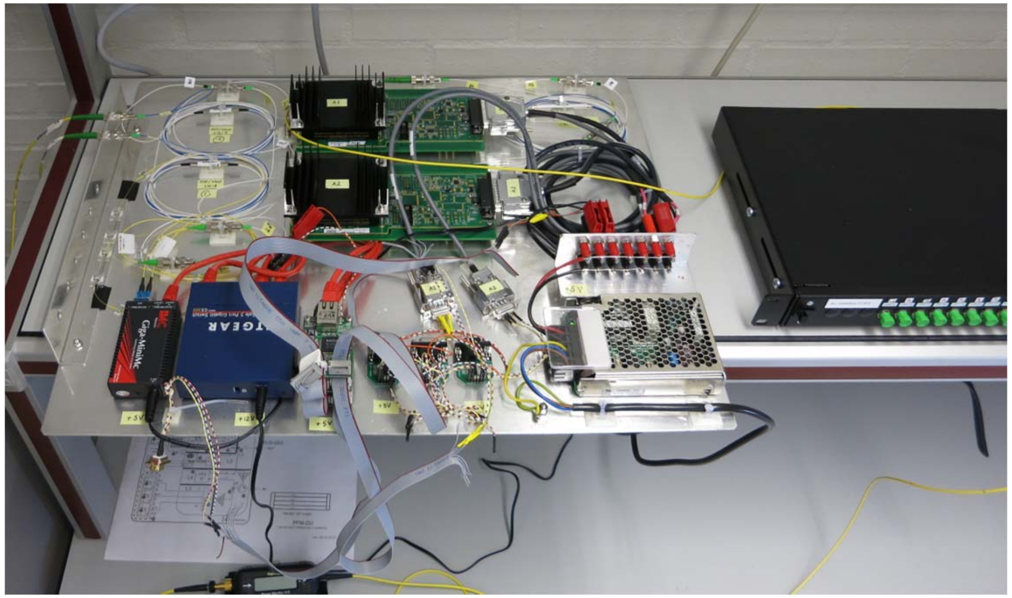
PPM-DU Optical Test Bench

Shore Station



Optical components for DU-container



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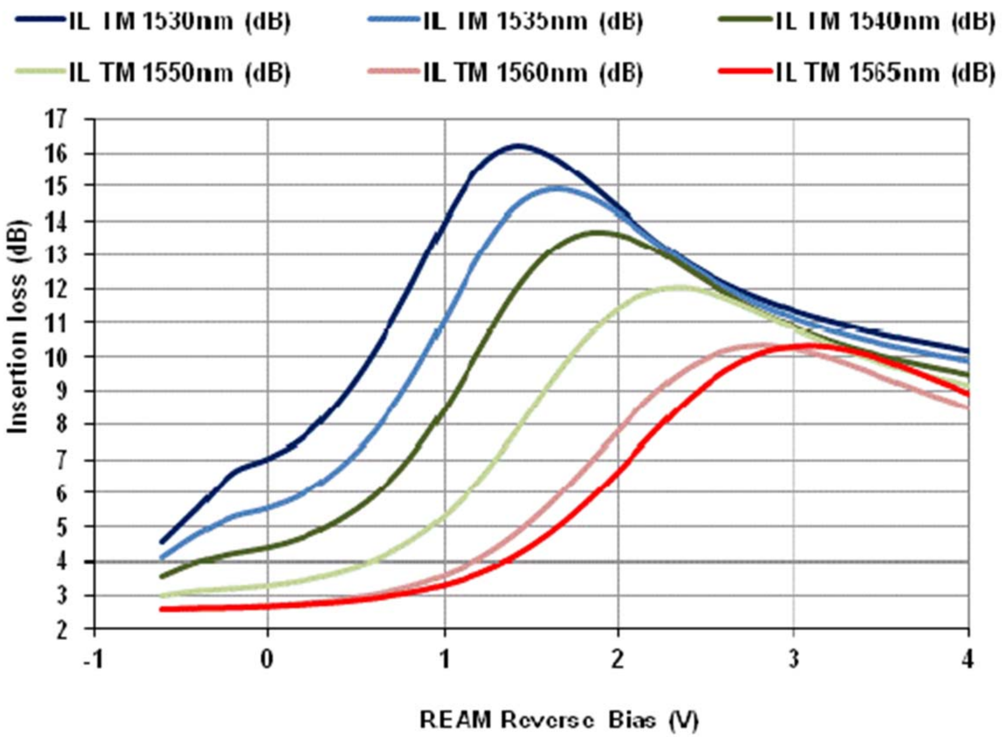
REAM: Characterization and Redesign

- Specifications in datasheet for REAM from CIP/Huawei are valid for one wavelength (1550nm)!
- Insertion loss and modulation depth of REAM turned out to be very wavelength dependent
- One type of REAM suitable for whole wavelength band (1530-1560nm) not realistic
- Redesign by CIP is needed to develop a ‘Red’-type and ‘Blue’-type of REAM to decrease the wavelength dependency



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REAM production by CIP/Huawei

- Because CIP was taken over by Huawai, the production of REAMs was stopped at CIP. However, special production run(s) of the REAM devices were offered by Huawai, but:
- Time line of delivery was not compliant with the KM3NeT schedule
- Price not compliant with KM3NeT budget
- No final agreement about specifications:
  KM3NeT: Extinction Ratio: typ 7.0dB (80%) - Min 6.5dB (100%)
  CIP/Huawei: Extinction Ratio: Min 6.0dB (100%)

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REAM versus Laser

- Reasons why is chosen for REAM (several years ago):
  - Colorless (not completely anymore because of Red and Blue REAM)
  - Mirror function for optical timing calibration (not used any more)
  - Suitable for >100Km (low chirp)
  - 10Gbs capability (not required anymore, now 1.25Gbs)
  - Reliable and long life time
  - Low power (but REAM driver ~1 watt)
- Properties of modern lasers:
  - Laser and receiver integrated in one SFP cage (swappable)
  - 50GHz DWDM grid compatible
  - Low power (~1 watt for laser + receiver)
  - Available for >100Km
  - Higher optical output power and higher extinction ratio (>8dB)
  - Not yet info about reliability and life time
  - Price of a lasers is comparable with the increased price of the REAMs
  - Multiple suppliers (REAM is single-source, only CIP!)

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Move from REAM to Laser

Motivation to change from REAM to Laser:

- In the meantime when was chosen for the REAM and now, the development of lasers has progressed a lot
- Due to the need to supply CW light to all the DOMs, the high insertion loss and the low modulation depth, many optical amplifiers are needed in a network based on REAMs.
- These EDFAs and the CW laser bank makes a network with REAMs more complex and more expensive than a network with lasers.
- The time line for the production of ‘Red’- and ‘Blue’-type of REAM by CIP is incompatible with the time line for KM3NeT Phase-1
- There exists only a single supplier for the REAM
- **Decision: KM3NeT will use Lasers instead of REAMs**

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Requirements for SFP (Small Form-factor Pluggable) Optical Transceivers:

Requirements:

	min	typ	max	
Wavelength range	1528		1564	nm
Extinction ratio	8			dB
Output power	0		5	dBm
Deviation From Central Frequency@EOL[1]	-6		+6	GHz
Bitrate transmitter[2]	1,25			Gbps
Link budget	24			dB
Lifetime	15			year
ITU channel spacing			50	GHz
Power consumption		1	1,2	Watt

Note 1:End Of Life is minimum 15 years.

Note 2: A bitrate of 1.25Gbps is minimum, higher capabilities are allowed but the unit will be used at 1.25Gbps.
A posibility is to use the rate-select pin/bit of an SFP+ module

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Lifetime and evaluation of SFP Transceivers

- No hard information available about lifetime of SFP DFB lasers
- Contacts with potential manufacturers and laser specialists are established
- Two main factors in lifetime specifications: (a) Optical output power and (b) Optical wavelength stability.
- Output power stability is achieved by built-in Optical Power Monitoring and laser current control
- Wavelength stabilization for a 100 GHz grid can be done by precise thermal stabilization of DFB laser, but DWDM on a 50 GHz grid requires additional wavelength monitoring / locking built into the DFB laser
- Environment temperature of the laser is an important factor. A lower temperature will cause a lower stress factor and will increase the lifetime a lot.
- For evaluation 2 sets of 1,25Gbs lasers at 50GHz are ordered from Optecom and Fiberstore. Every set consists of 4 lasers:
  1 low in C-Band, 1 high in C-band and 2 in the middle at 50Ghz.
- Also two 10Gbs lasers with rate select pin are ordered for evaluation.

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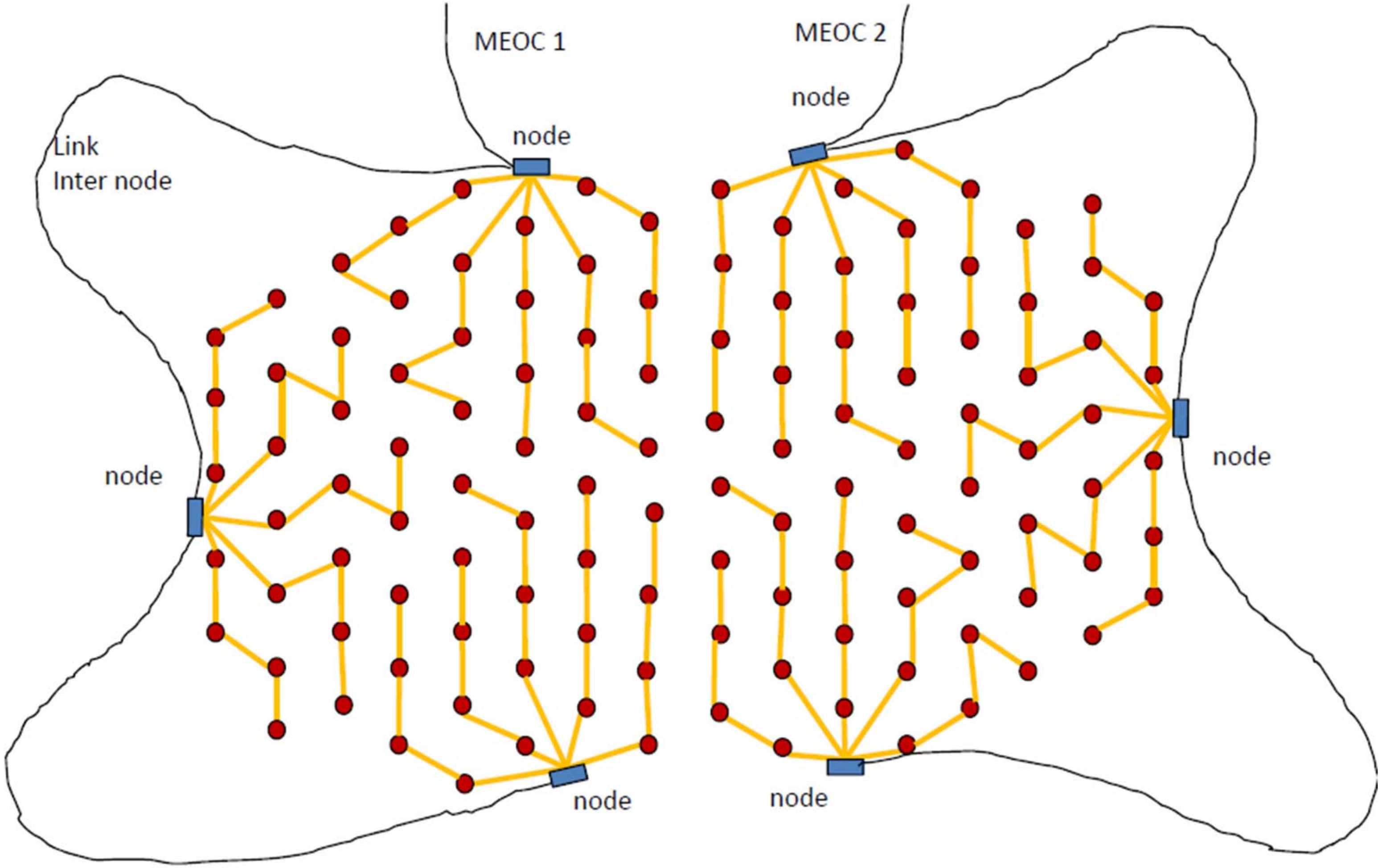
KM3Net-Fr Site



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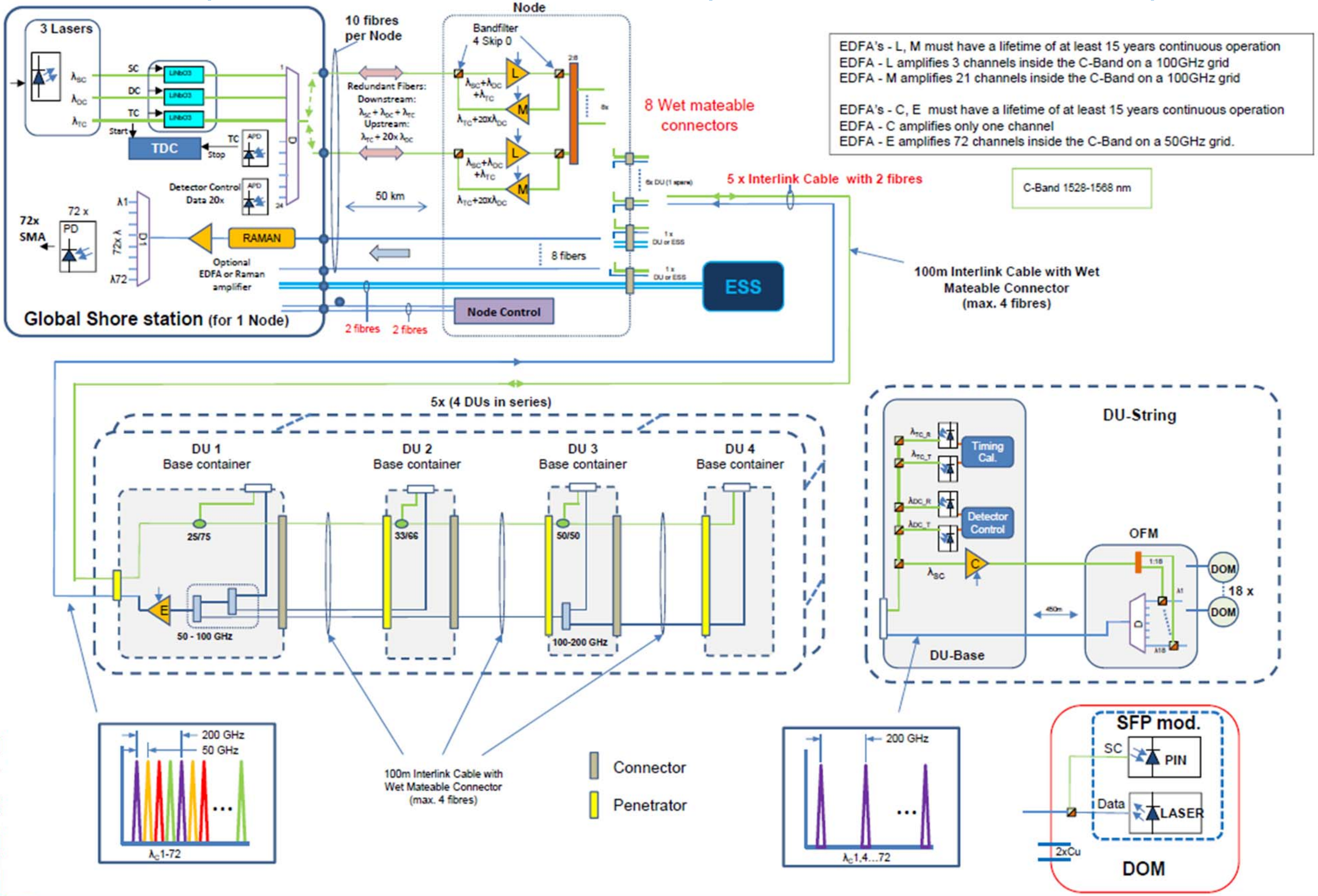
Concept Design for KM3NeT-Fr

(SFP Lasers, 72 Channels, Separate fiber for SC, DC, TC)



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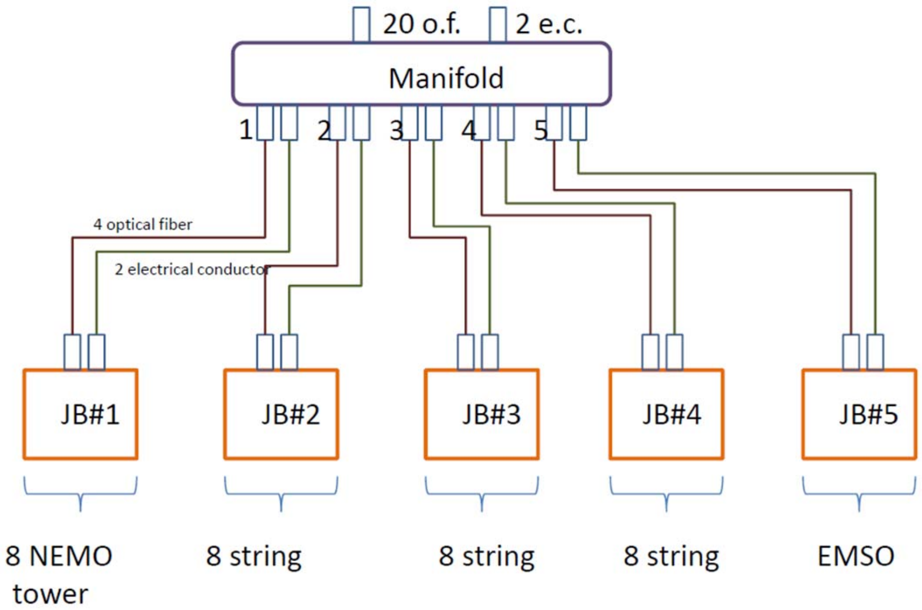
Phase-1: KM3Net-It



- Star network -> no DUs connected in series
- Manifold is completely passive (no EDFA's -> no splitters!)
- 4 optical fibres per JB: 1 fibre downstream, 3 fibres upstream
- 3 fibres upstream -> 3 x 4 = 12 DUs per JB
- But because of power limitation only maximum of 24 DUs in total
- 5 JBs of which 3 JBs for DUs -> 3 x 8 = 24 DUs

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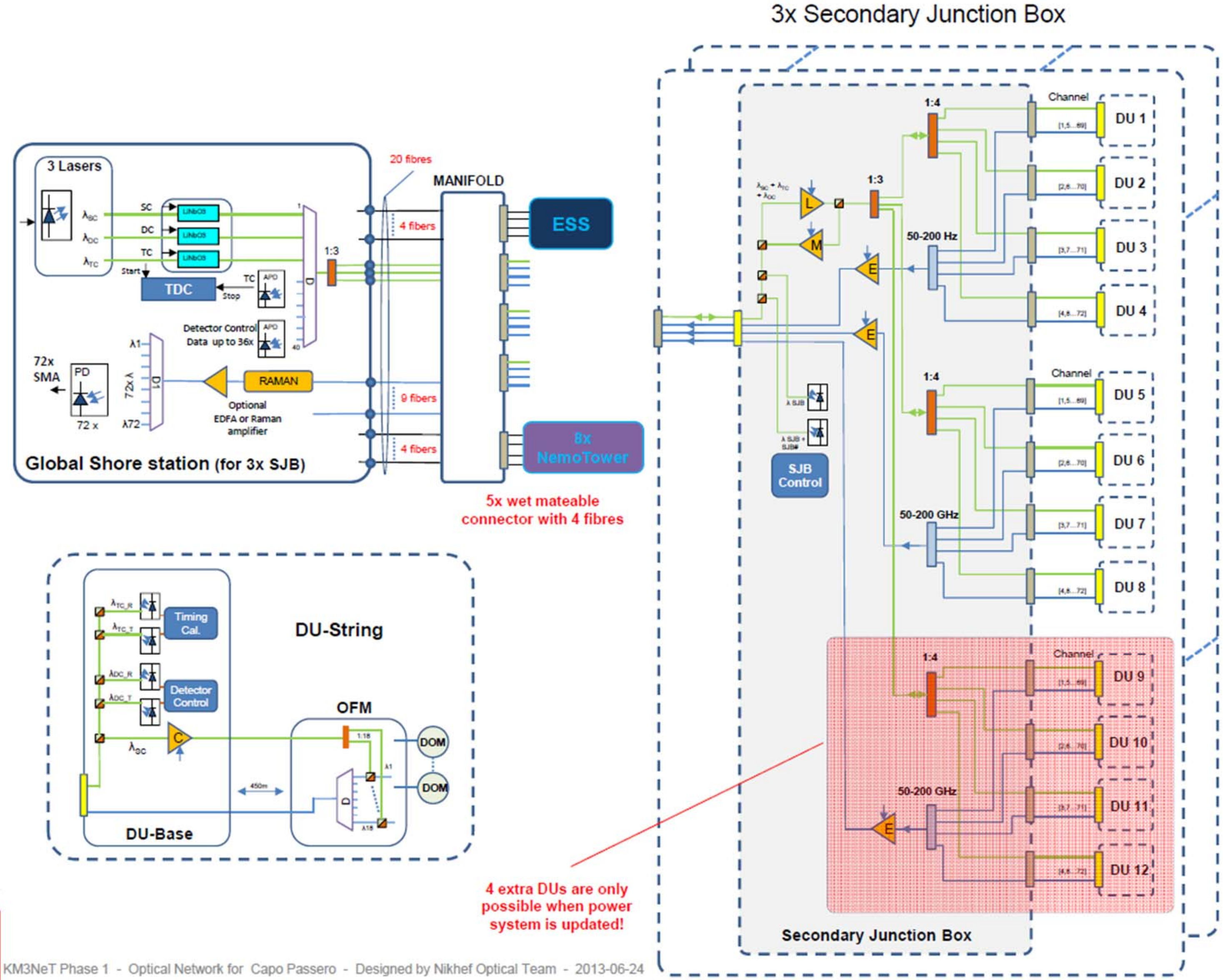
Concept Design for Phase-1: KM3NeT-It

(SFP Lasers, 72 Channels, Separate fiber for SC, DC, TC)



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Next Steps:

- Finish research about life time and reliability of SFP DFB lasers
- Validate the current optical scheme with VPI simulation software
- Define requirements and specify all the optical components
- Build test bench to qualify the optical network
- Prepare for tendering of optical components for KM3NeT Phase-1

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Summary:

- Using low-ER signals from shore for data and CW to the detector on same wavelength is working for a few wavelengths but not scalable to many wavelengths.
- DOMs using a REAM to modulate the data to shore are working in PPM-DOM and PPM-DU.
- Performance of REAM is wavelength dependent. For KM3NeT special production run of ‘Red’ and ‘Blue’ type of REAM would be needed but time line not compatible with KM3NeT.
- Optical network using Lasers instead of REAMs is less complicated and has more margin due to higher optical power levels.
- A general optical network concept has been implemented for KM3NeT-Fr and KM3NeT-It.

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Backup Slides

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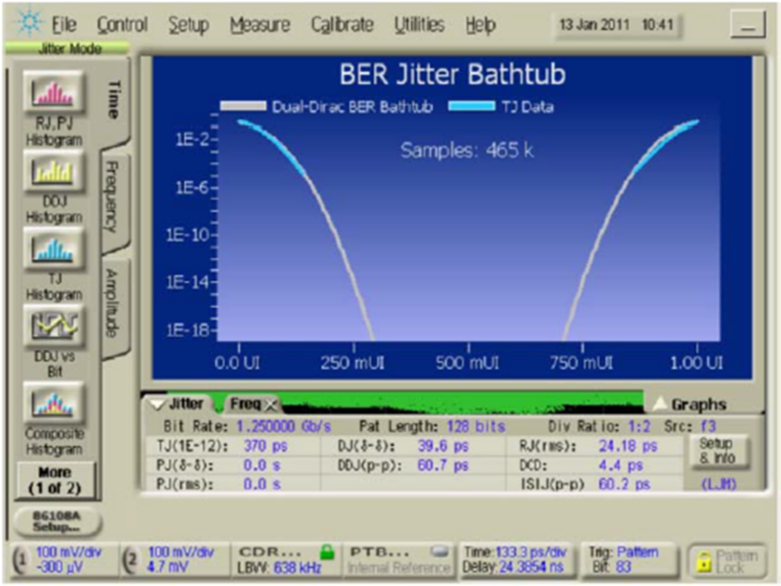
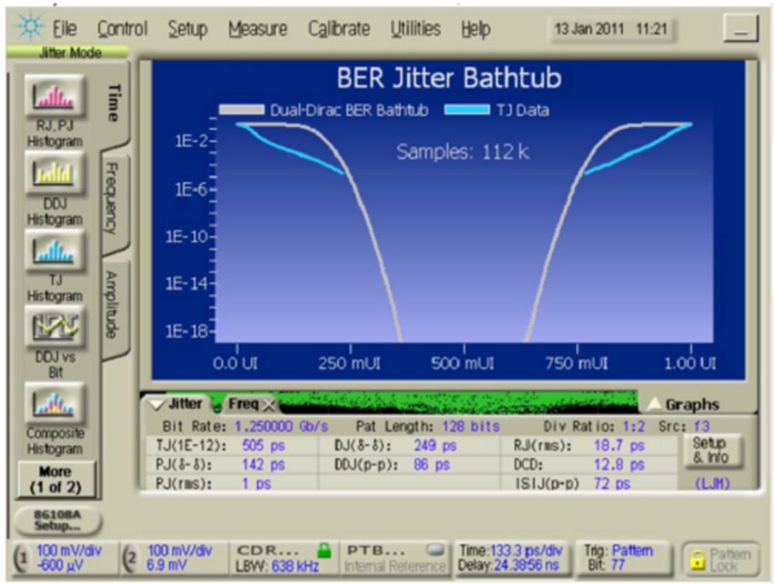
BER measurement of AC-signal and low-ER signal



R1)AC=-30dBm & DC=off



P1)AC=-13dBm & DC=-6dBm 1:5

Reference measurements on Antares Rx (APD) performance @ 1,25 Gbps, BER = 10^{-7}

AC= -30 dBm

DC = switched off

1.25 Gbps AC superimposed on DC optical power @ BER = 10^{-7}

AC= -13 dBm (= 50 μW average,100 μW peak)

DC = -6dBm (= 250μW)

Extinction ratio (ER) = P_{max} / P_{min} = 350/250 = 1.4

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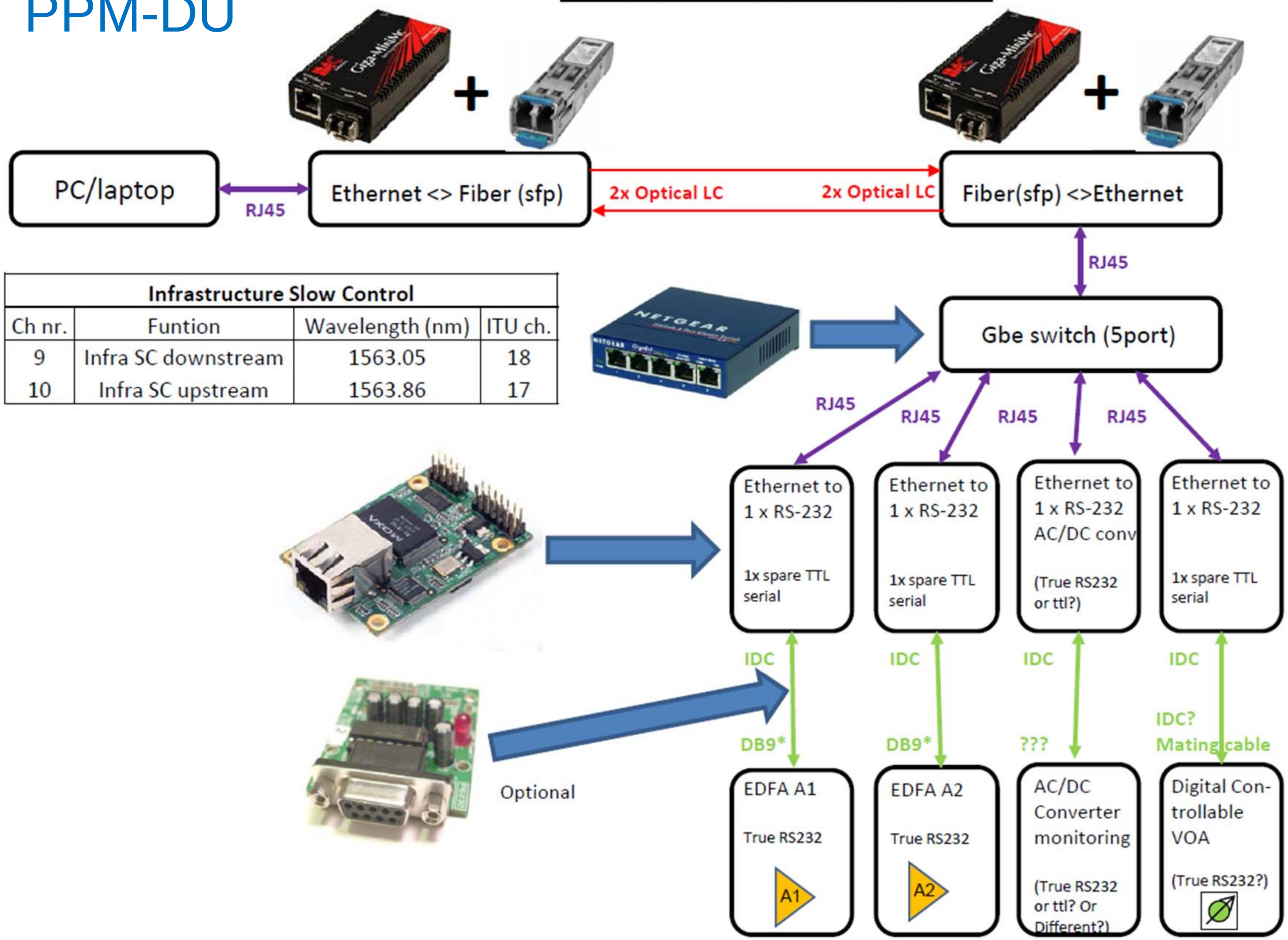
PPM-DU

Infrastructure Slow Control



Infrastructure Slow Control			
Ch nr.	Funtion	Wavelength (nm)	ITU ch.
9	Infra SC downstream	1563.05	18
10	Infra SC upstream	1563.86	17

*DB9 is only used in the test bench.
When installing in DU-container IDC will be used.

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Main conclusion of simulation when using REAMs:

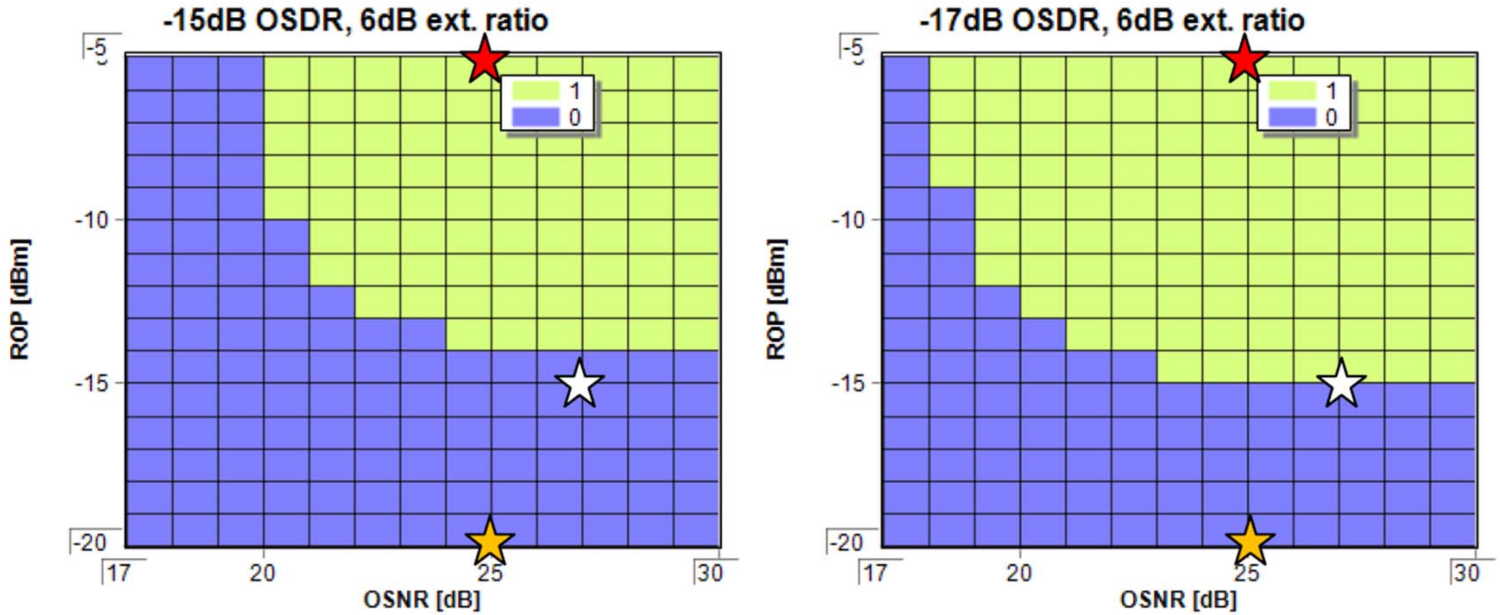

Figure 14: Requirement in terms of OSNR and insertion loss (ROP) as set by the *DOM* design assuming -15dB (left) and -17dB (right). The red star corresponds to the system characteristics with *bad* wet mateable connectors but with an additional EDFA in front of the AWG in the *Shore* station.

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Network will work for upstream path but only with optical amplifier in every DU-base and in the shore station!

Main conclusion of simulation when using Lasers:

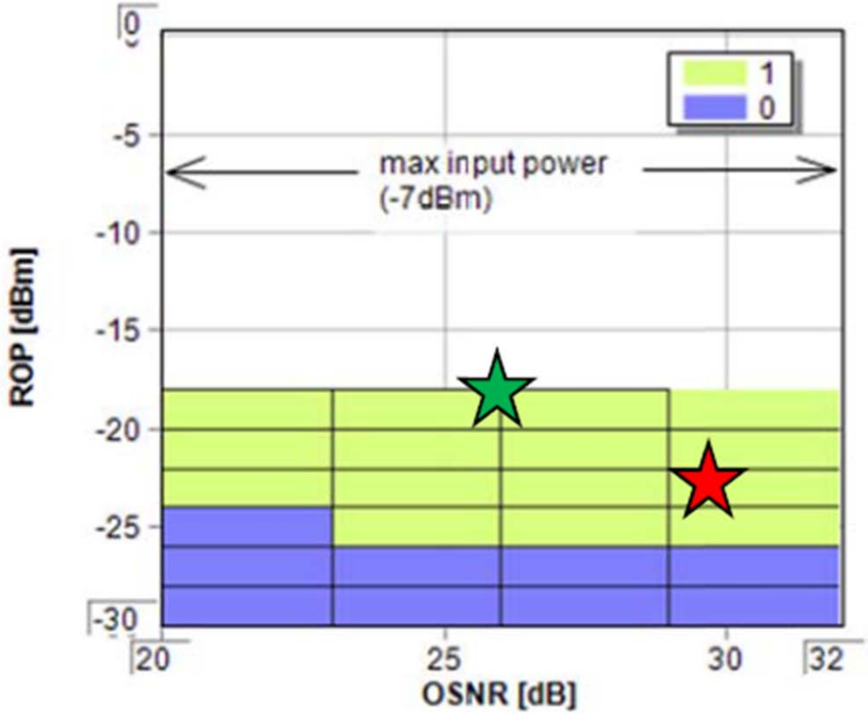

**Figure 10: Uplink operation condition assuming bad wet mateable connectors and an additional EDFA (green star) in the node.
BER below and above 1e-12 are displayed in green and blue respectively.**

Only one EDFA in the Node for every 4 DUs!

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Availability of SFP Optical Transceivers

- SFP optical transceivers for 1.25Gbs and suitable for 50GHz DWDM are available but not very common. 1.25Gbs is speed from some time ago (now 10Gbs) while 50GHz DWDM is rather new.

- 10Gbs SFP modules at 50GHz are more common. Not sure these can also work at 1.25Gbs. Some 10Gbs SFP modules have rate select pin to select lower speed (1Gbs – 4Gbs)

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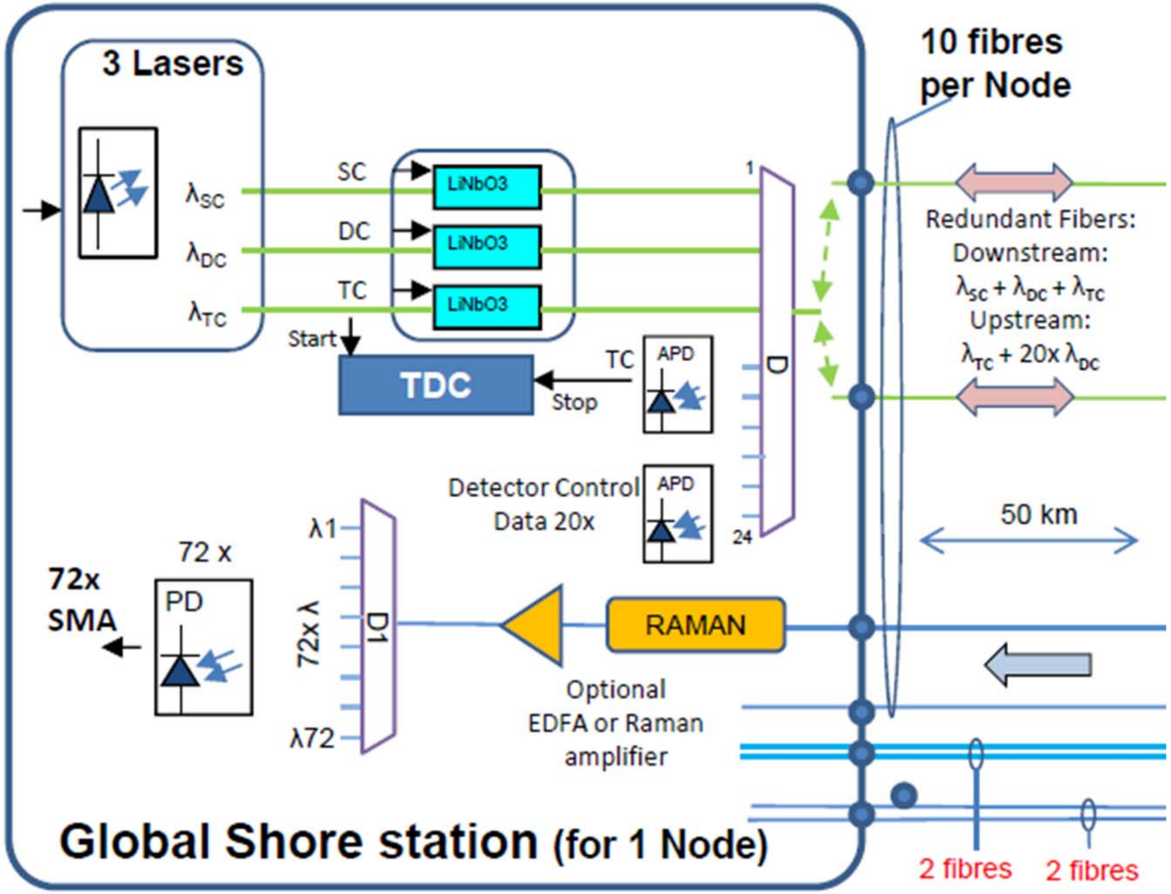
Shore Station



- Slow Control (SC), Detector Control (DC) and Timing Calibration (TC) on 1 separate fiber
- DC: 1 broadcast WL downstream and unique WL for each DU upstream
- TC: 1 WL for downstream and 1 WL for upstream. Only one DU can transmit at a time (selected via DC)

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Optical Timing Calibration

- One wavelength for downstream signal and one wavelength for upstream signal
- Via Detector Control only one DU is selected to transmit at a time
- Optical timing calibration covers path from Shore Station till base of the DU. Timing delay inside the DU is assumed to be fixed and has to be measured before deployment
- Optical timing calibration measures the same fiber used for clock signal but on a slightly different wavelength
- Optical timing calibration uses a pulse train containing a special pattern as start pulse. Pulse train allows for AC coupling (instead of DC coupling in case of one short pulse)
- Special electronics in DU base and Shore Station has to be developed!

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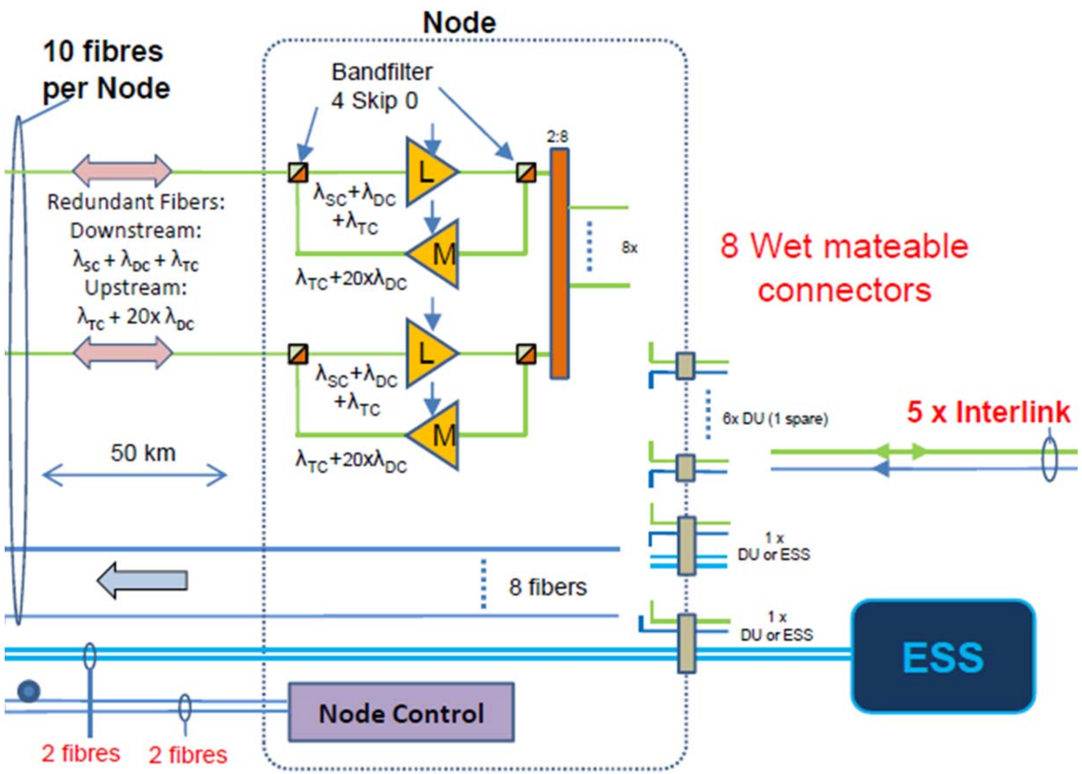
Node



- EDFA for 3 wavelengths (SC, DC and TC) downstream
- EDFA for 1 wavelength TC and up to 32 wavelengths DC upstream
- In case redundency is required for downstream between Shore Station and Node than 1 extra fibres in MEOC (available), 2 extra EDFA's, extra bandfilters and 2:8 splitter (instead of 1:8 splitter) have to be used! Extra costs and complexity in the Node but no penalty for optical power!

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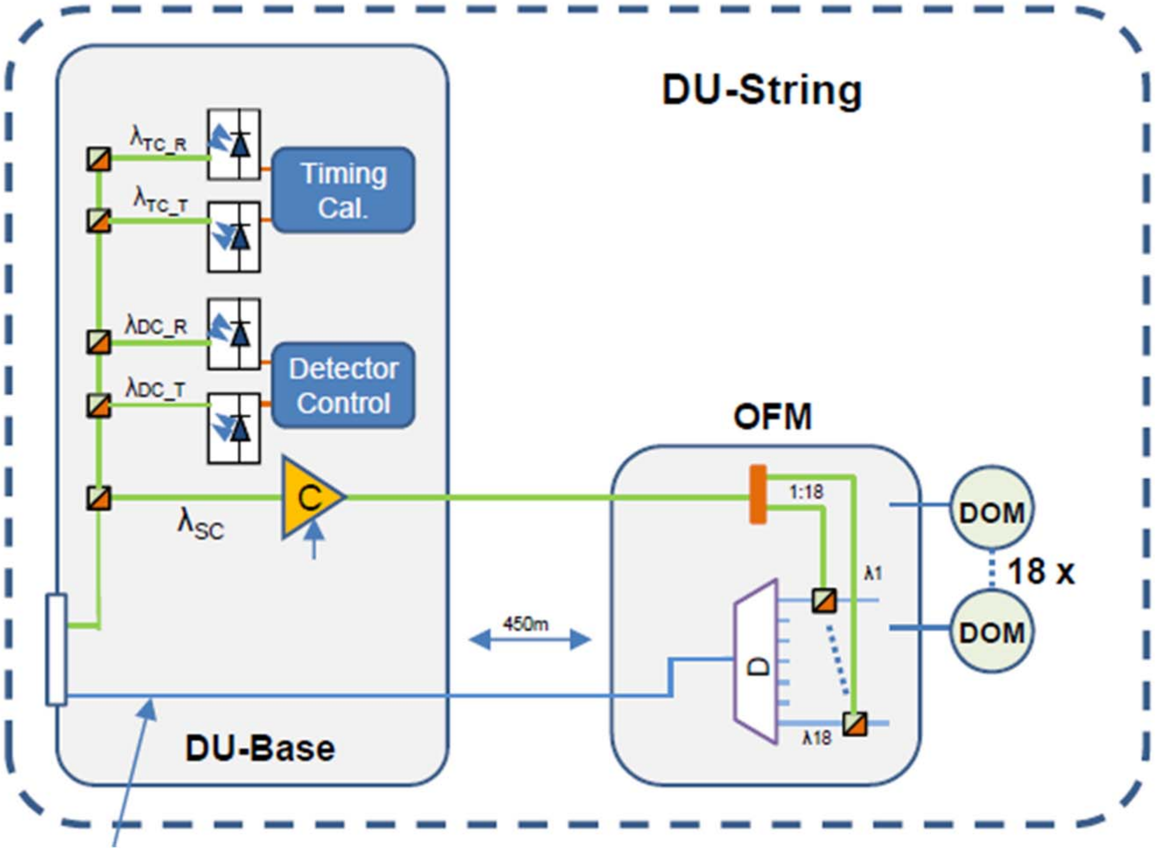
Detection Unit (DU)



- Only 1 EDFA in the DU-Base for Slow Control data to the DOM
- Detector Control in the DU-Base needed for control of EDFA's, TC, Power
- Optical timing calibration in the base of the DU, special electronics needed
- DC and TC use an SFP optical transceiver module in the DU-Base

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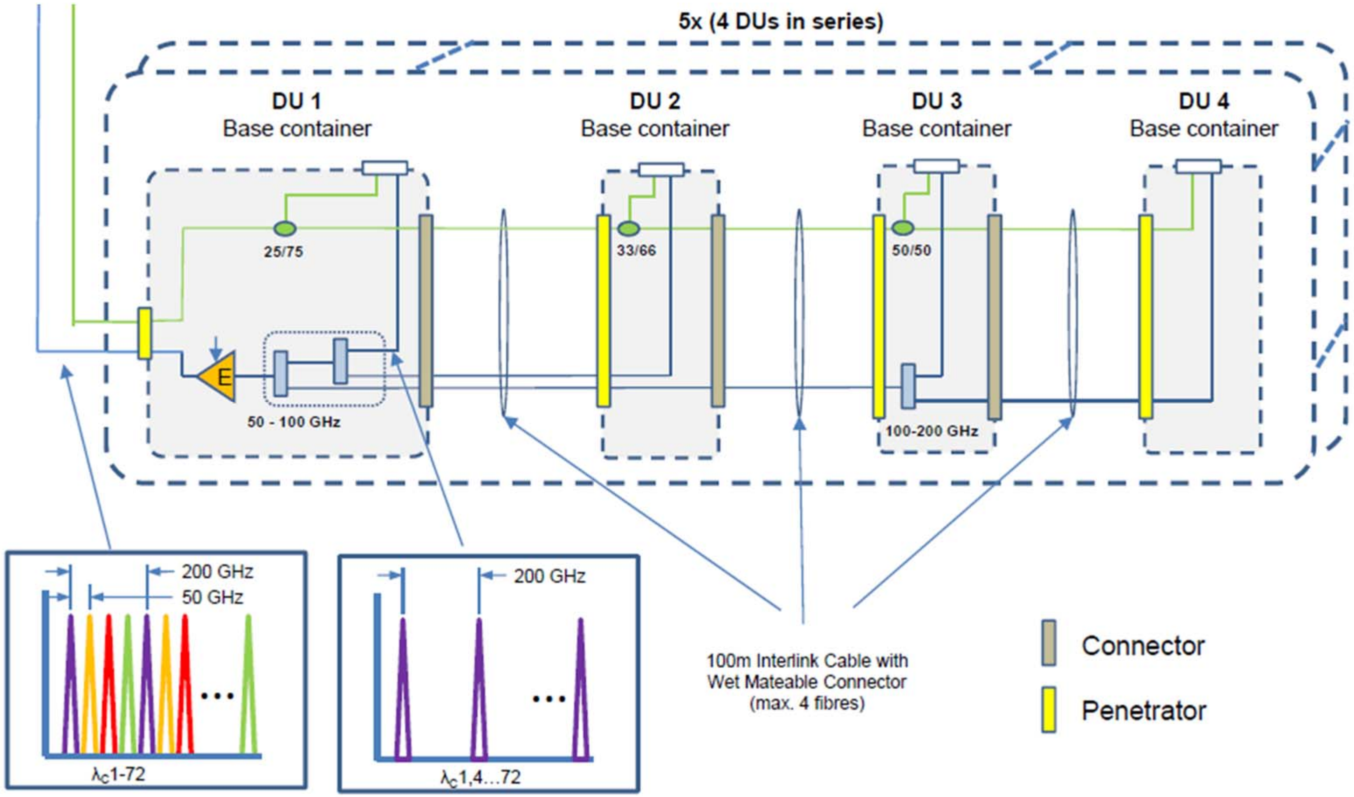
Connection of 4 DUs in series for KM3NeT-Fr



- 1 connector on the Node connects to 4 DUs in series
- Interlink Cable between Node - DU and between DUs maximum ~100m
- One EDFA per 4 DUs for the upstream detector data to shore
- Deployment order: DU1 - DU2 - DU3 - DU4

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