ADDAPT

Adaptive Data and Power Aware Transceivers for Optical Communications

Deliverable Report D 2.6

Dissemination and exploitation of ADDAPT results

Small or medium scale focused research project (STREP)
ICT-2013.3.2 Photonics

Project Start Date: 1st November 2013
Duration: 42 months
Project reference: 619197

FP7-ICT-2013-11 November 07, 2017 – Version 1.0

Project co-funded by the European Commission
within the Seventh Framework Programme (2007 - 2013)

Dissemination Level: Public

Document information

Title	D2.6 - Dissemination and exploitation of ADDAPT results
Work package	WP2 – Market studies, exploitation and dissemination, standardization
Responsible	VI-Systems (VIS)
Due date	Project M48 (October 2017)
Type	Report
Status	Final Version 1.0
Security	Public
Authors	Pieter van Leeuwen, Joerg Kropp, George Schaefer, VIS
	Iain Eddie, CSTG
	Michael Georgiades, Theodosis Theodosiou, PTL
	Thomas Toifl, Alessandro Cevrero, IBM
	Ronny Henker, TUD
	Martin Zoldak, AT
	Jarek Turkiewicz, WUT
Project URL	www.ADDAPT-fp7.eu

Confirmation

Any work or result described in this report is either genuinely a result of this project or properly referenced.

Table of Contents

1 Version Management

Table 1: List of Revisions.

Version	Description	Author	Released
V0.1	First setup	P. van Leeuwen (VIS)	Oct 10, 2017
V0.2	Updates from VIS on market research	P. van Leeuwen, George Schaefer, Joerg Kropp (VIS)	Oct 23, 2017
V0.3	Updated with feedback from AT, CSTG	P. van Leeuwen, M Zoldak, I Eddie	Oct 31, 2017
V0.4	Updated with feedback IBM, PTL, TUD	P. van Leeuwen (VIS), T. Toifl (IBM), M. Georgiades (PTL, R. Henker (TUD)	Nov 05, 2017
V0.5	Updated with Feedback from PTL, WUT	P. van Leeuwen (VIS), M. Georgiades (PTL, J. P. Turkiewicz (WUT)	Nov 7, 2017
V1.0	Final revisions	R. Henker (TUD)	Nov 10, 2017

2 Executive Summary

[ADDAPT] is a technology project, co-funded by the European Commission within the Seventh Framework Programme. ADDAPT aims to adapt the cable speed in the data-center to the offered data load, by interpreting the data stream and detect the idle data in it.

This report addresses market, impact, standardisation, dissemination ("how the spread the word"), and exploitation (use the results in the environmental system of the partner's organisation).

Chapter 3, Market.

The market of GaAs applications, particularly data communications, maintains a steady growth of 20 – 25% CAGR until at least 2020. After this, there is a reduced growth expected.

The market is approximately $ 1900 million, with a volume of 41 million pieces (transceivers) in 2022.

It is also believed that the age of VSCEL is coming to an end (Communications Industry Researchers) due to physical limitations. We doubt that this is the case: we already see, and have achieved ourselves (VI-Systems) data rates of 112 Gbps with VCSEL using PAM4.

Also Silicon Photonics (SiPh) is growing fast. For the time being in applications with a high level of integration. We do not see a threat (yet) in SiPh for the coming years. See also the summary of LightCounting.

Chapter 4, Standardization

In Ethernet most standards with 50 Gbps lane speed have been standardized, using PAM4. However, the market remains interested in 50 Gbps NRZ transmssion, as we see in the activities in Optical Interconnect Forum. The VSR (Active Optical Cable) distance has been standardized on 53 GBd / NRZ. Other distances are being standardized.

Also under OIF so-called Flex Ethernet has been standardized. This is a way to combine, or dis-aggregate, Ethernet links. We believe the potential capability of ADDAPT transceiver to switch off / on lanes depending on the demanded load, might be useful in combination with this feature.

Finally, IEEE received a request to standardize on (multiple) 50 Gbps multimode fibers. It is expected that a new working group will be formed around this theme per November 2017. This might be helpful for the ADDAPT technology.

Chapter 5, Competing Solutions

Quite a number of potentially competing solutions emerged in the 50 Gbps / NRZ domain, all in the InP technology, often using SiPh. An interesting technology is from Credo-Semiconductors, who are very active developing SERDES technology in this space.

We still do not see any attention and/or activity for the fast on/off technology, unless in the WiFi domain.

3 Market volumes according to market research organisations.

3.1 LightCounting

Optical transceivers based on GaAs optics accounted for 15-20% of the market in 2010-2015, and their market share will increase in 2016-2021.

Ethernet accounted for more than half of the market for GaAs optics in terms of shipments and sales in 2015. Rapidly increasing sales of 10GbE and 40GbE products stimulated market growth in 2010-2015. Deployments of 100G short reach optics inside mega-datacenters will drive market growth in 2016-2021. This is the main market for ADDAPT technology. The tables below contain numbers on volumes in units and sales of transceivers.

GaAs	**2020**	**2022**	
AOC-EOM	4800	6600	1000 units
Wireless	2200	500	1000 units
Ethernet	22600	22000	1000 units
Fibre Channel	10200	10700	1000 units

Technology	**2020**	**2022**	
GaAs	41	41	mill units
InP	141	154	mill units
SiPh	1	4	mill units

Sales	**2020**	**2022**	
GaAs	1900	2200	Mill $
InP	5500	7800	Mill $
SiPh	1100	1600	Mill $

Avg unitprice	**2020**	**2022**	
GaAs	46	54	$
InP	39	51	$
SiPh	1100	400	$

The sales in SiPh is 1600 mill $ of 11.000 mill $ in 2022, or 15%, and 4 mill units of 192 mill total (2.1%). The growth is in the high end markets of WDM and Ethernet.

If you look at the average price, (last table above), there is still a large gap between SiPh and ordinary GaAs and InP transceivers, but these prices are including low cost transceivers for FTTx.

If you look at InP however, you see average price for Ethernet is 685 $/unit, which is comparable to the average prices of SiPh (400$/unit). SiPh by its nature makes more sense in the InP market. We believe, the

coming years SiPh will not be a threat to the GaAs market, and certainly not to the GaAs VSCEL market. The costs of SiPh are too high.

3.2 Transparency Market Research

The global market for vertical-cavity surface-emitting lasers (VCSELs) is rising at a compound annual growth rate (CAGR) of 22.3% from $775.2m in 2015 to $4728.8m in 2024, according to the report 'Vertical Cavity Surface Emitting Laser (VCSELs) Market - Global Industry Analysis, Size, Share, Growth, Trends, and Forecast 2016 – 2024' from Transparency Market Research (TMR).

Currently, there is demand for efficient, low-cost and compact illumination systems, replacing traditional thermal imaging systems, notes the report. VCSELs are used for infrared illumination since they offer advantages including low cost, high reliability, efficiency, a narrow emission spectrum, and a low-divergence cylindrical beam. Infrared illuminators, in turn, find application in surveillance, imaging, covert operations and detection in several end-use sectors such as the military. This has had a considerable impact on the demand for VCSELs, says the report.

By raw materials, the VCSEL market is led by gallium arsenide (GaAs), which accounted for a massive 77% share in 2015. The segment is expected to register a CAGR of 41.1% during the forecast period.

By application, the overall VCSELs market is dominated by optical fiber data transmission, followed by laser printers and computer mice. Chip-sale atomic clocks and absorption spectroscopy, on the other hand, will register strong growth through 2024.

By geographical region, Europe accounts for the leading share of the VCSELs market, at just under 30% in 2015, but the Asia-Pacific will see an impressive CAGR of 23.1% over 2016-2024, forecasts the report.

3.3 MarketAndMarkets

Quoted from the summary of the report "VCSEL Market by Type (Single Mode VCSEL and Multimode VCSEL), Application (Data Communication, Sensing, Infrared Illumination, Pumping, Industrial Heating, and Emerging Applications) End users, and Geography - Global Forecast to 2022".

The VCSEL market was valued at USD 954.6 Million in 2015 and is expected to reach USD 3,124.1 Million by 2022, at a CAGR of 17.3 % during the forecast period.

Multimode VCSELs held the largest market share in 2015 and is expected to exhibit high growth rate during the forecast period. The multimode VCSEL is the major contributor to the overall market. The market for multimode is increasing rapidly. Multimode are suitable for long-haul transmissions as they offer better modulation compared to single-mode VCSELs. Multimode are thus used in precision sensing and datacom applications. The high-speed capability of multimode VCSELs has increased its use in data communication.

The major companies such as Broadcom Limited (U.S.), Finisar Corporation (U.S.), Lumentum Holdings Inc. (U.S.), II-VI Incorporated (U.S.) and Vixar Inc. (U.S.), among others, have been responsible for the dynamic growth of the market in North America. Data communication is a key application driving the demand for this in North America. The adoption of the Internet of Things (IoT) for effective performance has resulted in the generation of huge amounts of data. This has increased the implementation of data centers.

Other major players operating in this market include II-VI Incorporated (U.S.), IQE PLC (U.K.), Vertilas GmbH (Germany), Princeton Optronics Inc.(U.S.),Vixar Inc. (U.S.) and Santec Corporation (Japan).

3.4 Heavy Reading

2017 has proved to be the "hockey-stick" year for 100G Ethernet with optical module vendors struggling to meet demand. Growing 100G manufacturing volume and reducing costs are key objectives for optical module and component suppliers as they seek to "cash in" on this demand. Cost reduction approaches include innovative module assembly, silicon photonics, smaller modules such as SFP-DD and reducing the number of lanes/wavelengths.

The first 400G optical modules for use in data center and enterprise applications are becoming available in the CFP8 form factor, as shown below.

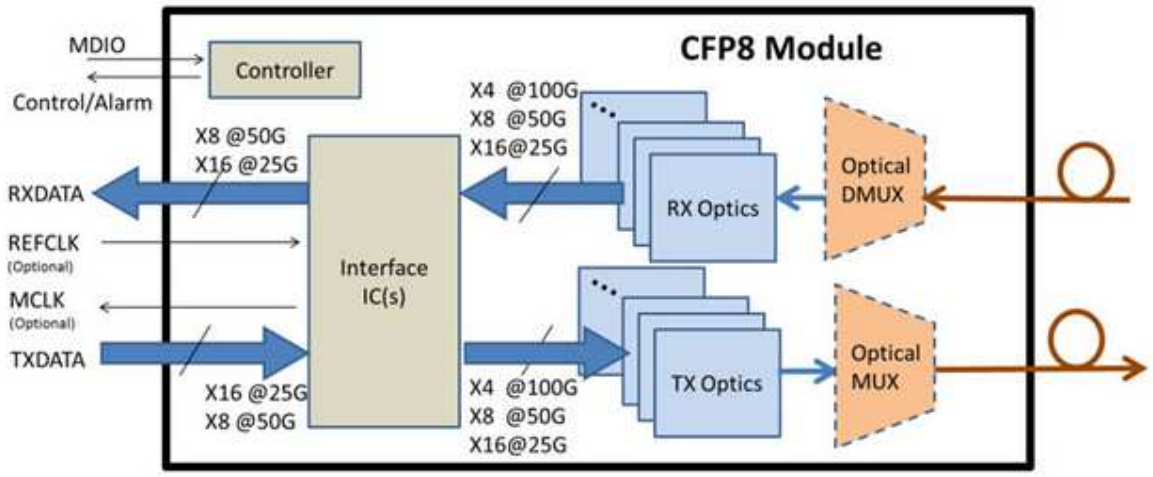


Figure 1: CFP8 module.

The next generation will use QSFP-DD or OSFP. Enhanced DSPs are now enabling 200G with 16QAM modulation and the next generation will support 400G and 600G with 64QAM modulation. These developments are crucial to meet the bandwidth demands between data centers.

QSFP28 modules and active optical cables for 100G data center and enterprise applications are available from almost 30 vendors. Many vendors have also introduced SFP28 modules to support 25G Ethernet to servers. 100G CFP, CFP2, CFP4 and CXP modules are available from some vendors. The highest volume QSFP28 modules are PSM4 and CWDM4 ports used in hyper-scale data centers and other applications. The first 200G optical modules have been introduced using QSFP56 with PAM4 coding or QSFP-DD with dual 100G ports.

We are seeing huge demand for 100G in the data center and elsewhere and expect the 100G optical module market to become very competitive through 2018, as the cost of modules is reduced and production volumes grow to meet the demand. The first solutions for 200G and 400G are already available. The industry is now working on cost reduced 100G, higher density 400G and possible solutions for 800G and 1.6 Tbps. All approaches are using advanced coding and modulation, particularly PAM4 for data centers and enterprise and 16/64QAM for DCI, metro and long haul. These developments require substantial investment by vendors and this is likely to lead to further consolidation in the industry.

3.5 Communications Industry Researchers, Inc

Quoted from CIR.

The market for embedded optics is expected to reach US$5.5 Billion in 2022, according to "The Embedded Optics Market: COBO and its Alternatives - 2017-2026," a new report from Communications Industry Researchers, Inc. an optical networking industry analyst firm. The report notes that the standardization efforts of the Consortium for on-Board Optics (COBO) group could make embedded optics technology much more popular in the optical networking industry and lead to a new "post-pluggable" transceiver era.

- COBO has recently formally defined its connector standards and is currently working on embedding coherent optics into its standards. By 2022 CIR expects COBO-compliant products to generate revenues of US$1.5 Billion. However, not all players believe that there is a need for COBO, claiming that optical networking that QSFP-DD and OSFP pluggables can support optical networking up to the Terabit networking era.

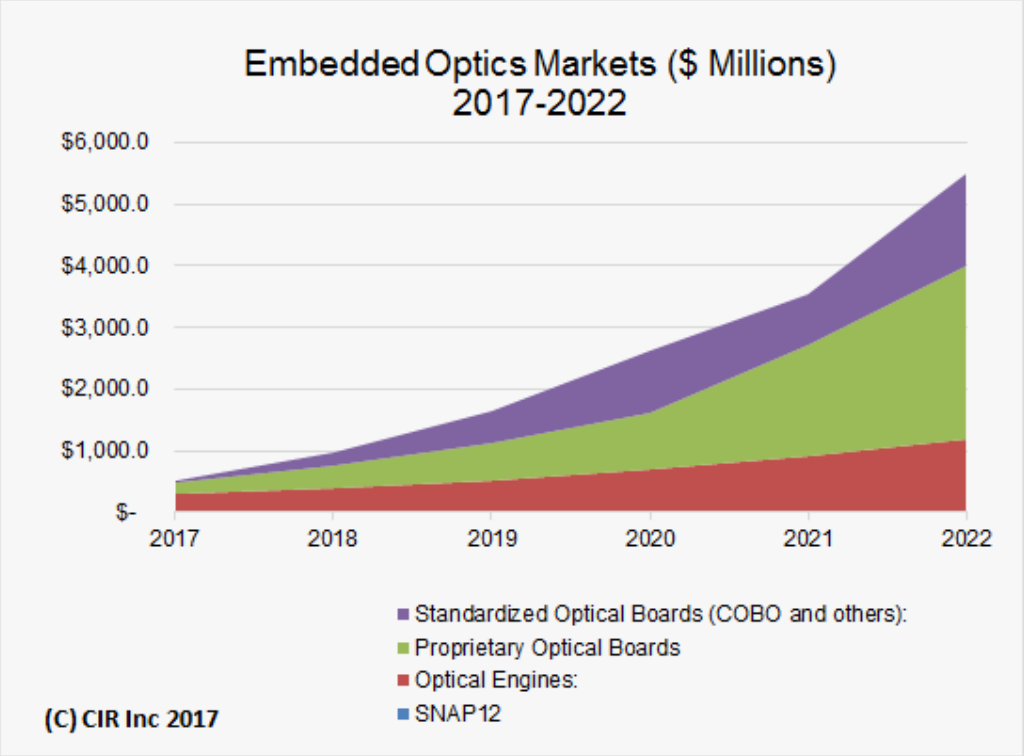


Figure 2: Embedded optics markets until 2022.

- The current generation of 200 Gbps to 300 Gbps optical engines have never been huge revenue generators, causing some firms (notably TE Connectivity) to drop out the market. However, the report anticipates that a new generation of optical engines will emerge that will be more appropriate to the needs of today's optical networks. For example, Furukawa Electric has demonstrated a 1.3 Tbps optical engine. Elenion Technologies' optical engine incorporates modulation flexibility. Gigalight, has also released an optical engine with advanced optical monitoring capability. Based on the new functionalities of optical engines, the optical engine will grow to reach US$2.8 Billion in revenues by 2022.

- The report also suggests that the rise of embedded optics will stimulate the need for novel component technologies. In particular, it notes that VCSEL technology will run out of steam at above 50 Gbps or below-data rates that embedded optics is expected to operate at. Embedded optics firms will increasingly need to think about alternatives. Ranovus, with its quantum dot lasers, looks especially interesting in this regard. There may also be some opportunities for additional cooling components and heat sinks for embedded optics - as data rates go up pre-heating of the air by high power ICs can present thermal challenges for optics.

4 Developments in relevant standards

This chapter is an update of the report D2.5 (market study, evaluation of application and product specification.) It touches briefly upon the application markets for ADDAPT technology, addresses briefly the issue of network protocols, and then focusses on volumes for the various markets.

As there is no big company in the consortium actively involved in (network) standardization and since it makes more sense to actively pursue standardization without having patented the key issues, we did follow recommendation number 4 “If the Consortium does not find a big company to sponsor the ADDAPT solution within the standardization groups, consider not to put more resources on that activity and concentrate on single sub-system exploitation. “

However, the development of standards have been followed and analysed for opportunities to implement ADDAPT technology

Where relevant, we mention a few updates.

4.1 Emerging standards

4.1.1 New PCI-express derived protocols expected in 2017 and later are:

1. **PCIe over fiber** products,[PLX][Adnaco][Samtec] but these generally find use only in specific cases where transparent PCIe bridging is preferable to using a more mainstream standard (such as InfiniBand or Ethernet) that may require additional software to support it; current implementations focus on distance rather than raw bandwidth and typically do not implement a full ×16 link. Products on the market have a range from few meters up to 8 km over single mode fiber, with throughputs up to 300 Mbps. Not relevant as a market for ADDAPT type of technology.
2. **OCuLink** (stands for "optical-copper link") is an extension for the "cable version of PCI Express". It seems to have disappeared, no products, no news in the last two years.

4.1.2 Intel Omni Path

Products are on the market. “Intel is also doing well on the networking front, with its OmniPath kit now present in 38 of the top 500 supercomputing list. A year ago Intel could count claim only eight machines. Ethernet's present on 207 machines compared to InfiniBand on 178. But InfiniBand is present in 42 of the top 100, where Ethernet claims just one user.” (www.theregister.co.uk/2017/06/20).

One of OmniPath (OPA) features is **Dynamic Lane Scaling**

Dynamic Lane Scaling allows an operation to continue even if one or more lanes of a 4x link fail, saving the need to restart or go to a previous checkpoint to keep the application running. The job can then run to completion before taking action to resolve the issue. Currently, InfiniBand typically drops the whole 4x link if any of its lanes drops, costing time and productivity.

It looks a bit like one of the applications of ADDAPT (but was not implemented): switch of lanes if load too low:

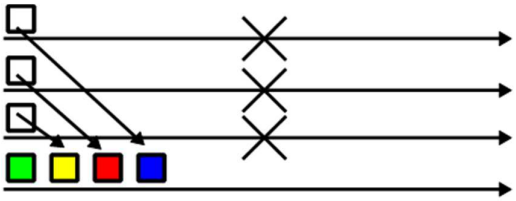


Figure 3: ADDAPTive switching approach of just keep 1 lane running.

In OmniPath's case the switching is done also, but with a different objective: uninterrupted data stream even with one of the lane disrupted, and probably differently: from 4 to 2 lanes, in contrast to ADDAPT, which switches from 4 to 1 lane with the objective to save energy.

OmniPath competes with Infiniband in latency, costs and ports per switch. On one hand, it is a further evaluation of already existing technology, yet it is also a new development and thus has more 'room' to accept new technologies like ADDAPT. We believe OmniPath is a high potential application for ADDAPT.

4.2 (Competing) Developments in Ethernet.

We did find quite some efforts to reduce the energy spent in the lower network layers (PHY and DLL), both for Ethernet and for Infiniband. However, except for ECONET (which is more a framework approach then a technical development project) and a paper, we found no evidence that anybody is working on fast switching on/off of lanes. See also report D2.5.

In Ethernet, most efforts are on optical single mode technology at 1300 – 1550 nm wavelength.

In November 2017, a new request for further emphasis on multimode technology at 850 nm will be discussed.

Below we will give examples of what we believe are the most relevant examples.

4.2.1 Developments in Energy Efficient Ethernet

There are no new development in EEE. (compared to report 2.5)

4.2.2 Developments in 400 Gbps Ethernet

2 km / SMF / PAM4 SMF

During the work in this Task Force, the insights emerged that 500 m and 2 km singlemode fibers (SMF) needs more emphasis, and that 200 GbE is to be standardized.

This resulted in extra focus on SMF / PAM-4 / 2 km distances.

The view that 2 km SMF is important and shall be standardized is supported by OEM's and Suppliers (802.3bs, Stassar01_o615_smf/pdf) in June 2015:

- OEM: Ciena, Coriant, Huawei, Brocade, Eriscson, Juniper, IBM, Infinera, NEC, ALU, ZTE,
- and suppliers: Cornich, DNS, Xilinx, Aurrion, Avago, Finisar, OFS, Broadcom, Panduit.

Eventually, this effort resulted in the DR4 (separated lanes up to 500 m) and FR (WDM lanes up to 2 km), and LR (WDM lanes up to 10 km).

The idea is, that longer distances (>0.5 km) justify the extra investments in the WDM modulator, compared to separated lanes until this 0.5 km distance. For the sort range (<100 m) multimode is cheaper.

Generally speaking, it has always been the case that after many years of technology development, faster rate optics become lower cost than lower rate optics.

This resulted in a re-formulation of objectives for this study-group are re-formulated (new objectives in italic font) in document 50G/NGOATH & 200GSMF Study Groups Joint Meeting, Macau, China, Mar 2016 Plenary 5

- Support a MAC data rate of 200 Gbps
- Support a MAC data rate of 400 Gbps
- Support a BER of better than or equal to 10^-13 at the MAC/PLS service interface (or the frame loss ratio equivalent)
- Support full---duplex operation only
- Preserve the Ethernet frame format utilizing the Ethernet MAC
- Preserve minimum and maximum FrameSize of current Ethernet standard
- Provide appropriate support for OTN
- *Provide physical layer specifications which support 200 Gbps operation over:*
    - *At least 500m of 4---lane parallel SMF*
    - *At least 2 km of SMF*
    - *At least 10 km of SMF*
- Provide physical layer specifications which support ***400 Gbps operation over:*** link distances of:
    - At least 100 m of MMF
    - At least 500 m of SMF
    - At least 2 km of SMF
    - At least 10 km of SMF
- Specify optional Energy Efficient Ethernet (EEE) capability for 400 Gbps PHYs
- Support optional 400 Gbps Attachment Unit Interfaces for chip-to-chip and chip-to-module applications

The standard is now (04 October 2017) at version D3.4. The expectation is that soon a version D3.5 will be released, that will transition to the final version.

The Task Force defined the following physical interface descriptions, see Table 2: Standard PMD's in taskforce 802.3bc.

Table 2: Standard PMD's in taskforce 802.3bc.

Name	Description	Baudrate	Modulation	wavelength
200GBASE-DR4	200 Gbps PHY using 200GBASE-R encoding over four lanes of one pair of single-mode fiber with reach up to at least 500 m (Clause 121)	26.5625 GBd	PAM4 / WDM	1304.5 to 1317.5 nm
200GBASE-FR4	200 Gbps PHY using 200GBASE-R encoding over four lanes of one pair of single-mode fiber with reach up to at least 500 m (Clause 122) wavelength-division-multiplexed lane	26.5625 GBd	PAM4 / WDM	1271 1331 nm

	assignments for 2 – 2000 m			
200GBASE-LR4	200 Gbps PHY using 200GBASE-R encoding over four lanes on one on pair of single-mode fiber with reach up to at least 10 km (Clause 122)	26.5625 GBd	PAM4 / WDM	1295 – 1309 nm
400GBASE-FR8	400 Gbps PHY using 400GBASE-R encoding over eight PAM4 modulated WDM lanes on one pair of single-mode fiber with reach up to at least 2 km (Clause 122)	26.5625 GBd	PAM4 / WDM	1273 – 1309 nm
400GBASE-LR8	400 Gbps PHY using 400GBASE-R encoding over eight PAM4 modulated WDM lanes on one pair of single-mode fiber with reach up to at least 10 km (Clause 122)	26.5625 GBd	PAM4 / WDM	1273 – 1309 nm
400GBASE-SR16	400 Gbps PHY using 400GBASE-R encoding over sixteen lanes of 16 pairs of multimode fiber with reach up to at least 100 m (Clause 123)	26.5625 GBd	NRZ	850 nm
400GBASE-DR4	400 Gbps PHY using 400GBASE-R encoding over four lanes of one pair of single-mode fiber with reach up to at least 500 m (Clause 124)	53.125 GBd	PAM4 / WDM	1310 nm

Status of 802.3bs

This version has been accepted with a few remarks:

Status

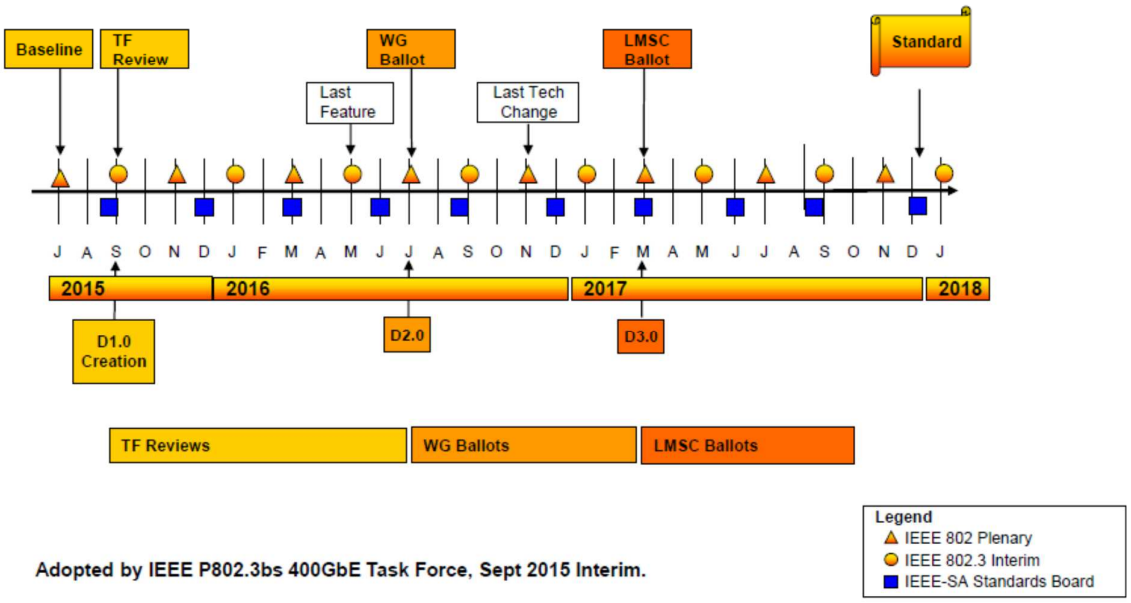
P802.3bs D3.4 Sponsor ballot recirc.

- Opened 18 September 2017
- Closed 3 October 2017
- 15 day comment period
- 12 comments (2 withdrawn)
- Thanks to those who commented
- Proposed responses posted

	D 3.4		
Voters	134		
Approve	114	99.1%	≥ 75%
Disapprove	1		
Abstain	4	3.4%	< 30%
Returns	119	88.8%	≥ 75%

The expectation is that the standard will be accepted per end of October 2017.

Timeline 802.3bs



4.2.3 Working-group 802.3dc (50 Gbps Ethernet).

In the plenary meeting in Sept 14th-16th, 2016 Fort Worth, Texas, it was decided to also standardize 50 Gbps MAC speeds and appropriate lanes for this.

The objective of this working-group has been formulated as:

General: (this is identical to 802.3bs)

- Support full-duplex operation only
- Preserve the Ethernet frame format utilizing the Ethernet MAC
- Preserve minimum and maximum FrameSize of current IEEE 802.3 standard
- Support optional Energy-Efficient Ethernet operation
- Provide appropriate support for OTN
- Support a MAC data rate of 50 Gbps and 100 Gbps
- Support a BER of better than or equal to 10^-12 at the MAC/PLS service
- interface (or the frame loss ratio equivalent) for 50 Gbps and 100 Gbps operation
- Support a MAC data rate of 200 Gbps
- Support a BER of better than or equal to 10^-13 at the MAC/PLS service
- interface (or the frame loss ratio equivalent) for 200 Gbps operation

50 Gbps Ethernet PHYs

- Define single-lane 50 Gbps PHYs for operation over
  - copper twin-axial cables with lengths up to at least 3m.
  - printed circuit board backplane with a total channel insertion loss of <= 30dB at 13.28125 GHz.

- At least 100 m of MMF
- At least 2 km of SMF
- At least 10 km of SMF

100 Gbps Ethernet PHY's

- Define a two-lane 100 Gbps PHY for operation over
    - copper twin-axial cables with lengths up to at least 3m.
    - printed circuit board backplane with a total channel insertion loss of <= 30dB at 13.28125 GHz.
    - At least 100 m of MMF
- Define a single lane 100 Gbps PHY for operation over duplex SMF with lengths up to at least 500 m, consistent with IEEE P802.3bs clause 124

200 Gbps Ethernet PHY's

- Define four-lane 200 Gbps PHYs for operation over
    - copper twin-axial cables with lengths up to at least 3m.
    - printed circuit board backplane with a total channel insertion loss of <= 30dB at 13.28125 GHz.
    - Define 200 Gbps PHYs for operation over MMF with lengths up to at least 100m

This work resulted in standardisation of the following lanes. See table Table 3: Standard PMD's in Task Force 802.3dc

Table 3: Standard PMD's in Task Force 802.3dc.

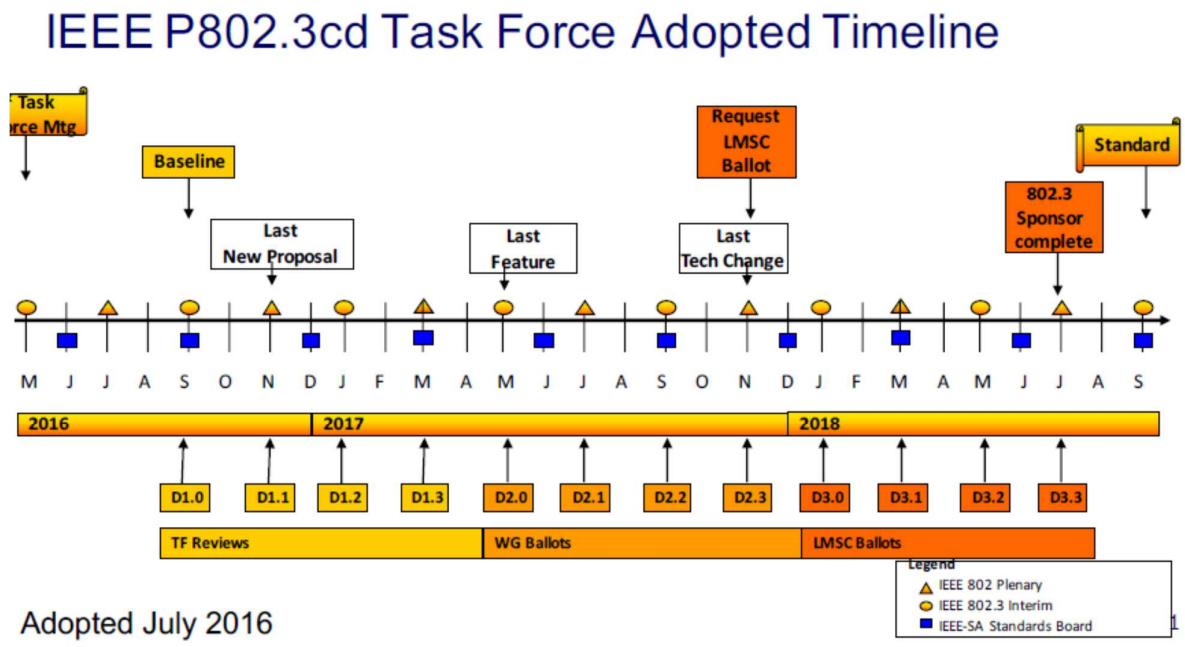
Name	Description	Baudrate	Mod'n	wavelength
50GBASE-CR, 100GBASE-CR2, 200GBASE-CR4	Cable assembly that supports single-lane links between two 50GBASE-CR PHYs with achievable cable length of at least 3 m (Clause 136)	26.5625 GBd	PAM4	Shielded twisted pair
50GBASE-KR, 100GBASE-KR2, 200GBASE-KR4	50GBASE-KR, 100GBASE-KR2 and 200GBASE-KR4 PHYs is an implementation-dependent direct electrical connection between the PMD and the medium. The MDI comprises 2 × n differential pairs, one pair for the transmit function and one pair for the receive function on each lane. Its use is for backplanes. (Clause 137)	26.5625 GBd	PAM4	backplane
50GBASE-SR, 100GBASE-SR2, 200GBASE-SR4	Multimode fiber medium. The optical signals generated by these three PMD types are modulated using a 4-level pulse amplitude modulation (PAM4) format. The PMD sublayers provide point-to-point 50, 100, and 200 Gigabit Ethernet links over one, two, or four pairs of multimode fiber, with a reach of up to at least 100 m. (Clause 138)	26.5625 GBd	PAM4	Multimode <100 m
50GBASE-FR,	50 Gbps PHY using 50GBASE-R encoding over onet PAM4 modulated WDM lanes on one pair	26.5625	PAM4	1311 nm

50GBASE-LR	of single-mode fiber with reach up to at least 2 km (Clause 139) / WDM	GBd		
100GBASE-DR	100 Gbps PHY using 100GBASE-R encoding over one lane of single-mode fiber with reach up to at least 500 m (Clause 140)	53.125 GBd	PAM4	1311 nm

Status

IEEE *Draft* P802.3cd/D2.2 IEEE P802.3cd Task Force was sent out on 25th September 2017 out for review and comment.

Timeline Task Force 802.3cd



4.2.4 Next-generation 200 Gbps and 400 Gbps MMF PHYs call for interest

IEEE received a request for a Next-generation 200 Gbps and 400 Gbps MMF PHYs call for interest from Robert Lingle. It will be discussed at the IEEE 802 LMSC November 2017 Plenary meeting in Orlando, FL, USA.

Links comprising multimode fiber (MMF) cable and VCSEL-based transceivers have played a key role in implementing 40 Gbps and 100 Gbps Ethernet in data centers for short reach. The continual growth of bandwidth demand has driven evolution of higher Ethernet speeds, most recently with 200 Gbps and 400 Gbps Ethernet, as demonstrated by related IEEE 802.3 projects over the past 4 years. To better support the installed base of MMF cables and to reduce the relative cost of short reach links, we request a call for interest to assess support for a Study Group to develop the PAR and CSD for next-generation 200 Gbps and 400 Gbps PHYs over fewer MMF pairs than existing Ethernet projects.

The call for interest will take place during the IEEE 802.3 Opening Plenary on the morning of Monday 6th November. A call for interest consensus building meeting has been scheduled to occur from 20:30 to 21:30 on the evening of Tuesday 7th November. The vote to determine if a Study Group will be formed will take place at the IEEE 802.3 Closing Plenary on the afternoon of Thursday 9th November.

This Study Group will be of high interest for ADDAPT: it is about defining new standards for multimode cable for 200 Gbps and 400 Gbps space, which is the area where ADDAPT is operational.

4.2.5 FlexE, Flexible Ethernet

FlexEthernet, also called FlexE, is a flexible Ethernet client interface standard defined by the OIF Flex Ethernet Implementation Agreement. FlexE provides a generic mechanism of supporting a variety of Ethernet MAC rates (10G, 40G, nx25G) that may or may not correspond to existing Ethernet PHY (physical layer) rates. The standard is being integrated in the 802.3 standard by the IEEE P802.3 Revision to IEEE Std 802.3-2015 (IEEE 802.3cj) Maintenance #12 Task Force. This means that FlexE allows for flexible Ethernet connectivity between routers and optical transport equipment that is independent of the physical interfaces between the two devices. The net benefit is the ability to remotely adjust service bandwidth as needed, more efficiently utilize each networking layer, and improve end-to-end manageability of the network.

FlexE dissociates the Ethernet rate on the client side from the actual physical interface (also called server) by introducing a new shim through the IEEE defined MAC and PCS layers.

FlexE was originally conceived to meet the challenges of Internet Content Providers (ICPs), to provide higher capacity and more efficient data center interconnect (DCI). With the list of Ethernet standards for use in the data center seemingly expanding by the day (e.g. 10GE, 25GE, 50GE, 100GE, 400GE), efficiently mapping these rates across an optical transport network for data center interconnect gets increasingly complicated. That is where FlexEthernet comes into play.

FlexE is all about introducing flexibility at the service layer. FlexE dissociates the Ethernet rate on the client side from the actual physical interface (also called server) by introducing a new shim through the IEEE defined MAC and PCS layers. This creates new configuration options that can be used to realize the savings and scale that are so vital to networking success. The current FlexE standard is defined for 100G PHYs, with 200G/400G PHYs being defined in subsequent Implementation Agreements.

Impact for ADDAPT

ADDAPT is flexible with its capacity. Its lanes can be dynamically reconfigured (albeit with some latency) to other speeds. In our implementation, it can operate at 7 – 14 – 28 – 56 Gbps, but other speeds are possible as well.

FlexE supports both sub-rating (routing a 100 Gbps MAC to a e.g. 4 x 7 Gbps physical medium), as well as over-rating: routing several lower speed Ethernet services over a high speed 4 x 56 Gbps physical network.

ADDAPT needs a strong supporter to discuss this in the (yet-to-be-founded) FlexE studygroup.

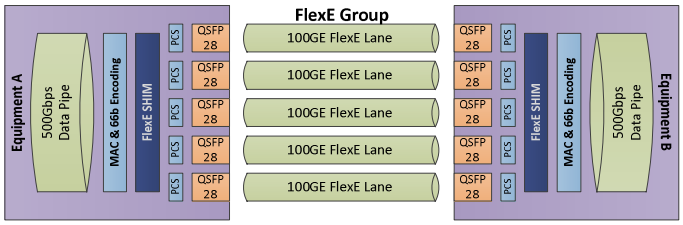
Status of FlexE in OIF.

A draft standard in OIF has been produced. Document oif2015.420.06 and an upgrade in oif2016.246.01 and defines 100G PHYs. Right now, FlexE 2.0 is being discussed in OIF.

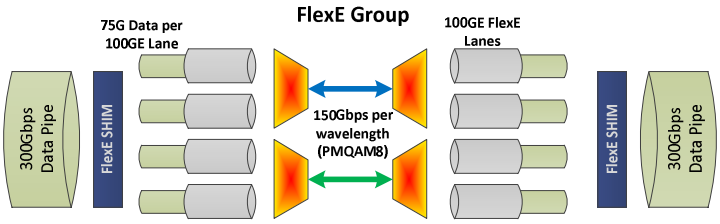
System vendors are in the process of implementing FlexE into their equipment and we will see the first FlexE-capable products starting to become available in 2018.

The **key features** that the FlexE IA supports are:

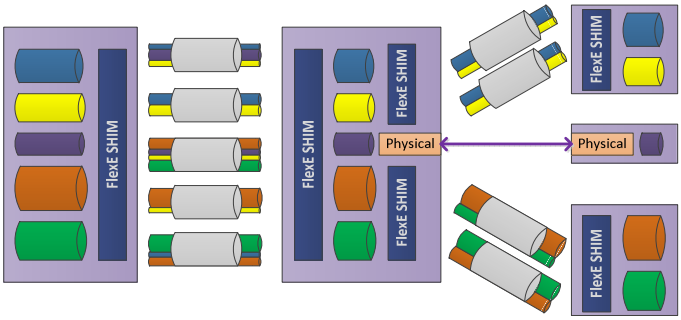
- **Bonding of Multiple Links** – this allows an operator to create a larger link out of multiple slower links.



- **Sub-rating of Links** – this allows an operator to only use a portion of a link.



- **Channelization of Links** – this allows one link to carry several lower-speed or sub-rated links from different sources.



The **key properties** of FlexE are:

- FlexE is backwards compatible with existing physical layer solutions. A FlexE compatible interface can leverage standards-based optical modules, electrical cables and backplanes.
- FlexE reuses many mechanisms from Ethernet. Much of the new functionality is achieved by adding a calendar that interacts with the existing Ethernet 64b66b mechanism, allowing bandwidth to be allocated with 5 Gbps granularity.
- FlexE is defined to make use of standards-defined physical lanes.
- FlexE is backwards compatible with the existing transport infrastructure. A FlexE compatible interface can be connected to a piece of transport gear that is not aware of FlexE.
- The optional use of FlexE-aware transport equipment provides additional functionality such as matching client and line rates.
- FlexE can utilize the entire aggregated link, creating a compelling an alternative to traditional Link Aggregation (LAG) solutions, which use 70-80% of a link. FlexE has deterministic performance, whereas LAG does not.

- FlexE has low added latency as compared to Ethernet.
- FlexE has a set of features to support its use in transport networks.
- The OIF task group that developed FlexE has active liaison relationships with the IEEE.802.3 and the ITU.

Products with FlexE 1.0

Ciena recently announced the Liquid Spectrum solution that combines programmable hardware with advanced software applications to provide increased automation and the ability to flexibly adjust capacity as needed in the network. Ciena's new WaveLogic Ai coherent chipset expands channel capacity options from what has been possible to-date – allowing users to tune capacity from 100G to 400G in 50G increments. With FlexE, users will now have a very simple means of adjusting and matching the service rate to any flexible line rate – with no site visits required – resulting in a more efficient and simpler-to-manage network.

4.3 Infiniband

No effort has been spent further on Infiniband, as there is no longer an OEM in the consortium.

Instead, we focussed on the method to implement "adaptivity" in Ethernet. Cool Optics (a spin off initiated from ADDAPT but not part of ADDAPT consortium) came to the conclusion that following the "dedicated decoding layer in PMD" approach is the most effective way to implement "ADDAPT" in Ethernet. We have reasons to believe (but no proof) that this approach will also work for Infiniband. Some aspects of Infiniband in the physical coding layer are to a certain extend similar to those of Ethernet.

4.3.1 Conclusion

Several ways exist to enable the ADDAPTive feature in an Infiniband context. We investigated three methods in the previous project period, and they all have their strong and weak points, and have more or less impact on the Infiniband Architecture (IBA). Following recommendation no. 4 of the last review we decided to not spend effort in discussing this with IBTA due to the lack of big involved partner.

4.4 ADDAPTiveness in Ethernet Standard

4.4.1 Benefit of ADDAPT in an Ethernet Context

In Report D2.5 we reported there are three basic ways to control the usage of ADDAPT:

1. related to the appearance of idle,
2. related to the Fast Wake state, or
3. related to the Deep Sleep state.

In this last period, Cool Optics worked further on the concept of "switching off when idle" and how to fit that in the Ethernet standard.

Within the ADDAPT consortium, due to the absence of 1) an OEM, and 2) proof of concept, and 3) submitted patents, and 4) recommendation no. 4 ("do not spend effort on standardization if no OEM"), we did not spend efforts on trying to standardize this approach into Ethernet.

4.4.2 50 Gbps NRZ in Ethernet standardization

Presently the 802.3bs Task Force is formulating the 400 Gbps clauses, see also Section "4.2.2 Developments in 400 Gbps Ethernet". No NRZ standard has emerged into this standardization effort.

Our demonstrator should provide convincing evidence w.r.t. costs or energy consumption. Our assessment is that a 400GBASE-SR8 specification based on ADDAPT, can easily compete with a 400GBASE-SR16 specification. To be investigated and pursued.

However, the OIF formulated a number of 50 Gbps / NRZ electrical standards (see Section 4.5 Optical Interconnect Forum).

Also, see Section 4.2.4 "Next-generation 200 Gbps and 400 Gbps MMF PHYs call for interest", a request has been made to work further within IEEE on multimode standardization for higher speeds.

4.5 Optical Interconnect Forum

The OIF facilitates the development and deployment of interoperable networking solutions and services. Members collaborate to drive Implementation Agreements (IAeements) and interoperability demonstrations to accelerate and maximize market adoption of advanced internetworking technologies. OIF work applies to optical and electrical interconnects, optical component and network processing technologies, and to network control and operations including software defined networks and network function virtualization. The OIF actively supports and extends the work of national and international standards bodies. Launched in 1998, the OIF is the only industry group uniting representatives from across the spectrum of networking, including many of the world's leading service providers, system vendors, component manufacturers, software and testing vendors.

OIF work is important, and there is a lot of interaction and collaboration between IEEE (Ethernet) and OIF. Generally speaking, you can say that OIF focusses more on the physical aspects of the transmission, whereas IEEE focusses more on signals and higher network layers.

Other than the IEEE802.3 groups, OIF spends a lot of effort on NRZ modulation.

For our work, particularly the work of OIF-CEI is important.

Current work is:

4.5.1 Physical and Link Layer Working Group/Physical Layer User Group Working Group

Table 4: Electrical 56 Gbps Standards by OIF-CEI.

standard	description	speed	length	Application	Conn	Loss
CEI-56G-USR	Ultra Short Reach	56 G	1 cm	2.5D / 3D applications,	0	
CEI-56G-XSR	Extra Short Reach	56 G	5 cm	Chip to nearby Optic Engine	0	5-10dB @ 28 GHz
CEI-56G-VSR	Very Short Reach	56 G	10 cm	Chip to Module	1	10-20dB @ 28 GHz
CEI-56G-MR	Medium Reach	56 G	50 cm	Chip to Chip & Midplane	1	15-25dB @ 14 GHz 20-50dB @ 28 GHz
CEI-56G-LR	Long Reach	56 G	100 cm	Backplane or Passive Copper Cable	2	35 dB @ 14 GHz
CEI-112G-VSR	Very Short Reach	112 G	10 cm	Chip to Module	1	56 Gbd / PAM-4

For our application, the following milestones are important:

Table 5: OIF standard documents.

Specification	Date	Remark
2014.277.08	31. August 2017 #307	CEI-56G-VSR-NRZ IA Draft Text Total # ballots received: 29 (23 “quorum voters” and 6 “non-quorum voters”) Total # of “Yes” votes: 15 Total # of “Yes with comments” votes: 2 Total # of “No with comments” votes: 1 Total # of “Abstain” votes: 11
2014.380.08	10 oct 2017 #310	CEI-56G-LR-PAM IA Draft Text Total # ballots received: 27 (20 “quorum voters” and 7 “non-quorum voters”) Total # of “Yes” votes: 17 Total # of “Yes with comments” votes: 3 Total # of “No with comments” votes: 1 Total # of “Abstain” votes: 6
2014.286.15	10 oct 2017 #311	CEI-56G-XSR-PAM IA Draft Text Total # ballots received: 27 (20”quorum voters” and 7 “non-quorum voters”) Total # of “Yes” votes: 18 Total # of “Yes with comments” votes: 1 Total # of “No with comments” votes: 2 Total # of “Abstain” votes: 6
2014.245.12	10 oct 2017 #309	CEI-56G-MR-PAM IA Draft Text Total # ballots received: 27 (20 “quorum voters” and 7 “non-quorum voters”) Total # of “Yes” votes: 18 Total # of “Yes with comments” votes: 3 Total # of “No with comments” votes: 0 Total # of “Abstain” votes: 6
2014.230.12	18 Sep 2017 #	CEI-56G-VSR-PAM IA Draft Text # “Yes” votes: 23 # “No” votes: 0 # “Abstain” votes: 6
2015.420.06	October 2015	Flex Ethernet 1.0, Implementation Agreement IA # OIF-FLEXE-01.0. Per *June 21, 2017* this upgraded to IA OIF-FLEXE-01.1 in document oif2016.246.01
2017.256.02	August 2017	FlexE 2.0 Implementation Agreement, Initial Text Proposal

This basically means that the industry developed a physical standard on 56 Gbps / NRZ. As a result, developers know the specifications of drivers, modulators, and traces on substrates and PCB’s to support this modulation.

Companies who supported this NRZ work are:

Brocade, Ciena Corporation, Credo Semiconductor (HK), Fujitsu, Huawei Technologies Co., Ltd., Inphi, Integrated Device Technology, Intel, Kandou Bus, Lumentum, Microsoft Corporation, NeoPhotonics, Nokia, Semtech, Sumitomo Osaka Cement, Xilinx, Broadcom Limited, Cavium, Mellanox.

Cisco voted against.

There are quite some differences between the OIF-CEI-VSR-PAM4 and NRZ standards, for which we refer to the relevant documents. Some key graphs are depicted below (derived from 2014.277.08)

(VSR is the standard for the electrical path between the network IC, over PCB (max. 10 cm), over connector, over interposer/PCB (max. 5 sm), and as such relevant for Active Optical Cable. AOC's are a high proportion of applications for ADDAPT technology)

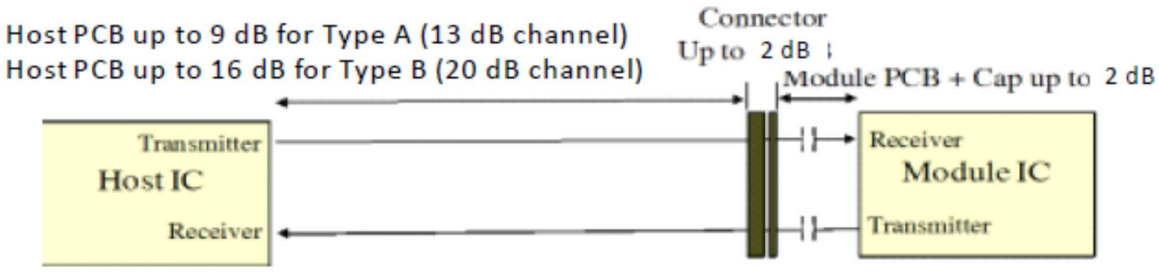
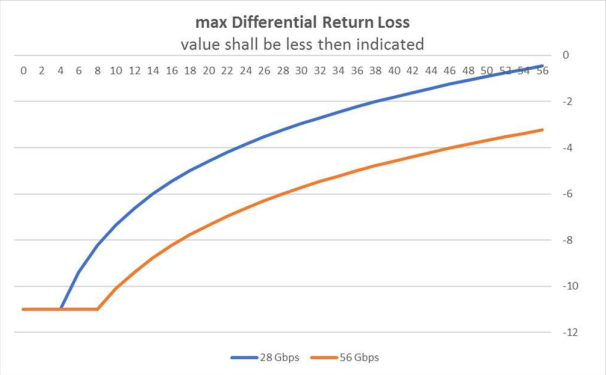
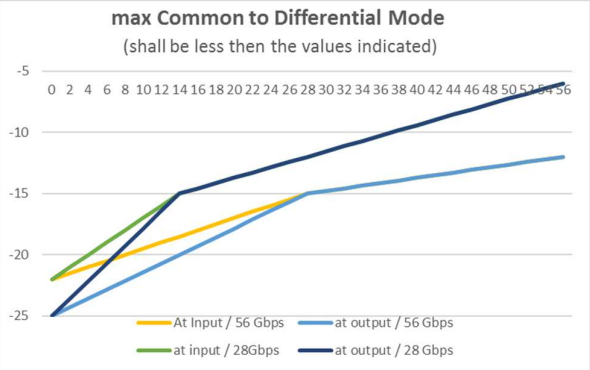


Figure 15-17. CEI-56G-VSR-NRZ full Channel Reference Model





5 Competing Solutions in the market

5.1 Summary/conclusion

It is hard to draw hard conclusions, but we observe the following:

1. 56 Gbps / PAM4 is now state of the art. The first products are all appearing. But so far all in 1300 – 1550 nm range
2. There are some examples of proprietary 50 Gbps / NRZ implementations. See Credo and Mellanox.
3. Silicon Photonics is getting more successful, albeit exclusively in 1300 – 1550 nm range in the high value solution where a lot of integrated functions are needed.

5.2 General Observation from OFC 2017

5.2.1 200 / 400 Gbps modules

A prominent issue at the show is the debate as to whether there is room for 200 Gigabit Ethernet modules or whether the industry is best served by going straight from 100 to 400 Gigabit Ethernet.

Facebook and Microsoft say they will go straight to 400G. Cisco agrees, arguing that developing an interim 200 Gigabit Ethernet interface does not justify the investment. In contrast, Finisar argues that 200 Gigabit Ethernet has a compelling cost-per-bit performance and that it will supply customers that want it. Google supported 200G at OFC 2016.

5.2.2 Silicon Photonics

Silicon photonics was one topic of interest at the OFC 2017 show and in particular how the technology continues to evolve. Based on the evidence at OFC, silicon photonics continues to progress but there were no significant developments. However, many companies are releasing silicon photonics based products, see a number of successful companies below releasing such products.

(from ExtremeTech, March 2015): The reason so many companies have pushed to bring this technology to market, despite the slow pace of progress, is that silicon photonics is generally believed to be necessary for exascale-level computing. Right now, copper and fiber typically split the transmission market by distance. Short-run cables between servers or racks tend to use copper, while longer distances rely on fiber.

Figure 4: roadmap on exascale computing and networking according to an Intel presentation on silicon photonics.

	2013	2016	2019	2022
Flops	20 P	160 P	1.28 E	10.2 E
Aggregate BW	80 Pbps	640 Pbps	5.12 Ebps	40.8 Ebps
Energy/bit	75 pJ/bit	11 pJ/bit	1.7 pJ/bit	250 fJ/bit
Size	< 2400 mm^3 / Gbps	< 120 mm^3 / Gbps	< 6 mm^3 / Gbps	< 50 mm^3 / Tbps
Cost	6 $/Gbps	1 $/Gbps	0.16 $/Gbps	< 0.02 $/Gbps

Above one can see a roadmap as believed feasible by the (photonics) industry. It is not really clear what the numbers exactly are, but it is clear that the industry believe that no a not-too-long timescale, networks hit the 1$/Gbps and the 1 mW/Gpbs marks. The ADDAPT consortium believes those numbers are far too optimistic. Also Market research bureaus are not so optimistic about SiPh, see chapter 3 "Market volumes according to market research organisations."

5.3 SWDM Technology

A group of companies (Commscope, Finisar, HBC, Hisense, Juniper, Lumentum, OFS, Prsymian) formed the shortwave wavelength division multiplexing (SWDM) alliance, who believe that the adoption of SWDM is a cost-effective means of transmitting multiple channels on one duplex MMF pair. The goal of the organization is to create and promote an industry ecosystem that fosters the adoption of SWDM for cost-effective data center interconnections over duplex multimode fiber at data rates at or above 40 Gbps. The SWDM Alliance is focused first on 40 Gbps (using four 10 Gbps wavelengths) and then on 100 Gbps (using four 25 Gbps wavelengths).

Shortwave data center connections are usually powered by VCSELs operating near a wavelength of 850 nm. SWDM is a technology that uses multiple VCSELs at different wavelengths around that 850 nm region to generate individual data streams, all multiplexed onto a single fiber pair. This is the same concept that is used in the Coarse Wavelength Division Multiplexing (CWDM) standards used in the longwave 1310 nm region operating over single mode fiber, except that SWDM is generated by VCSELs , which are a lower cost technology.

In an SWDM module, multiple SWDM VCSELs produce optical signals that are multiplexed onto a single fiber. All of the VCSELs and the optical multiplexing occur within the optical module. On the receive side of the module, the wavelengths are demultiplexed and then converted to parallel electrical signals.

SWDM offers users an alternate solution for 40 Gbps and higher connectivity over duplex MMF. Some of the many advantages of SWDM are:

- Reach – up to 440 m for 40G and 150 m for 100G
- Power Dissipation – As low as 1.5W* for 40 Gpbs
- Ability to easily tap for network security appliances
- Full DDM – including Tx power monitoring
- Operational and measurement simplicity – single Tx and Rx ports

5.3.1 Evaluation

Normally every three years the ICT infrastructure of a datacentre is renewed, due to obsoleteness of the technology. The question is, how does the cost of the extra MMF cabling compare to the extra cost of the more complex transceivers?

From a power dissipation point of view, this development is not a threat to ADDAPT: ADDAPT performs, even without adaptivity, at 4 mW/Gpbs, whereas SWDM performs at 37 mW/Gpbs, almost 10x as much. In fact, a single pair of ADDAPT also performs at 40 Gbps, and is as such a direct competitor of this initiative, at a 10x lower power dissipation.

5.4 Credo Semiconductors

5.4.1 Competing 56 GBps NRZ modulation by Credo.

In 802.3bs and 802.3cd, Huawei, Molex, Mitsubishi and Credo Semiconductor play a major role in promoting 56 Gbps / NRZ. Their efforts resulted not in an agreed "PAR" (IEEE word for an approved project to actually standardize a particular idea). Particularly Huawei, Molex and Credo-Semiconductor work together in this. They mentioned a number of demonstrations, such as:

5.4.2 Credo 50 Gbps at DesignCon 2015

Molex and Credo to Demonstrate 50 Gbps NRZ live serial traffic at DesignCon 2015. Demo will utilize Molex zQSFP+™ cable assembly and zQSFP+ SMT connector interface.

LISLE, IL – January 22, 2015–Molex Incorporated and Credo Semiconductor, Milpitas, CA, announced they will be demonstrating 50 Gbps NRZ live serial traffic at the upcoming DesignCon 2015, to be held Jan. 27-30 in Santa Clara, Calif. The demonstration will take place in Molex booth 619. The companies will use a high speed copper cable to demonstrate, for the first time, 50 Gbps NRZ live serial traffic on the zQSFP+™ form factor.

Credo will supply transmitting and receiving electronics and will drive a cable assembly using a 50 Gbps, NRZ encoded data stream, demonstrating this new level of performance at acceptable BER across existing interconnects. The demo will use a Molex zQSFP+ cable assembly and a zQSFP+ SMT connector interface. The Credo 56G NRZ SerDes will drive three live demonstrations:

- a CEI-56G-VSR-NRZ channel,
- a CEI-56G-MR/LR-NRZ backplane and
- a CEI-56G-MR-NRZ passive copper cable.

Credo at DesignCon 2017

Credo Demonstrates 112G PAM4 SR, 56G PAM4 LR, and 56G NRZ SerDes Technology at DesignCon 2017:

- Keysight (Booth #725) and Amphenol (Booth #641) will showcase Credo's low power 112G PAM4-SR and 56G PAM4-LR technology.
- Molex (Booth #619) demos leverage Credo's 56G PAM4-LR and 56G NRZ LR SerDes IP over copper cables and backplanes.
    1. showing error-free 56G NRZ and 56G PAM4 live serial traffic ***Backplanes and Copper Cables*** with crosstalk aggressors on Molex's Impulse™ OD Backplane Connector System.
    2. Molex's Impel™ PLUS Backplane Connector System using Credo's 56G PAM4 LR evaluation system to transmit 56 Gbps PAM4 data, showing error-free performance.
    3. error-free 56G PAM4 traffic through an eight meter copper cable using the zQSFP+™form factor.
- Leoni (Booth #946), Credo is demonstrating long-reach 28G technology with showcasing 10-meter cables for data center connectivity.

5.5 Competing solution by Luxtera

5.5.1 Luxtera Ships Industry's First 2x100G PSM4 Silicon Photonics Embedded Optical Modules

(quoted from Luxtera announcement at OFC 2017)

LOS ANGELES, March 21, 2017 – OFC 2017 – Luxtera, the global leader in Silicon Photonics, today announced it is now shipping in volume the industry's first 2x100G-PSM4 (Parallel Single Mode fiber 4-lane) embedded optical transceiver, designed for cloud data center, enterprise, and telecom networking applications. The LUX62608 OptoPHY™ module was developed using Luxtera's patented and market proven Silicon Photonics integration platform, demonstrating its leadership and commitment to data center and mobile infrastructure networking innovation and excellence.

With its compact size and high-level of optoelectronic integration, the OptoPHY 2x100G-PSM4 embedded optical module can deliver high density, long reach optics at a fraction of the cost of two 100G front panel pluggable QSFP modules. As the prices of optical modules have come to dominate the interconnect equation, cost effective single mode optics have become increasingly important in the market.

The OptoPHY 2x100G-PSM4 optical transceiver has been selected by Ericsson as the optical interconnect for its industry leading Hyperscale Datacenter System HDS 8000. The HDS 8000 is the latest generation of cloud computing systems that uses a disaggregated architecture to improve efficiency, utilization, automation and total cost of ownership. OptoPHY functions as the optical interconnect for the HDS 8000's compute, networking, and storage sleds, allowing the system designers to avoid tradeoffs between reach and cost that constrain other disaggregated hardware solutions. This enables a more efficient pooling of key resources, improving performance, latency, utilization and energy consumption.

"With the growing demands of the hyperscale 29ieter2929g29, Ericsson has seen single mode optics become an increasingly critical part of the system network and PSM4 is a critical element in the design of our HDS 8000 optical interconnect," said Jason Hoffman, Global Head of Product Area, Cloud Infrastructure with Ericsson. "As data rates and reaches have increased, the limitations of contemporary optics have become more apparent, forcing end users to choose between low cost and long reach, placing hard constraints on 29ieter2929g29 architects. Luxtera's 200G silicon photonics solution changes this paradigm, by allowing long reach and low cost with best in class performance."

"Hyperscale datacenters are undergoing a tectonic shift as the industry moves to 100G infrastructure and single mode photonics become the mainstream interconnect," said Greg Young, president and CEO of Luxtera. "With the introduction of OptoPHY, we continue to lead the industry transition by delivering the only optical transceiver technology that can deliver 200G aggregate bandwidth with up to 2km of reach at the aggressive cost points needed for high volume deployments."

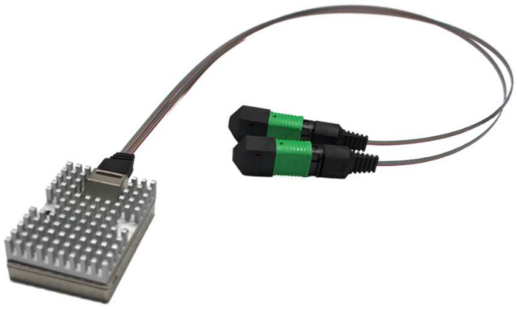
5.5.2 LUX62608 OptoPHY Product Details

Each Luxtera OptoPHY includes eight independently operating transmitter and receiver channels, integrating high-speed phase modulators, photodetectors, waveguides, grating couplers, high-speed electrical retimers, and integrated control circuitry, powered by a single integrated laser. These components combine into a fully integrated silicon photonics chipset with no additional external elements required.

Key Features:

- 200 Gbps aggregate bandwidth optical transceiver
- 2x100G PSM4 compliant
- Eight 26 Gbps independently operating channels, full-duplex operation
- Embedded optical module form-factor
- Multirate: 1 – 25.78 Gbps (per channel)
- Proven light source and packaging technology

- Extended reach up to 2000 meters
- Less than 5W typical power



5.5.3 Comparison to ADDAPT

Of course it is comparing apples to pears, yet there are few comments to be made:

	LUX62608	ADDAPT
Range	2000 m	100 m
Power	5 W	1 W without "ADDAPTivity" 0.25 W with "ADDAPTivity"
Technology	Silicon Photonics with InP	14 nm CMOS with GaAs optics
Lanes	8 * 25 Gbps	4 * 50 Gbps
Multirate	1 – 25 Gbps	7 – 56 Gbps
Potential fit to QSFP formfactor	No	Yes

5.6 Mellanox

5.6.1 OmniPath a treath to Infiniband?

From www.theregister.co.uk, June 2016:

OmniPath a threat? Paugh, says Mellanox, feel our gorgeous 200 Gbps. Mellanox reckons it can shrug off the threat posed by Intel's OmniPath technology, announcing silicon photonics-based devices running at 50 Gbps per QSFP lane for a total of 200 Gbps.

The silicon photonics devices demonstrated at this week's Optical Fiber Conference in the US will, the company says, form the basis of a suite of new products: direct attach copper cables for 50 Gbps and 200 Gbps for in-rack applications and silicon photonics optical transceivers for 200 metre and 2,000 metre reaches.

If 2,000 metres sounds excessive for data centre applications, there are two things to keep in mind. First, it's easy to rack up distance on a campus-scale bit-barn; and second, as Martin said, distance is frequently a shorthand for link budget, because cables go through patch panels and connectors.

"Often we use that reach number as shorthand for a 3.5 dB link, so it might be 500 to 1,000 metres plus connector loss."

Martin told *The Register* the company expects 200 Gbps data centre connections to start taking off during 2017 and accelerate during 2018, although "there are companies that would take it today, if it were available".

"We see servers moving to 50 Gbps connections, and if you have a 50 Gbps server, the 4:1 breakout the data centres user means they'll want the network to run at 200 Gbps – just like networks needed to run at 40 Gbps when we had 10 Gbps servers."

Sticking with the QSFP form factor maintains the symmetry that already exists when 200 Gbps networks are running through the data centres.

The key to Mellanox's silicon photonics work is a Franz–Keldysh modulator that's "on the order of 40 microns long", Martin said, while much of the industry is working on modulators "10 to 40 times larger".

"We've driven the modulator to 50-60 GHz, so we know it's ready for 50 Gbps channels", he added, and "it's the same modulator we already use for 4 x 25 Gbps … it's hard to tell the difference between a 100 Gbps and 200 Gbps chip."

The other key announcement at OFC is Mellanox's interoperability demonstration with InnoLight Technology, trading photons at 1300 nm and 1550 nm.

The different wavelengths, Martin said, reflect technologies with different heritage.

"The reason 1550 nm is used in the telecommunications world is that they want devices to suit the fibre amplifiers and DWDM systems," he said, "while 1310 nm is typical in shorter reach applications.

"We use 1550 nm because it works better with silicon photonics systems." Others like InnoLight are using 1310 nm transceivers.

The interoperability demonstration showed that the transmitters can operate at their native wavelengths, because optical detectors are "very wideband, and don't really care about the wavelength", he said. ®

5.6.2 Mellanox on Optical Fiber Conference, March 2016 by hpcwire.com

At the Optical Fiber Conference taking place from March 22-24 in Anaheim, Calif., Mellanox Technologies is announcing an "important milestone" on the road to High Data Rate (HDR) 200 Gbps InfiniBand and Ethernet networks. At the trade show, the company is demonstrating 50 Gbps silicon photonics optical modulators and detectors, which will comprise key elements of 200 Gbps and 400 Gbps LinkX cables and transceivers.

The 200 Gbps target assumes a 4-lane port and a50 Gbps signal rate. With 36 4x QSFP ports on the front panel of Mellanox's EDR Switch-IB,the 100 Gbps switch delivers7.2 Tb/s of aggregate throughput. Moving fromQSFP28 to QSFP56 modules doubles the front panel density for next generation switches to a potential 14.4 Tb/s switching capacity.

Mellanox says it is planning to offer 50 Gbps and 200 Gbps Direct Attach Copper cables (DACs); copper splitter cables; silicon photonics based AOCs for reaches to 200m; and silicon photonics transceivers for reaches to 2km. The 200 Gbps cables and transceivers will support previous generation 40 and 100 Gbps networks.

Technology based on silicon photonics:

- The FK modulator that Mellanox uses is 40 microns long and has achieved 60 gigahertz and higher in terms of performance.

- 50 Gbps / PAM4 modulation
- The detector architecture is germanium.
- The physical dimension which governs the speed of the device is the width of the waveguide. “In order to make it very fast, we narrow the width of that waveguide to speed the conversion of electrons to photons,” We can narrow the width of that waveguide at the modulator section very precisely and that gives us very high-speed devices – we use the same physical effect when we make the detectors.
- 4.5 – 5 W / 200 Gbps.
- 1550 nm, not 1300 nm because better integration with silicon photonics

5.6.3 InnoLight Technology

Mellanox and InnoLight announce the availability and interoperability of 100Gbps PSM4 Transceivers at 1310 (Innolight) and 1550nm (Mellanox) Wavelengths. InnoLight Showcases 400G OSFP and 400G QSFP-DD Products at ECOC 2017. It is all based upon Silicon Photonics technology.

- 400G OSFP SR8 -400G QSFP-DD SR8
- 400G OSFP AOC - 400G QSFP-DD AOC
- 400G OSFP 2X FR4 – 400G QSFP-DD FR4
- 400G OSFP LR8 – 400G QSFP-DD DR4
- 100G QSFP28 Single Channel DR/FR product.

5.6.4 Mellanox and Accelink Partner to Provide 100Gbps PSM4 Ethernet Transceivers

Mellanox Technologies, and Accelink Technologies, Co., Ltd. (SHENZHEN: 002281.SZ), a leading Chinese manufacturer of end-to-end optoelectronics components, today introduced a 1550nm 100Gbps PSM4 transceiver based on the silicon photonics optical engine from Mellanox.

5.7 Other solutions

The OIF’s Physical and Link Layer working group demonstrations include live 56G electrical interface interoperability with multiple silicon suppliers over a range of channel reaches from VSR (chip to module) to LR (backplane and copper cables) using both NRZ and PAM4 modulations. The expanding ecosystem for CFP2-ACO pluggable coherent optics will be showcased through live demos. Test equipment for 56G and coherent optics will also be demonstrated. The FlexE demo provides on-going validation of the implementation agreement.

OIF member companies have teamed up to demonstrate significant progress in delivering an interoperable ecosystem of suppliers and solutions for critical market needs:

- 56 Gbps live electrical signalling over all reaches
- CFP2-ACO Optical Interoperability
- FlexE (Flex Ethernet)

Public demonstrations will be on display March 21-23, 2017 at OFC in Los Angeles, CA in OIF Booth #3853. Additional information can be found here.

Also at OFC, the OIF will present “Enabling Next Generation Physical Layer Solutions” and host a workshop on “Serial 100Gbps electrical”. With the above mentioned 50Gbps CEI projects nearing completion, the industry is beginning the task of addressing serial 100G electrical links.

http://www.businesswire.com/news/home/20170221006330/en/OIF-Announces-Multi-Vendor-Interop-Demo-OFC

The OIF's Physical and Link Layer working group demonstrations include live 56G electrical interface interoperability with multiple silicon suppliers over a range of channel reaches from VSR (chip to module) to LR (backplane and copper cables) using both NRZ and PAM4 modulations.

Demo participants include Amphenol, Credo Semiconductor, Finisar, GlobalFoundries, Keysight Technologies, Inc., Lumentum, Molex, TE Connectivity, Xilinx and Yamaichi Electronics.

5.8 Startups

Many startups are emerging in the transceiver and/or silicon photonics space. A few of the more successful ones are mentioned below. This list certainly is not exhaustive and/or complete.

5.8.1 Rockley Photonics

(from their website)

Rockley Photonics was founded in 2013 by a leadership team previously successful with two silicon photonics companies. We are rapidly building an impressive multi-disciplinary team with extraordinary experience in integrated optics, CMOS electronics, software and computer networking. Rockley Photonics represents the commercialization of silicon photonics in its most exciting form to date.

We are expanding the utilization of light in the network by taking it out of the fiber and harnessing the superior characteristics of the photon over the electron for some specific tasks that allow us to drive photonics deeper into areas where electronics presently predominate. By relying on the inherent strengths of each medium, we apply the right mix of optics and electronics to enable high-speed networks to operate faster, more economically and at greater scalability than traditional systems allow.

Rockley Photonics Demonstrates Breakthrough Technology to Enable Scalable Next-Generation Data Center Networks

Pasadena, California, September 14, 2015:

Rockley Photonics is now prototyping its architecture using programmable chips (FPGAs) and custom photonic devices to prove the concept of scalable optical packet switching in a realistic system environment. Once it has fully evaluated the scalable system architecture, the company will move the design from its prototyping platform to system chips for production purposes. Commercial availability of these products is scheduled in 2017.

Rockley Photonics matches government funding from the Engineering and Physical Research Council (EPSRC) in a 'Prosperity Partnership' with the University of Southampton

Oxford, UK, 13 July 2017 – Rockley Photonics Limited, the UK's leading integrated technology and systems innovator for next-generation networks, will, over the next five years, match government funding from the EPSRC, and form a 'Prosperity Partnership' with the University of Southampton's Optoelectronics Research Centre (ORC). The money, totalling around £4.8 million, will be used to support research into how silicon photonics technology can be used to improve data centre communication networks and support a new integrated photonics platform for broader mass market applications.

5.8.2 Skorpios

Skorpios Technologies, Inc., an Albuquerque, New Mexico-based company offers unique intellectual property that represents a paradigm shift for the optical communications industry. The company's technological advantage will permit the industry to move away from expensive and difficult 3/5 materials as the chip platform to much lower-cost and widely understood Silicon materials. The company has raised over $40 million since formation, a majority of which has been received from strategic corporate investors including Ericsson, Juniper, NSN, Vodafone and Deutsche Telekom. www.skorpiosinc.com

Skorpios' unique technology and proprietary wafer scale process allow to monolithically integrate silicon with III-V gain materials used as the active medium, to create Silicon Photonic Ics.

This platform called Skorpios' Template Assisted Bonding (STAB) can be easily integrated into existing mature Silicon CMOS manufacturing facilities, enabling the generation, detection and modulation of light to be monolithically integrated with existing CMOS technologies on a single chip.

In a similar modular approach to the electronic ASIC industry, Silicon Photonic Ics are constructed from a set of photonic and electrical "macrocell" building blocks. Our macrocells include modulators, detectors, lasers, and other active elements and can be configured together with companion CMOS control electronics to form Customer Specific Standard Products (CSSPs). The CSSPs can thus be rapidly designed to address varied applications, both custom, and subject to multi-source agreements (MSAs).

6 Competing Research

6.1 Summary/Conclusion

1. There is some activity on 50 Gbps / NRZ / 850 nm. See e.g. the work done by IBM / Finisar
2. In the domain of optical communication, our approach seems unique. Nevertheless, in the domain of Internet of Things ("Things" communicating wirelessly to servers, see e.g. the new WiFi HaLow standard) there is lot of emphasis on low power and fast locking. Further study is required to understand if this is really the case and if comparison with ADDAPT is valid at all. Some publications are listed below in Section 6.2.
3. Also within the EU attention remains on low power Tx/Rx. See e.g. the COSMIC project, which targets similar power numbers, but is mainly targeting low manufacturing costs. No attention for fast locking CDR.
4. A lot of activity in improving SiPh. Still a very expensive technology, where, as e.g. LightCounting states: 'nothing can be achieved with Silicon Photonics that cannot also be achieved by normal technology: separated electronics and III-V components. Efforts are particularly on InP integration. Also GaAs integration has some attention. In the long run, this technology might also be competing in the space with simple solutions. Normally in this market, once volume application happens, the costs go down.

6.2 Competitive ADDAPTive approaches

We found little evidence that organisations are working on the concept of switching on/off optical lanes on a fast manor (ADDAPTive) for energy saving purposes. We only found one example in 2015 (already reported in D2.5): a paper was found called "A 7Gbps Rapid On/Off Embedded-Clock Serial-Link Transceiver with 20ns Power-On Time, 740µW Off-State Power for Energy-Proportional Links in 65nm CMOS", published at 2015 IEEE International Solid-State Circuits Conference, by Tejasvi Anand et al. [5].

This research was supported in part by Intel Labs University Research Office, SRC under task ID: 1836.129, and NSF under CAREER EECS-0954969.

The Transceiver consumes 64 mW in "On-state", and only 740µW "Off-State". When on, it consumes 9 mW/Gbps, which is double the amount of ADDAPT. On top of that, ADDAPT performs at 56 Gbps, and on MMF. This study refers to an unspecified serial link, believed to be copper based.

We found no evidence that companies are working on product development in this respect. Nor was there any reflection on how to integrate into the various standards.

But in the domain of Internet of Things and wireless, fast synchronizing CDR's do have attention. Examples are:

1. "A Pin-Efficient 20.83Gbps/wire 0.94pJ/bit Forwarded Clock CNRZ-5-Coded SerDes up to 12mm for MCM Packages in 28nm CMOS", Lausanne, Switzerland
2. 38mW 40Gbps 4-Lane Tri-Band PAM-4 / 16-QAM Transceiver in 28nm CMOS for High-Speed Memory Interface", the transceiver achieves the aggregate data rate of 40Gbps and link energy efficiency of 0.95pJ/bit, University of California, Los Angeles, CA.
3. "A 12Gbps 0.9mW/Gbps Wide-Bandwidth Injection-Type CDR in 28nm CMOS with Reference-Free Frequency Capture." A 12Gbps, injection-locked-oscillator-type CDR with a capture range of -25% to +15% at a power dissipation of 11mW. The CDR is equipped with a robust phase/frequency

detection algorithm that continuously calibrates its free-running frequency and clock phase, all without an external reference. Sony, Tokyo, Japan.

4. "A 6.75-to-8.25GHz, 250fsrms-Integrated-Jitter 3.25mW Rapid On/Off PVT-Insensitive Fractional-N Injection-Locked Clock Multiplier in 65nm CMOS". A LC-based rapid on/off fractional-N injection-locked clock multiplier in 65nm CMOS. The proposed PLL generates an output clock in the range of 6.75 to 8.25GHz using a 125MHz reference clock and achieves the best-reported FoM in both integer-N (-255dB) and fractional-N (-247dB) modes. The power-on lock time is less than 4ns. University of Illinois, Urbana-Champaign, IL
5. "5-10 Gbps 70 mW burst mode AC coupled receiver in 90-nm CMOS". The front-end recovers NRZ signals up to 13 Gbps burning only 26 mW in 90 nm CMOS (that is 2.6 pJ/bit). A low power- and area-efficient clock recovery scheme uses the linear path to injection lock an oscillator. The clock recovery technique is verified with experimental results at 5-10 Gbps in 90 nm CMOS consuming 70 mW and acquiring lock within 1.5 ns.

It is of course comparing apples and pears, nevertheless some typical numbers (pJ/bit and ns lock time) are comparable with ADDAPT figures. It must be better understood what the similarities and differences are.

6.3 FINISAR / IBM

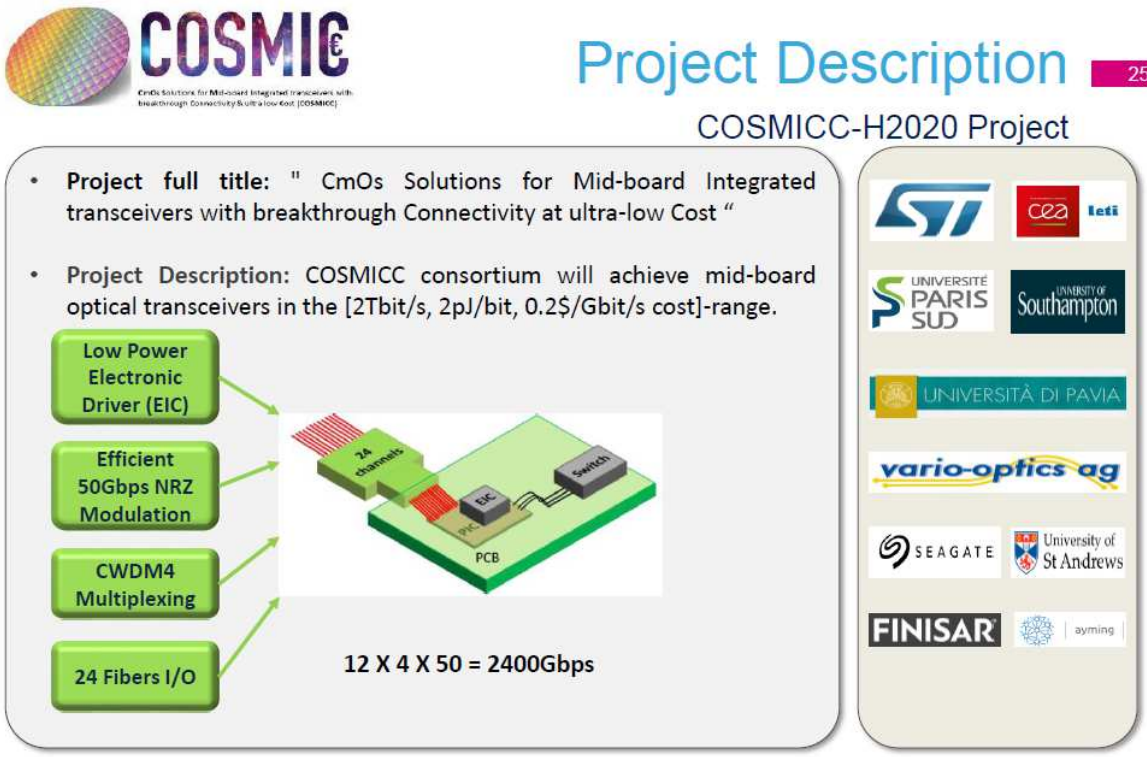
4×50 Gbps NRZ Shortwave-Wavelength Division Multiplexing VCSEL link over 50m Multimode Fiber (See PDF at https://www.researchgate.net/publication/314660686_4x50Gbs_NRZ_Shortwave-Wavelength_Division_Multiplexing_VCSEL_link_over_50m_Multimode_Fiber [Jan, 2017]:

"We demonstrate for the first time a 4x50Gbps NRZ SWDM VCSEL link over 50m OM4 multimode fiber achieving error free operation (BER<1E-12). Transmission of 4×44Gbps SWDM over 100m OM4 fiber with error free is also presented.

This looks more or less similar to our solution, except for:

- WDM over MMF
- No ADDAPT feature (start/stop)
- Also done by IBM

6.4 Cosmic



6.5 IBM

IBM has announced a breakthrough in the field of SiPh — the first fully integrated wavelength multiplexed chip. This new device is designed to enable the manufacture of 100 Gbps optical transceivers and allow both the optical and electrical components to exist side-by-side on the same package.

6.6 Silicon Photonics / GaAs

We see few SiPh developments in GaAs, which makes sense as SiPh is not very suitable for multimode. In the long run, it might become competitive to the present integration approach of separated CMOS / GaAs components on a substrate or PCB.

Some activity is going on, e.g.

1. "850 nm hybrid vertical cavity laser integration for on-chip silicon photonics light sources". From university of Ghent / IMEC and Chalmers University of Technology, Goteborg, Sweden
2. "Single-chip photonic transceiver based on bulk-silicon, as a chip-level photonic I/O platform for optical interconnects" from Electronics &Telecommunications Research Institute, Korea.
3. "Monolithic Integration of InGaAsP MZI Modulator and InGaAs Driver MOSFET using III-V CMOS Photonics" from University of Tokyo.

While SiPh is generally considered to be based on silicon-on-insulator (SOI) waveguide circuits, there is a growing interest in the use of SiN waveguide circuits at visible / near-infrared wavelengths (VIS/NIR), telecom/37ieter37 wavelengths and mid-infrared wavelengths. These circuits can also be fabricated using the CMOS fabrication infrastructure and have a medium refractive index contrast, leading to relatively

compact devices. In the near-infrared, the applications are mainly related to optical sensing and short-reach optical interconnects. These applications require the integration of near-infrared light sources on the SiN waveguide platform. Considering operation at 850 nm wavelength, GaAs VCSELs are nearly ideal sources, featuring high wall-plug efficiency and high bandwidth. In this paper we elaborate on a scalable method to integrate such laser sources on a SiN waveguide circuit. Nevertheless, this solution did not yet come with breakthrough solution with respect to costs or performance. We did not further investigate on these developments. Most applications are IC to IC interconnects.

7 Exploitation & Dissemination plans and achievements.

In this paragraph the exploitation and dissemination activities of the ADDAPT partners are described. For the plans and achievements in the recent project periods, please refer to D2.4 and D2.5 reports. Therefore, primarily the differences compared to D2.4 and D2.5 are mentioned. Only the organisation characteristics are repeated for the reader's convenience.

7.1 Summary of publications

Some publications are done by two or more partners. Below an overview of all publications by the various partners over the three project periods is given.

Table 6: Overview of ADDAPT publications.

Period	# of pubs	TUD	IBM	VIS	AT	WUT	CSTG	PTL
1 (11/2013-12/2014)	0							
2 (01/2015-02/2016)	9	03, 04, 05, 06, 07	04, 05	01, 02, 04, 05, 09	04, 05	02, 04, 05,	04, 05, 09	04, 05, 08
3 (03/2016-10/2017)	39	10, 14, 18, 21, 23, 25, 26, 27, 28, 30, 31, 34, 35, 40, 42, 46, 47, 48	24, 29, 32, 35, 37, 43, 44, 45, 47	10, 11, 12, 15, 16, 19, 20, 22, 25, 27, 33, 36, 37, 38, 39, 41, 47	17, 21, 47,	10, 11, 12, 13, 15, 16, 19, 20, 22, 25, 27, 33, 38, 39, 41, 47	36, 47	35

#	Authors	Title	Medium	Date
(01)	V. A. Shchukin; N. N. Ledentsov; J.–R. Kropp; G. Steinle; K. D. Choquette; S. Burger; F. Schmidt	Engineering of optical modes in vertical-cavity microresonators by aperture placement: applications to single-mode and near-field lasers	SPIE Photonics West – OPTO, p. 9381-30	Feb, 2015
(02)	Ledentsov; J.–R. Kropp; V. A. Shchukin; G. Steinle; J. P. Turkiewicz; B. Wu; Q. Shaofeng; Y. Ma; Z. Feng; S. Burger; F. Schmidt; R. Freund; K. D. Choquette	High-speed modulation, wavelength, and mode control in vertical-cavity surface-emitting lasers (Invited Paper)	SPIE Photonics West – OPTO, p. 9381-14	Feb, 2015
(03)	L. Szilagyi, G. Belfiore, R. Henker and F. Ellinger,	Area-efficient offset compensation and common-mode control circuit with switched-capacitor technique in an 18 Gbps optical receiver in 80 nm CMOS	Optical Interconnects Conference (OIC), San Diego, USA, pp. 58-59	April, 2015
(04)	R. Henker, J. Pliva, M. Khafaji, F. Ellinger, T. Toifl, B. Offrein, A. Cevrero, I. Oezkaya, M. Seifried, N. Ledentsove, J.-R. Kropp, V. Shchukin, M. Zoldak, L. Halmo, J. Turkiewicz, W. Meredith, I. Eddie, M. Georgiades, S. Charalambides, J. Duis and P. van Leeuwen	Adaptive Optical Interconnects – The ADDAPT Project (Invited Paper)	Proc. SPIE 9662, Photonics Applications in Astronomy, Communications, Industry, and High-Energy Physics Experiments (WILGA Symposium), Wilga, Poland, pp. 966207	May, 2015
(05)	T. Toifl, R. Henker, A. Cevrero, I. Oezkaya, J. Pliva, M. Khafaji, F. Ellinger, B. Offrein, M. Seifried, N. Ledentsov, J. Kropp, V. Shchukin, M. Zoldak, L. Halmo, J. Turkiewicz, W. Meredith, I. Eddie, M. Georgiades, S. Charalambides, J. Duis, P. van Leeuwen	Adaptive Ultra-low power 56Gbps optical communications	Symposium on Optical Interconnect in Data Centers, Valencia, Spain	Sept 29, 2015
(06)	G. Belfiore, L. Szilagyi, R. Henker and F. Ellinger,	Low Power Laser Driver Design in 28 nm CMOS for on-Chip and Chip-to-Chip Optical Interconnect (Invited Paper)	Proc. SPIE 9662, Photonics Applications in Astronomy, Communications, Industry, and High-Energy Physics Experiments (WILGA Symposium), Wilga, Poland, pp. 966208	May, 2015

(07)	L. Szilagyi, R. Henker and F. Ellinger	Bandwidth and Power Adaptive Receiver Amplifier Design for Optical Communications in 80 nm CMOS	IEEE MTT-S International Microwave and Optoelectronics Conference (IMOC), Porto de Galinhas, Brazil	3-6 November, 2015
(08)	S. Charalambides, M. Georgiades, G. Dimosthenous, D. Christofi,	Investigating an ISP's core network	10-th International Conference on Broadband and Wireless Computing,Communication and Applications, Poland	Nov, 2015
(09)	Wu Bo, Z Xian, Ma Yanan, L Jun, Z Kangping, Q Shaofeng, F Zhiyong, Luo Yazhi, Mikel Agustin, N. Ledentsov Jr., J. Kropp, V. Shchukin, N.N. Ledentsov, I, Eddie , Lu Chao,	Close to 100 Gbps Discrete Multitone Transmission over 100m of Multimode Fibre Using a Single Transverse Mode 850nm VCSEL	Photonics West, San Francisco, CA, US	Feb, 2016
(10)	Puerta, M. Agustin, L. Chorchos, J. Tonski, J.-R. Kropp, N. Ledentsov, V. A. Shchukin, N. N. Ledentsov, R. Henker, I. Tafur Monroy, J. J. Vegas Olmos, J. P. Turkiewicz,	107.5 Gbps 850 nm multi- and single-mode VCSEL transmission over 10 and 100 m of multi-mode fiber	Optical Fiber Communication Conference (OFC) Post-deadline Papers, paper Th5B.5., San Francisco, US	Mar, 2016
(11)	G. Stepniak; J. Kropp; N.N. Ledentsov; V.A., Shchukin; N. Ledentsov; G. Schaefer; J.P. Turkiewicz	54 Gbps OOK Transmission Using Single Mode VCSEL up to 1 km OM4 MMF	Optical Fiber Communication Conference (OFC), paper Th4D.5., San Francisco, US,	Mar, 2016
(12)	G. Stepniak, A. Lewandowski, J.R. Kropp, N.N. Ledentsov, V.A. Shchukin, N. Ledentsov Jr., G. Schaefer, M. Agustin, J.P. Turkiewicz	54 Gbps OOK transmission using single mode VCSEL up to 2.2 km MMF	Electronics Letters, Vol. 52, No. 8, pp. 633-635,	Apr, 2016
(13)	R. Puerta, J. J. Vegas Olmos, I. Tafur Monroy, J. P. Turkiewicz, and S. Echeverri-Chacón	Adaptive MultiCAP modulation for short range VCSEL based transmissions	Latin America Optics and Photonics Conference, Medellin, Colombia, paper LW4C.3	22–26 Aug. 2016
(14)	G. Belfiore, M. Khafaji, R. Henker and F. Ellinger	A compact electro-optical VCSEL model for high-speed IC design	12th Conference on Ph.D. Research in Microelectronics and Electronics (PRIME), Lisbon, Portugal, pp. 1-4	27-30 June, 2016
(15)	J. P. Turkiewicz, Ł. Chorchos, R. P. Ramirez, J. J. Vegas Olmos, Nikolay Ledentsov	On high speed transmission with the 850nm VCSELs	Proc. SPIE, vol. 10031, Photonics Applications in Astronomy, Communications, Industry, and High-	Sept. 2016

			Energy Physics Experiments, pp. 100311B	
(16)	G. Stepniak, L. Chorchos, M. Agustin, J.-R. Kropp, N.N. Ledentsov, V.A. Shchukin, N.Ledentsov Jr., J.P. Turkiewicz	Up to 108 Gbps PAM 850 nm Multi and Single Mode VCSEL Transmission over 100 m of Multi Mode Fiber	ECOC 2016, Düsseldorf, 18-, Proc. 42nd European Conference on Optical Communication, ISBN 978-3-8007-4274-5	Sept, 2016
(17)	M. Zoldak	Packaging for Microelectronics and Optoelectronics	FINETECH Micro Assembly Day, Berlin, Germany	May, 2016
(18)	L. Szilagyi, D. Schoeniger, R. Henker and F. Ellinger	Optical Receiver Amplifier with Adaptive Power and Bandwidth for up to 30 Gbps s in 28 nm CMOS	11th European Microwave Integrated Circuits Conference (EuMIC), London, UK, pp. 105-108	3-4 October, 2016
(19)	Ł. Chorchos, J. P. Turkiewicz, J.R. Kropp, N.N. Ledentsov, V.A. Shchukin, M. Agustin, N. Ledentsov Jr.	High speed 850 nm single mode and multi mode VCSEL transmission over multimode fiber	OFTA 2017, Suprasl, Poland (Invited Paper) Proc SPIE, 0277-786X, V.10325-21	23-27 January, 2017
(20)	J.-R. Kropp, N. Ledentsov, M. Agustin, V. A. Shchukin, N. N. Ledentsov, J. P. Turkiewicz, I. Eddie	Impact of the sample modal composition of 850nm VCSELs on high speed data transmission over multimode fiber applying different modulation formats	OFTA 2017, Suprasl, Poland, Proc SPIE, 0277-786X, V.10325-25	23-27 January, 2017
(21)	M. Zoldak , L. Halmo, J. P. Turkiewicz, S. Schumann, R. Henker	Packaging of ultra-high speed optical fiber data interconnects	Proc. SPIE, Optical Fibers and Their Applications 2017, vol. 10325, Suprasl, Poland, pp. 103250R	23-27 January, 2017
(22)	Ł. Chorchos, J. P. Turkiewicz, J.R. Kropp, N.N. Ledentsov, V.A. Shchukin, M. Agustin, N. Ledentsov Jr.	Relative intensity noise of single- and multi-mode 850nm vertical cavity surface-emitting lasers	OFTA 2017, Suprasl, Poland Proc SPIE, 0277-786X, V.10325-30	23-27 Jan, 2017
(23)	R. Henker, D. Schoeniger, G. Belfiore, L. Szilagyi, J. Pliva, M. Khafaji, F. Ellinger, K. Nieweglowski, T. Tiedje, K. Bock	Tunable broadband integrated circuits for adaptive optical interconnects	Proc. SPIE, Optical Fibers and Their Applications 2017, vol. 10325, Suprasl, Poland, pp. 103250P	23-27 January, 2017
(24)	A. Cevrero, I. Ozkaya, P. A. Francese, C. Menolfi, T. Morf, M. Brändli, D. Kuchta, L. Kull, J. Proesel, M. Kossel, D. Luu, B. Lee, F. Doany, M. Meghelli, Y. Leblebici, T. Toifl	A 64Gb/s 1.4pJ/b NRZ Optical-Receiver Data-Path in 14nm CMOS FinFET	IEEE International Solid-State Circuits Conference (ISSCC) 2017, San Francisco	Feb, 2017
(25)	R. Puerta, M. Agustin, L. Chorchos, J. Tońsk, J.-R. Kropp, N. Ledentsov Jr., V. A. Shchukin, N. N. Ledentsov, R. Henker, I. T.	Effective 100 Gbps IM/DD 850-nm Multi- and Single-Mode VCSEL Transmission Through OM4 MMF'	Journal of Lightwave Technology, vol. 35, no. 3, pp. 423-429	Feb, 2017

	Monroy, J. J. V. Olmos and J. P. Turkiewicz			
(26)	L. Szilagyi, G. Belfiore, R. Henker and F. Ellinger	20–25 Gbps low-power inductor-less single-chip optical receiver and transmitter frontend in 28 nm digital CMOS'	International Journal of Microwave and Wireless Technologies, pp. 1-11	May, 2017
(27)	R. Puerta, M. Agustin, L. Chorchos, J. Tońaski, J.-R. Kropp, N. Ledentsov Jr., V. A. Shchukin, N. N. Ledentsov, R. Henker, I. T. Monroy, J. J. V. Olmos and J. P. Turkiewicz	Short-range links beyond 100Gbps with vertical-cavity surface-emitting lasers'	SPIE Newsroom, Optoelectronics & Communications	April, 2017
(28)	J. Pliva, R. Ma, B. Lindner, L. Szilagyi, F. Protze, R. Henker and F. Ellinger	Design of a custom standard-cell library for mixed-signal applications in 28 nm CMOS'	IEEE International Workshop of Electronics, Control, Measurement, Signals and their Application to Mechatronics (ECMSM), Donostia-San Sebastian, Spain, pp. 293-298	24-26 May, 2017
(29)	T. Toifl, A. Cevrero, P. Francese, M. Kossel, L. Kull, D. Luu, C. Menolfi, M. Brändli, T. Morf	Ultra-low Power 56Gbps VCSEL-based Optical Links	CMOS Emerging Technologies Conference, Warsaw, Poland (invited)	May, 2017
(30)	L. Szilagyi, G. Belfiore, R. Henker and F. Ellinger	30 Gbps 1.7 pJ/bit common-cathode tunable 850-nm-VCSEL driver in 28 nm digital CMOS'	IEEE Optical Interconnects Conference (OI), Santa Fe, NM, USA, pp. 51-52,	05-07 June, 2017
(31)	M. Khafaji, G. Belfiore, R. Henker, and F. Ellinger	A 2×2 80 Gbps 2^15 – 1 PRBS generator with three operational modes and a clock divider'	IEEE MTT-S International Microwave Symposium (IMS), Honolulu, Hawaii, USA	4-9 June, 2017
(32)	A.Cevrero. I. Oezkaya, P. Francese, C. Menolfi, T. Morf, M. Brändli, D. Kuchta, L. Kull, C. Baks, J. Proesel, M. Kossel, D. Luu, B. Lee, F. Doany, M. Meghelli, Y. Leblebici, T. Toifl	A 60 Gbps 1.9 pJ/bit NRZ Optical-Receiver with Low Latency Digital CDR in 14nm CMOS FinFET	VLSI Circuits, Kyoto, Japan	June, 2017
(33)	N. N. Ledentsov, V. A. Shchukin, V. P. Kalosha, N. N. Ledentsov Jr., J.-R. Kropp, M. Agustin, Ł. Chorchos, and J. P. Turkiewicz	Progress in design and development of anti-guiding vertical cavity surface emitting laser at 850nm: above 50Gbps and single mode"	ICTON'17 (19th International Conference on Transparent Optical Networks) Girona, Spain	July 2-6, 2017
(34)	G. Belfiore, L. Szilagyi, R. Henker and F. Ellinger	25 Gbps Adaptive 3-Tap FFE VCSEL Driver in 28-nm CMOS for Data Center Communications'	19th International Conference on Transparent Optical Networks (ICTON), 3rd workshop on Technology for Data Center Interconnects (DACINT) Girona,	02-06 July, 2017

			Spain,	
(35)	R. Henker, T. Toifl, A. Cevrero, I. Oezkaya, M. Georgiades, M. Khafaji, J. Pliva and F. Ellinger	Adaptive High-Speed and Ultra-Low Power Optical Interconnect for Data Center Communications	3rd workshop on Technology for Data Center Interconnects (DACINT)', 19th International Conference on Transparent Optical Networks (ICTON), Girona, Spain	02-06 July, 2017
(36)	I. Eddie, A. McKee, G. Masterton, M. Armstrong, K. Kennedy, J. Kropp, V. Shchukin, and N. Ledentsov	Development of High Speed 850nm VCSELs	VCSEL Day, Cardiff, UK	08-09 June, 2017
(37)	T. Morf et al.,	VCSEL-based optical links in burst-mode slow optical power ramp-up and how to achieve ultra-short wake-up times	Electronics Letters, vol. 53, no. 19, pp. 1325-1327	Sept. 2017
(38)	J.P. Turkiewicz, Ł. Chorchos, V.A. Shchukin, V.M. Kalosha, J-R. Kropp, M. Augustin, N. Ledentsov Jr, and N.N. Ledentsov	High speed transmission with 850 nm SM and MM VCSELs	Invited Paper. 2017 19th International Conference on Transparent Optical Networks (ICTON), Girona, Spain, 2017, pp. 1-9., Mo.D3.5, doi: 10.1109 ICTON.2017.8024802	July 2-6, 2017
(39)	R. Puerta, J. J. V. Olmos, I. T. Monroy, N. N. Ledentsov and J. P. Turkiewicz	Flexible MultiCAP Modulation and its Application to 850 nm VCSEL-MMF Links	Journal of Lightwave Technology, vol. 35, no. 15, pp. 3168-3173	Aug., 2017
(40)	J. Pliva, M. Khafaji, L. Szilagyi, R. Henker and F. Ellinger	Opto-Electrical Analog Front-End with Rapid Power-On and 0.82 pJ/bit for 28 Gbps in 14 nm FinFET CMOS', achieved Best Paper Award	IEEE International System-on-Chip Conference (SOCC), Munich, Germany	05-08 Sept, 2017
(41)	Xiaofeng Lu, Vladimir S. Lyubopytov, Łukasz Chorchos, Grzegorz Stepniak, Mikel Agustin, Jörg-R. Kropp, Nikolay N. Ledentsov, Vitaly A. Shchukin, Nikolay Ledentsov Jr., Jarosław P. Turkiewicz, Idelfonso Tafur Monroy	100G Flexible IM-DD 850 nm VCSEL Transceiver with Fractional Bit Rate Using Eight-Dimensional PAM	European Conference on Optical Communication (ECOC) 2017, paper Tu.2.A.4, Gothenborg, Sweden	Sep-17
(42)	M. Khafaji , J. Pliva, M. Zoldak, R. Henker and F. Ellinger	A 42 Gbps VCSEL Driver with Adjustable 2-Tap Feed-Forward Equalizer in 14 nm SOI CMOS'	12th European Microwave Integrated Circuits Conference (EuMIC), Nuremberg, Germany	08-13 Oct, 2017
(43)	I. Oezkaya, A. Cevrero, P. Francese, C. Menolfi, T. Morf, M. Brändli, D. Kuchta, L.	A 64 Gb/s 1.4 pJ/bit NRZ Optical Receiver Data-Path in 14 nm CMOS FinFET	Journal on Solid-State Circuits (JSSC), Vol. 52, Issue 12	Dec., 2017

	Kull, C. Baks, J. Proesel, M. Kossel, D. Luu, B. Lee, F. Doany, M. Meghelli, Y. Leblebici, T. Toifl			
(44)	I. Oezkaya, A. Cevrero, P. Francese, C. Menolfi, T. Morf, M. Brändli, D. Kuchta, L. Kull, C. Baks, J. Proesel, M. Kossel, D. Luu, B. Lee, F. Doany, M. Meghelli, Y. Leblebici, T. Toifl	A 60 Gb/s 1.9 pJ/bit NRZ Optical Receiver with Low Latency Digital CDR in 14 nm CMOS FinFET	to appear in Journal on Solid-State Circuits (JSSC)	2018
(45)	A. Cevrero. et al	A 56Gbp s Burst Mode NRZ Optical Receiver with 6.8ns Power-on and CDR-Lock time for Adaptive Optical links in 14nm FinFET"	IEEE International Solid-State Circuits Conference (ISSCC) 2018, San Francisco, (accepted for publication)	Feb, 2018
(46)	M. Khafaji, J. Pliva, R. Henker and F. Ellinger,	A 42 Gbps VCSEL Driver Suitable for Burst Mode Operation in 14 nm Bulk CMOS	To appear in IEEE Photonics Technology Letters	Dec, 2017
(47)	A. Cevrero et al.	4x40 Gb/s 2 pJ/bit Optical RX with 8ns Power-on and CDRLock Time in 14nm CMOS	submitted to Optical Fiber Communication Conference and Exhibition (OFC)	March, 2018
(48)	Mahdi Khafaji, Guido Belfiore, Jan Pliva, Ronny Henker, Frank Ellinger	A 45 Gb/s 2-Tap FFE VCSEL Driver in 14 nm FinFET CMOS Suitable for Burst Mode Operation	Submitted to IEEE Custom Integrated Circuits Conference (CICC)	April 2018

7.2 Argotech (AT)

7.2.1 Organization

Argotech a.s. is a company with corporate office located in Náchod, Czech Republic and with production site located in Trutnov, Czech Republic. The company is an EMS provider working in CM, ODM and OEM contractual models. Argotech is specialized for high precision micro-packaging on wafer scale and discrete component level. Delivery amount of products from single samples up to 1 – 500k pcs per year shows high level of flexibility. On top of that Argotech provides also R&D, engineering and consultant services.

7.2.2 Objective of organization

Packaging of microelectronic and optoelectronic components is a key competence of Argotech with a high level of experience in this field. People at Argotech constitute a highly skilled team with experience in optoelectronic and fiber optic industry more than 15 years. The key strength of Argotech is a unique technology chain from wafer level packaging via TO-CAN packaging to optical subassemblies or customized applications. The R&D services mostly focus in customized optoelectronic units and very high speed optoelectronic components with capability to provide the final assembly on site. Also the capability of design of special technologies used for customized products is a next level of R&D services. All assembly and R&D activities have been done in Europe, Czech Republic.

7.2.3 Dissemination

Dissemination achievements

1. Presentation of the ADDAPT project at Czech Technical University in Prague, Faculty of Electrical Engineering, Department of Electromagnetic Field – 11/2015.
2. A presentation at Micro Assembly Conference (March 10, 2016, Berlin) in which packaging approaches within Argotech are discussed, amongst others those applied in ADDAPT. This all to the extent that the approaches are sufficiently mature for presentation, and sufficient time is given to us to do this to a sufficient detailed level.
3. We presented the ADDAPT work and especially the interested HF packaging approach to the EU PIXAPP project where such results are highly demanded and participants are very interested in such an experience. It seems there is not too much real experience within companies with 50Gbaud+ multichannel packaging. There are coming commercial request in this kind of packaging and especially regarding to HF design for new customized solutions for 50G+ applications.
4. See the list in **Section 7.1** Summary of publications

Dissemination plans

- Publication on the packaging techniques/test board measurements/GSSG vs GSGSG configuration

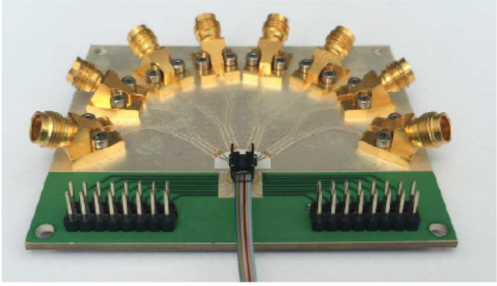
7.2.4 Exploitation

Products and services

1. With present insights based on simulations and partial tests so far, the use of NFC does not bring the interconnect efficiency we expected. It will not be implemented in the demonstrator. After the VCSELs are released and characterized, we will execute separate testing and assess if the NFC approach makes sense and has a positive impact on exploitation.

2. Also, we will bring the test board as a commercial product to the market (see picture of product brief below). The low insertion loss of data lines is typically 1.5 dB @ 42 GHz (or 56 Gbps) and 2.4-3.0 dB @ 67 GHz (or 90 Gbps). Low back reflection better than -15 dB for GSSG and -10 dB for GSGSG configuration at full bandwidth. This is better than the latest OIF-CEI-56-VSR-NRZ specification (document oif2014.277.08). The bandwidth of this packaging approach can be extended beyond 100 Gbps (100 Gbaud) by exchange of current 1.85 mm / 67 GHz coaxial connectors with 1.0 mm which grants the bandwidth of 110 GHz.

56+ Gb/s NRZ universal IC test and evaluation packaging platform



ARGOTECH offers universal and flexible platform designed for testing, demonstration and evaluation of digital communication integrated circuits with bandwidth equivalent to 56 Gb/s NRZ data signal and beyond in single channel or multichannel configuration. It enables characterization of ICs for fibre optic and silicon photonics applications combined with transmitting and receiving optical modules. Possibility of opto-coupling ensure connection of optical signal from fiber to optical chip while keeping high coupling efficiency.

3. There is not too much real experience within companies with 50 Gbaud+ multichannel packaging. There are coming commercial request in this kind of packaging and especially regarding to HF design for new customized solutions for 50G+ applications.

IP and Patents

No new insights

7.3 Compound Semiconductor Technologies (CSTG)

7.3.1 Organization

CSTG is a 'pure play' semiconductor foundry specialising in the design, development, and manufacture of discrete and integrated III-V opto-electronic devices, based in Glasgow, UK. Since 1999, CSTG has provided specialist foundry services to clients in the Telecommunications, Defence, Medical and Instrumentation markets. We offer full product support from design to manufacturing, levered off a comprehensive library of qualified fabrication processes and a suite of high performance device platforms. CSTG is an SME with 45 employees servicing both fabless and vertically integrated customers in UK, US, Europe and Japan, and is recognised as a flagship project for the UK opto-electronics industry.

7.3.2 Objective of organization

Our business model is focussed on servicing optical component or sub-system vendors in the Telecommunication, Defence, Medical and Instrumentation markets. We aim to offer:

- Development capability to fabless optical component ventures
- Manufacturing capacity to fabless optical component ventures
- Ring-fenced new product development for established optical component suppliers
- Second source supply of wafers or chips to vertically integrated optical component vendors

CSTG also welcome enquiries from entrepreneurs and universities at an early stage of in their company development. The company has a well-established track record of helping emerging companies exploit their ideas and cost effectively utilise their investment finance.

7.3.3 Dissemination

Achievements

- Workshop during VCSEL Day 2017 Cardiff at Wales, United Kingdom on "Development of High Speed 850nm VCSELs"
- Presentation of a paper on VCSEL production during this workshop with the same title: "Development of High Speed 850nm VCSELs" by I. Eddie. See the list in **Section 7.1** Summary of publications

Abstract: High speed VCSELs are a key component in modern optical communications systems, due to their high bandwidth, high efficiency and low cost. VCSELs are particularly suited for use in Active Optical Cables (AOCs) for short distance links in datacentres and high performance computing. As the volume of traffic in the network increases, the next generation of AOCs require VCSELs that can operate at data rates of 50Gbps or more.

This paper reports progress on the development of high speed VCSELs and GaAs PIN photodiodes within the EU FP7 project ADDAPT. VCSELs and photodetectors with a novel design with low capacitance for high speed operation were designed and fabricated within the ADDAPT project. Recent results from VCSELs with differing aperture sizes are shown, with transmission speeds of up to 50Gbps and modulation bandwidth up to 27GHz.

Further Plans on Dissemination

Continuation of the policy explained in earlier reports.

Products and Services

More than earlier in D2.4, the emphasis is on the exploitation through DFR's. CSTG's specific know-how is contained in Device Fabrication Routes (DFRs). Each device type has a specific DFR that contains work instructions and process design information for the manufacture of the device, CST have developed DFRs for high speed VCSELs and detectors for the ADDAPT project. Novel processes that are developed during the project can also be used to fabricate other high-speed components (e.g. Distributed Feedback Lasers, Modulators, etc.). ADDAPT is substantially contributing the portfolio of DFR's.

IRP and Patents

Together with VIS, CSTG will publish on the development and design of the high-speed adaptive VCSELs and PDs. For novel process techniques and fabrication methods, either Trade Secret or formal patent protection will be used where appropriate.

7.4 International Business Machines (IBM)

7.4.1 Organization

IBM is a globally integrated technology and consulting company headquartered in Armonk, New York. With operations in more than 170 countries, IBM attracts and retains some of the world's most talented people to help solve problems and provide an edge for businesses, governments and non-profits.

7.4.2 Objective of organization

Innovation is at the core of IBM's strategy. The company develops and sells software and systems hardware and a broad range of infrastructure, cloud and consulting services. Today, IBM is focused on four growth initiatives – business analytics, cloud computing, growth markets and Smarter Planet. IBM Research is dedicated not only to fundamental research, but also to exploring and creating innovative industry and customer-oriented solutions based on several key areas including; future chip technology; smarter planet; nanotechnology; storage; supercomputing; security and privacy; risk and compliance as well as business optimization and transformation.

7.4.3 Dissemination

Achievements

- Presentation on ADDAPTive technology at Optical Interconnect Workshop during ECOC 2015
- **Publications** see the list in **Section 7.1** Summary of publications

7.4.4 Exploitation

IPR

IBM filed 3 patent application related to the work done in ADDAPT:

1. VCSEL based optical links in burst mode
2. Continuous time linear equalizer with complementary current summation
3. High bandwidth variable-gain-amplifier for optical receivers

Products and Services

Parts of the technologies developed in ADDAPT (low-power RX architecture) will directly be used in the high-speed links of next generation of P-series computers, Z-series mainframes and HPC systems.

7.5 PrimeTel PLC (PTL)

7.5.1 Organization

PrimeTel PLC (PTL) is the largest private telecommunications provider and information Technology Company in Cyprus having branches in each city inside the island and its main offices are located in Limassol. PrimeTel was established on the 18th of June 2003 and it currently employs 300 people making it one of the biggest companies in Cyprus. Moreover, the company maintains and operates its own high performance optical network and it has also acquired the license for a 3rd mobile network in Cyprus which enables it to evolve from a Mobile Virtual Network Operator (MVNO) to a Mobile Network Operator (MNO).

After years of network expansion, PrimeTel entered the telecommunications market, and brought technological revolution to the fields of communication, mass media and entertainment. Today, its network expands across the country, offering innovative services to consumers.

PrimeTel invested in the expansion of its autonomous fiber optics network and the amelioration of its services. With its advanced and independent network, PrimeTel is able to offer both personal and business customers a variety of complete communication solutions, supported by competitive offers aiming to meet the market's need for quality, reliability and economy.

7.5.2 Objective of organization

Among the key services offered by PrimeTel are the following ones:

- High-Speed Internet
- Fixed and Mobile Telephony
- Digital Television

One of PrimeTel's main goals is to strengthen its position as the biggest telecommunication provider in Cyprus. This will be achieved by introducing novel services as well as by constantly upgrading the quality of service (QoS) it currently offers to its increasing number of customers which include corporate or residential customers, mobile telephony users as well as telecommunication carriers, creating new business opportunities.

Furthermore, PrimeTel strives to consistently use the latest and cutting edge technologies in an effort to offer the best possible services and at the same time minimise its OPEX and CAPEX. By achieving this, the company will be able to attract additional strategic partners and form additional partnerships and business deals thus further increasing its revenue and strengthen its position in the telecommunications market.

7.5.3 Dissemination

Dissemination plans

PrimeTel's dissemination plans involve creating awareness and achieving the wide publicity of the project's results. On an international level the company will work closely together with the consortium partners to present ADDAPT's results in high calibre scientific conferences and journals as well as participating in related international workshops and.

Further to the network analysis Primetel is looking for a reasonable conference or journal publication to publish any obtained outcomes. The publication could be solely based on the network analysis results as well as in combination with the system components developed and a more holistic view of the project targeting a more prestigious journal/magazine higher tier papers.

Dissemination achievements

- In terms of domestic dissemination in Cyprus, PrimeTel mentions its participation in research project, such as ADDAPT. An introduction to ADDAPT is given on our website, and reference is given to ADDAPT website
- In addition, PrimeTel's marketing department promoted the technology developed in ADDAPT and its results by this information in the company's monthly magazine 'PrimeTime magazine' and use additional printed mediums such as leaflets, posters etc.
- Primetel customers are regularly informed of recent updates which also includes links to the aforementioned sites.
- **Publications** see the list in **Section 7.1** Summary of publications

7.5.4 Exploitation

Specific ADDAPT Know-how to be exploited

ADDAPT aims to address the high power consumption that takes place in today's data and communication networks due to links being statically driven at maximum power irrespective of data load. The project will introduce adaptivity to optical networks by developing a high speed electro optical transceiver module. This

will facilitate the adjustment to varying data loads as well as performance requirements and thus reduce the power consumption and electrical costs to the degree that is actually needed.

PrimeTel can potentially benefit from the technology developed within the frames of ADDAPT by minimising the energy and power consumption costs inside its data centre and core network which will lead to lowering the company's OPEX and CAPEX. In addition, such a technology will lead to better utilisation of the interfaces on switches and optical transports based on the throughput inside the data centre. PrimeTel will provide results of an extensive network analysis of its high speed network in terms of traffic variation over time and users' bandwidth requirements. These results will offer valuable information and insights for the procedures that will involve the design and implementation of the ADDAPT components that relate to adaptivity. In addition, PrimeTel will work on the development of a verification platform as well as its testing and benchmarking.

Application

As the biggest private telecommunications operator in Cyprus, PrimeTel owns and manages a high performance fibre optic network with points of presence in Cyprus, Greece, Russia and United Kingdom. It combines key components that that are critical for the provisioning of state-of-the-arts services: a high capacity backbone, a 24 hour Network Operations Centre and superior engineering. PrimeTel's network has been engineered from the ground up to accommodate the high availability demands of the most strict service level agreements.

ADDAPT aims to produce a transceiver module that will render current networks more flexible, since it will be able to adapt to the networks actual needs, and more efficient since it will reduce the power consumption and energy costs to the degree that is required. Hence, PrimeTel could apply the technology developed within ADDAPT to its high speed fibre optic network both inside the data centre and its backhaul network. More precisely, the high speed optical transceiver module could be utilized in the company's optical transports and switches.

Market and customers

Network operators such as PrimeTel could benefit from the technology developed in ADDAPT. Adopting the results produced inside the frames of the project and applying them onto their core network and data centres could yield in a decrease of their CAPEX and OPEX as well as facilitate the offering of better quality of service to their customers. Moreover the ADDAPT technology could provide more eco-friendly solutions to business customers who are supported with FTTB or are being provided with their own intranet supported with optical networking.

PrimeTel can exploit the technology proposed and developed in ADDAPT by optimizing utilization of its optical network resources while maintaining and even improving the QoS offered on different parts of the network, servicing its customers. This will raise the reliability of the customers and help secure PrimeTel's position in Cyprus telecommunications market. Also, the reduction of expenses due to the reduction of the energy and power consumption costs due to the flexibility of the technology to adapt accordingly to the load will give the opportunity to even lowing the costs for upgraded and even new services. All this will contribute to maintain and attract new customers, offer innovating technology services to them, so PrimeTel can improve its position in the telecommunications sector if Cyprus and increase as well its market share.

Products and Services

PrimeTel offers an IPTV service (PrimeTV) as part of its triple-play bundle and it constitutes one of its key business options. PrimeTel's IPTV service can benefit by the use of ADDAPT technology which can offer data rates of up to 56 Gbps. Similarly, HD video streaming is a service that requires high link bandwidth with high reliability. By employing the results of ADDAPT PrimeTel could benefit from the 56 Gbps link bandwidth in order to offer a high QoS to its clients. Moreover, an adjustment of its network performance to actual client demand will be possible since the transceiver module developed within the frames of the project will poses the required adaptive capabilities. This will allows PrimeTel to reduce its OPEX and CAPEX since the power consumption and energy costs (a decrease of 50% in power consumption and 30% of energy cost is expected within the frames of the project) can be kept at the levels that are required based on the data load. Finally, PrimeTel can take advantage of the speeds of 56 Gbps to provide fast access to data and storage cloud facilities.

Based on the Network Analysis has identified times of low and high traffic load. For example there was long-term variation is the diurnal traffic fluctuation where the traffic load reaches a minimum during the early morning hours of each day and increases until it reaches a peak between the afternoon to early night hours. In addition, variation was also observed when comparing specific days; weekdays exhibit more load than during the weekends or even public (bank) holidays. Due to the fact that these variations are predictable the ADDAPT technology could be utilised to exploit periods of channel underutilisation.

Another area where channel bandwidth is purposely underutilised is in the area of operations and management and more specifically recovery when links typically use under 50% so that in case of failure, faults, or underperformance traffic could be offloaded accordingly to other links. ADDAPT technology could support these operations by e.g. doubling or halving the transmission rates accordingly in the case of traffic offloading.

IP and Patents

Primetel has established close collaboration with companies like GCH UK (Viavi Solutions), NapaTech (Denmark), Profitap (Netherlands) with the possibility in obtaining products such as the X-Gig, Pandion, and In-Line Fiber TAPs respectively for deeper packet based inspection monitoring. This to support the need of utilizing and exploiting the ADDAPT technology but also to support further research which requires this level of monitoring. Further to the industrial collaboration Primetel will maintain close collaboration with the universities involved in ADDAPT to further extend research in the area and on associated research.

7.6 Technische Universität Dresden (TUD)

7.6.1 Organization

The Technische Universität Dresden (TUD) is a technical university in Dresden the capital of Saxony, Germany. Founded in 1828, TUD is one of eleven German universities that were identified as an "excellence university". TUD has about 37.000 students, 4.400 publicly funded staff members – among them over 500 professors – and approximately 3.500 externally funded staff members, and, thus, is the largest university in Saxony, today. TUD is a multi-discipline university, committed to a wide range of fields such as science, engineering, humanities and social sciences as well as medicine. In 2011 it was ranked no. 1 in electrical engineering among all universities in Germany.

The Chair for Circuit Design and Network Theory (CCN) was established in 2006 and is placed on the main campus of TUD in Barkhausen-building on Helmholtzstreet 18. CCN incorporates the experience of around

50 employees including two professors, nine post-docs (working as group leaders, project leaders and researcher), 35 research associates (working toward Ph.D. degree), three technicians and one secretary.

For more information please see: http://tu-dresden.de/, http://ccn.et.tu-dresden.de/.

7.6.2 Objective of organization

TUD is one of the strongest research and education oriented university among Germany. Its aim is to keep and improve this leading position in future. One basis for this is the intensive exchange and cooperation between the different sciences with industry and society. Within Silicon Saxony which is an area with a deep tradition and focus in microelectronics, TUD is a big partner for companies and research institutes. Successes in research results and the transfer of basic knowledge are inherent parts of education, studies, research and advanced training at TUD.

The CCN is devoted to the design of high-speed integrated circuits using advanced circuit techniques and technologies such as CMOS, BiCMOS and III/IV as well as advanced "Beyond Moore" technologies like carbon nano tubes, nanowires and organic and polymer devices. The key activities are analogue and mixed signal circuit design. Moreover, the design of complete systems involving the design of PCBs and hybrid solutions, digital signal processing and algorithms for FPGAs is covered by the chair activities. Applications involve low frequency and RF systems and wireless communications up to 220 GHz as well as optical communications up to 80 Gbps, high resolution local positioning, adaptive power saving circuits with intelligent dynamic power control and wake-up functionalities and energy harvesting circuits. In addition, the chair has experience in the development and optimization of high-end audio systems. Six lectures and one practical training course in the area of analogue circuit design and network theory are offered by the chair where the experience, insights and results of research projects are transferred. Next to the research activities, the education, training and strengthening of future leading researcher is one goal of the CCN's work.

7.6.3 ADDAPT Technology

In the context of ADDAPT the CCN of TUD develops, designs and tests ICs which are required for the operation of electro-optical transceiver module. The design focus is especially on laser-diode drivers (LDD) and transimpedance-/limiting (TIA/LA) amplifiers. For the design the following goals and strategies are followed:

- Development of ICs that can be adapted regarding performance versus power consumption trade-off. Up to now, circuits are mainly optimized for fixed dc operation leading to fixed bitrates, modulation formats and high power consumption although the network link load can also show much lower data rates.
- Bandwidth peaking techniques such as inductive series peaking, inductive load peaking, transformer coupled peaking and emitter generation with parallel RC elements to further relax the speed to power consumption trade-off.
- To match the needs for future systems and to enable a relatively low number of parallel links, up to 56 Gbps per link path is targeted mapping corresponding requirements for the circuits.
- The power consumption is reduced using aggressively scaled CMOS (32 nm or more advanced). Actually, 14 nm IBM CMOS technology is applied for the IC design.

7.6.4 Dissemination

Achievements

CCN of TUD had planned different dissemination actions. Most of them are accomplished. As coordinator TUD will encourage and manage joint dissemination activities among the partners. The dissemination activities included:

- Implementation and updating of a public web page on a ".EU" domain: The webpage was created at the beginning of the project (see picture of homepage below) and launched on the domain http://www.addapt-fp7.eu. This webpage opens the research results and news about the project advancement to a broad public audience. It is updated regularly and extended for example with publications, press releases and project results.
- Organization and placing of press releases or public materials (e.g. leaflets, posters etc.) in media or on technical events/conferences/exhibitions: At the beginning of the project TUD has already placed press releases for the launch of ADDAPT on TUD's online media and in the university journal as well as in local press. Further press releases are planned at the end of ADDAPT. Some examples of achieved releases are listed in the following:
    - Announcement on Faculty of Electrical and Computer Engineering webpage (03. February 2014, in English www.et.tu-dresden.de/etit/index.php?id=765&L=1 and German http://www.et.tu-dresden.de/etit/index.php?id=765&L=0).
    - Article in local newspaper Dresdner Neueste Nachrichten (DNN online, 30. January 2014) http://www.dnn-online.de/web/dnn/nachrichten/detail/-/specific/4-8-Millionen-Euro-Foerdergeld-TU-daempft-bald-Stromhunger-der-Datennetze-895360478.
    - A project fact sheet as well as a project presentation has been prepared for public audience. Both can be disseminated on various events and can also be found on the ADDAPT webpage. The public fact sheet and presentation will be updated with project results at the end of the ADDAPT.
    - The coordinator of ADDAPT, Prof. Frank Ellinger, received the Alcatel Lucent Award for technical communications 2014 also for the inventions and work on adaptive circuits which are pursued in ADDAPT for optical communications (12. November 2014, see http://www.stiftungaktuell.de/wp-content/uploads/2014/11/PM_Forschungspreis-Technische-Kommunikation_2014.pdf or http://tu-dresden.de/aktuelles/newsarchiv/2014/11/alcatel_forschungspreis/newsarticle_view?set_language=de)
    - Announcement on TUD news webpage (31. January 2014) http://tu-dresden.de/en/news/addapt/newsarticle_view.
    - Article in Dresden university journal 02/2014 (04. February 2014, http://tu-dresden.de/die_tu_dresden/rektoratskollegium/stk/sg57/uj/bilder/pdf2014/UJ02-14.pdf).
- Organization of student colloquiums and exchanges to allow optimum dissemination of results from educational perspective into practice: The experience, insights and results of the ADDAPT project will be integrated into lectures given at TUD. Several students will be involved in ADDAPT, e.g. by means of PhD and master theses. Subsequently, after graduation these students will transfer their experience into companies. Two students which will work in ADDAPT toward the PhD degree were already for a research visit at the partner IBM Zurich during June/July 2014. During their stay they learned to handle the challenging highly scaled CMOS technology which will be used in ADDAPT.

- Promoting the project (results) via research centers/clusters: TUD CCN is involved in the research clusters cfaed, HAEC and CoolSilicon where project information (poster, fact sheet, leaflets, overview presentation etc.) can be disseminated and presented to a broad international technical oriented audience containing students, researchers, engineers and company members.
- Organization of a workshop in the area for efficient dissemination of results and knowledge exchange with external experts or other projects (planed during or towards the end of the project): One special session on optical interconnects at Optical Fibers and their Applications Conference (OFTA) 2017 in Suprasl, Poland have been organized. The ADDAPT project was present there with five talks. Furthermore, ADDAPT co-organized the 3rd Workshop of Data Center Interconnect Technologies (DACINT) at International Conference on Transparent Optical Networks (ICTON) 2017. ADDAPT was invited for four talks there.
- Organization of customer events for promoting the project results and approaches (encouraged for the industry partners)
- Organizing the participation of exhibition with ADDAPT project booths during local conferences and workshops, e.g. on IEEE International Semiconductor Conference Dresden Grenoble which takes place in Dresden every two years.
- Organization of information and knowledge transfer into scientific and technical expertise forums
- Production of "Dissemination Kit" including project results (at the end of the project)
- Organization and authoring of (joint) scientific publications in leading journals and at renowned conferences: Publications of project results are planned e.g. in IET Journal on Circuits, Devices and Systems, IEEE Journal on Solid-State Circuits, IEEE Journal on Circuits and Systems, IEEE Transactions on Microwave Theory and Techniques and at European Microwave Conference, IEEE International Solid-State Circuits Conference, IEEE Global Communication Conference, IEEE International Microwave Symposium, OFC, CLEO, ECOC. The focus of the contributions will be in the area energy-efficient high-speed circuit design for optical transceiver.
- **Publications** see the list in **Section 7.1** Summary of publications
- Press releases for the launch of ADDAPT on TUD's online media and in the university journal as well as in local press. See above and D2.5 for details.
- Two students are working on ADDAPT toward a PhD degree. They have visited our partner IBM Zurich for a research visit in June/July 2014. During their stay they learned to handle the challenging highly scaled CMOS technology which are being used in ADDAPT.
- Established ADDAPT project in ResearchGate

Dissem*ination plans after ADDAPT finalization*

Further press releases and publications are planned, e.g. on / in:

- 1/4-ch 14 nm CMOS TX with equalization and rapid on/off switching in IEEE Photonics Technology Letters
- 4-ch 14 nm CMOS TX with equalization and rapid on/off switching at ISSCC 2018
- 14 nm CMOS RX analog front-end with photodiode subassembly; e.g. in Photonics Technology Letter, Photonics Letters or at ECOC2018
- General overview on ADDAPT approach and results; e.g. on PRIME, ECOC, ISSC, OFC and/or other

Dissemination Related to Education

1. Organization of student colloquiums exchanges and joint activities to allow optimum dissemination of results from educational perspective into practice:
   - The experience, insights and results of the ADDAPT project will be integrated into lectures given at TUD.
   - Several students will be involved in ADDAPT, e.g. by means of PhD and master theses. Subsequently, after graduation these students will transfer their experience into companies.
   - March 2016: a joint measurement run on high-speed VCSEL among IBM and TUD in Dresden. By these measurements the experience and results with regard to VCSEL modelling will be exchanged. This enables best qualification of the involved PhD students and it is planned to write a joint paper on the results.
2. Promoting the project (results) via research centres/clusters:
   - TUD CCN is involved in the research clusters cfaed, HAEC and CoolSilicon as well as in Silicon Saxony e. V., a trade association for the microelectronics, where project information (poster, fact sheet, leaflets, overview presentation etc.) can be disseminated and presented to a broad international technical oriented audience containing students, researchers, engineers and company members.
3. Including ADDAPT topics and results into CCN lectures and workshops where many students participate:
   - Including ADDAPT insights into lecture “Integrated Circuits for Broadband Communication”
   - Including ADDAPT results into the CCN Workshop which takes place twice a year in spring and fall
   - Involving student assistance into measurements

7.6.5 Exploitation

TUD CCN as non-profit institution, research and educational oriented university cannot sell a product directly. However, within ADDAPT CCN of TUD mainly strengthens and enhances its experience and skills in the field of broadband IC design for optical interconnects, e.g. by gaining novel know-how on adaptive circuits approaches. This includes basic circuits of the optical transceiver up to complex system implementations. In addition the modelling capabilities of optical components and electrical interconnections for high-speed data transmission will be improved. On the one hand, this enables the continuation of national/international research in the field after ADDAPT. On the other hand, all those expertises can directly be incorporated into lectures and thus will gain the knowledge and skills of upcoming young academics. Therefore, well-educated and highly-skilled PhDs, researchers and engineers can be offered to industry after the project finishes. Moreover, the know-how will be provided to chair partners and the work in the project will also improve the connections and relationship to international industrial and academic/research partners.

In particular, the following actions are considered to exploit the ADDAPT project results:

- Offer of design, modelling, simulation and measurement know-how and services for broadband ICs to academic and industrial partners or other interested parties
- Provide IC IPs to interested companies/foundries and project partners
- Knowledge transfer to and education of students/PhDs, engineers and researches who will take leading positions in industry in future
- Issuing patents and offer for sale of patents generated in ADDAPT to interested parties

- Establishing a start-up company for electro-optic circuit design where the project results of ADDAPT could be commercially offered

Specific ADDAPT Know-how to be exploited

- High-speed/broadband integrated circuits
- Know-How on IC design techniques
- Adaptive IC design techniques
- Device, schematic design, (circuit) simulations and measurements
- Education and studies of young academics

Application

- ICs for transceivers for optical data-communication e.g. in data centers, HPC, etc.
- Adaptive techniques could also be implemented in non-optical communication components.
- Suitable for optical interconnects (rack-to-rack, board-to-board, on-board, inter-chip, chip-to-chip)
- Research and education (provision of know-how and expertise)

Market and customers

- Engineering and communication techniques
- Component and transceiver manufacturers
- IC foundries
- Research institutes
- Relevant student population, industrial and academic partners

Enabling conditions

- Access to advanced CMOS technologies and design kits
- Availability and use of design and measurement environments
- Courses to be provided to students, engineers, researchers or other interested parties

IPR

The following exploitation action has been conducted:

- Publication of patent application for adaptive circuit methods. F. Ellinger, R. Henker, R. Eickhoff, and R. Rieske, “Verfahren zur Steuerung oder Regelung eines Energiebedarfs und/oder einer Leistungsfähigkeit einer elektronischen Schaltung”, EP Patent Application, EP20 130 191 801, August 06, 2014.

Achieved Exploitation activities

- Mahdi Khafaji, TUD’s circuit designer for the 14 nm CMOS TX (laser driver and equalizer), gained a lot from the experience in ADDAPT project and has already achieved his Ph.D. degree on the topic of high-speed current-steering DACs in March 2015.

7.7 VI Systems (VIS)

7.7.1 Organization

VI Systems GmbH, based in Berlin, Germany, is a fabless developer and manufacturer of components for optical communication. The company designs and manufactures vertical cavity surface laser (VCSEL), photo detectors, integrated circuits and ultrahigh-speed packages for short reach optical interconnects. VI

Systems staff consists of 7 highly experienced experts most of them holding PhD degrees. The company holds 9 patents. Website: www.v-i-systems.com

7.7.2 Objective of organization

VI Systems is a technology leader which provides the most advanced components to customers which assembly short reach optical communication links.

7.7.3 Dissemination achievements:

- Press releases about achievements related to ADDAPT
- **Publications** see the list in **Section 7.1** Summary of publications
- Presentations in dedicated conferences and exhibitions (Photonics West, OFC, ECOC, etc.)
- Introduction of the concept to international customers which currently implementing VI Systems short reach optical interconnect products.

7.7.4 Exploitation

Specific ADDAPT Know-how to be exploited

Oxide-confined 850 nm, GaAs technology based vertical cavity surface emitting lasers (VCSELs) and photo-detectors chips with power adaptivity that will be achieved by adjusting the modulation currents and modulation voltages to yield adjustable data rates from 8 up to 56 Gbps. For signal transmission the use of feed forward equalization or pre/deemphasize techniques and advanced modulation coding schemes will also be considered. To obtain easy coupling and low power consumption of the entire optical transceiver, a novel near field coupling will be investigated.

Application

The VCSEL and photodetector chips are enabling key components in optical transceivers products (e.g. transceivers products, active optical cables, midboard transceiver products).

Market and customers

The market application segments include supercomputers, large size data-centers and networking equipment. Customers are high performance computer (HPC) systems and networking equipment manufacturer as well as suppliers of data interconnect products for HPC systems and network systems.

Enabling conditions

The availability of energy efficient VCSEL driver electronic that is capable of transmitting up to 56 Gbps and the availability of energy efficient amplifier electronics at price points which enable data transmission at the cost of less than $1 per Gbps.

Standardisation of optical interconnect technologies by standard bodies or industry partners typically increase the customer adaption rate rapidly.

VIS as Foundry partner for epitaxial growth of GaAs wafer structures and foundry partners for wafer processing. Closer co-operation with test laboratory for wafer characterisation and high speed transmission tests.

Products and Services

- Sales of vertical cavity surface emitting lasers (VCSELs) and photo-detectors chips for the adaptive IC technology.

- Sales of subassemblies which consist of VCSEL chip or photo-detectors chips and the adaptive IC technology.

7.8 Warsaw University of Technology (WUT)

7.8.1 Organization

WUT (https://www.pw.edu.pl/) is a leading technical university in Poland covering 28 fields of study. Founded in 1915, WUT has more than 36,000 students, more than 5,000 employees and more than 350 professors. In 2015 100-years of WUT presence have celebrated (http://www.100lecie.pw.edu.pl/?lang=en). The Optical Communications Group (OCG) of Institute of Telecommunications focuses on application of photonic technology in telecommunications and has considerable knowledge and experience in development of optical communication systems http://ocg.tele.pw.edu.pl. OCG is a leading optical communication research group in Poland with state of the art photonics communication laboratory established in the framework of the POIG.02.01.00-14-197/09 FOTEH project, (Innovative Economy Programme – founded by Polish Government and European Union European Regional Development Founds).

7.8.2 Objective of organization

Core competences of the WUT OCG are the optical communication system design, component and system testing as well as a high-speed laboratory test-bed up to 56 Gbps (including e.g. a 56 Gbps BER tester). The key research areas of WUT OCG include a high-speed transmission and MMF-based short-range transmission. Current research includes the advanced modulation formats like CAP for high speed optical communication or extended capacity 1310 nm transmission.

7.8.3 Achievements Dissemination

Papers

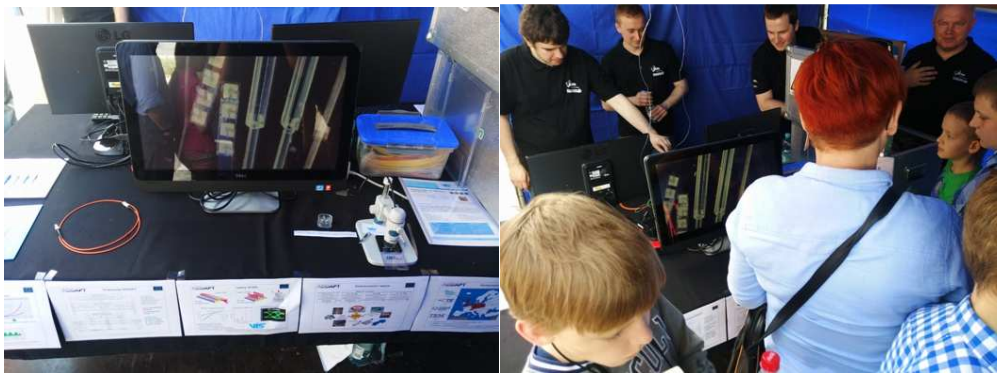
- **Publications** see the list in **Section 7.1** Summary of publications

Other achievements

- In cooperation with VI Systems the course material for the lecture "Fundaments of wire transmission" (Transmisja Przewodowa –TRP) was expanded with the VCSELs based transmission. The lecture is obligatory for B.Sc. and M.Sc. students.
- Information of the ADDAPT project has been published in the Warsaw University of Technology project database.
- The ADDAPT project as well as the developed in the project electro-optical components like VCSELs have been presented to the broad audience at Science Picnic (Piknik Naukowy – http://www.pikniknaukowy.pl) in Warsaw on 9 May 2015.
  19th Scientific Picnic has been held in Warsaw on 9 May 2015 at National Stadium, with light as the main topic. The Science Picnic is an initiative of Polish Radio and the Copernicus Science Centre to promote science. As the largest in Europe outdoor event promoting natural, social science and humanities it attracts every year over 100 000 visitors involving about 200 scientific institutions from Poland and abroad. During the Picnic, the ADDAPT project was presented to the broad audience. The great interest from the audience captured VCSEL's lasers coming from the ADDAPT

consortium member VISystems. For many visitors it was the only one opportunity to see such small light sources, which intrigued them.

- Announcements on WUT websites about the record transmission experiments and OFC post-deadline papers, e.g.
  https://www.biuletyn.pw.edu.pl/Konferencje-i-sympozja/Konferencja-OFC-z-rekordowa-transmisja-Instytutu-Telekomunikacji
  http://www.elka.pw.edu.pl/Aktualnosci/Sukcesy-i-dokonania-Studentow-WeiTI/Sukces-Instytutu-Telekomunikacji



Pictures showing the ADDAPT project info as well as VCSELs at science picnic in Warsaw

- Organization of a workshop in the area for efficient dissemination of results and knowledge exchange with external experts or other projects (planed during or towards the end of the project): One special session on optical interconnects at Optical Fibers and their Applications Conference (OFTA) 2017 in Suprasl, Poland have been organized. The ADDAPT project was present there with five talks. Furthermore, ADDAPT co-organized the 3rd Workshop of Data Center Interconnect Technologies (DACINT) at International Conference on Transparent Optical Networks (ICTON) 2017. ADDAPT was invited for four talks there.

Dissemination plan:

- Further scientific publications in journals and conferences
- Integration of the gained knowledge and experience in the courses given at WUT

7.8.4 Exploitation

Specific ADDAPT Know-how to be exploited

- High-speed data interconnect design
- High speed component and system measurements
- Student education

Application

- Development of ultra-high speed communication systems
- Education services

Market and customers

- Components and system manufacturers
- Academic and research institutes

- Students

Enabling conditions

- Availability and use of the measurement equipment
- Courses to be provided to students, engineers, researchers or other interested parties

Products and Services

The following actions are considered to exploit the ADDAPT project results:

- Offer of design, modelling, simulation and measurement know-how and services for high speed transmission components and systems to academic and industrial partners as well as other interested parties
- Knowledge transfer to and education of students/PhDs, engineers and researches who will take leading positions in industry in future

Achieved Exploitation activities

- Continuation of work with VIS systems on the VCSEL based photonic systems in the framework of the Poland – Berlin-Brandenburg call for proposals in the field of photonics
- A former WUT student has been employed by VIS.

Planned Exploitation activities

Continuation of the policy explained in earlier reports.

7.9 Cool Optics

We believe, with the stepping out of the consortium of TE, space arises for a startup exploiting particularly, but not only, the ADDAPTive part of ADDAPT. This startup will combine the several ADDAPT developments and achieve a joint exploitation of potential ADDAPT system (if licenses are granted).

The intention of this startup is to develop the ADDAPTive technology further to products. The startup should be in the position to offer on one hand a portfolio of IP, on the other hand be a marketing vehicle for the individual products and capabilities of the industrial partners VIS and AT to develop end-products embedded with productized ADDAPT technologies.

2016 and 2017 have been used to work further work on this startup concept. Key issue is the integration into standards. If standards do not accept the approach, the application will be limited to niche solutions. See also the chapters on standardization to get an understanding of the issues.

Cool Optics is not part of the consortium.

We foresee two different business models, each with their pro's and con's.

1. The deliverable of the startup are IP blocks (functional blocks delivered as synthesizable RTL, or hard macro's in various semicon processes). Example of IP blocks are drivers, TIA's, LA's, Addaptive Control Logic, Idle detect logic, Idle Block Generators, Low Power Algorithm, LPI Clients etc. The semicon industry is the natural client of this model.
2. Another approach could be to develop PICs with the logic fully integrated. This is of course a completely different business model, but probably easier from a sales point of view. Natural clients are the AOC and Network Card OEM's. This business model is not considered feasible by a startup.

Applications will not be different as already denoted by TE and IBM.

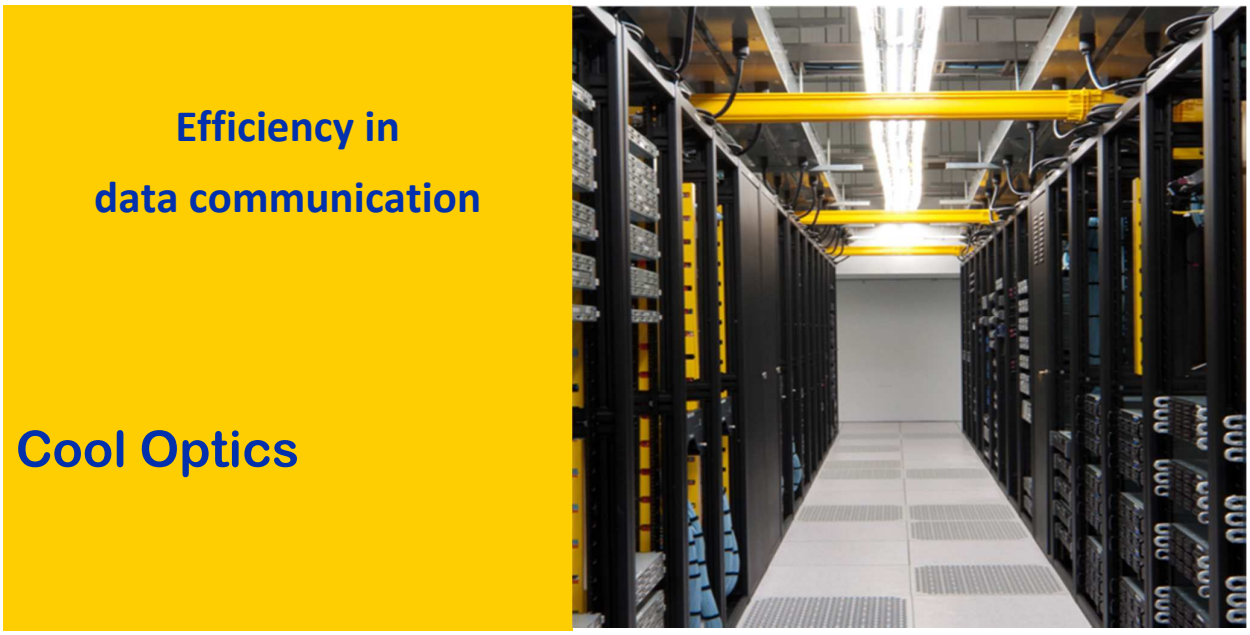
Cool Optics is now validating its ideas for integrating the ADDAPT technology into the Ethernet stack, and is in discussion with an investor.

The key selling points are that the technology allows for savings in the network stack (see also report D2.5), and is an enabler for optical switching.

7.9.1 Enabling Conditions

- Substantial Funding from private parties
- Granting of licenses by IBM
- More clear understanding of the business model.

7.9.2 Commercial Narrative



A step towards performance improvement and energy reduction

Why?

The Paris Agreement on climate change forces governments and industries to drastically reduce their carbon footprint. This will be done by moving to renewable sources and by reducing energy consumption. At the same time energy consumption in Data Center is growing at 35% CAGR and reached over 400 GWh last year, more than the total UK electricity consumption. This results in a carbon footprint of 200 Mton /year, of which 40 Mton/year alone in Europe.

This growth is mainly driven by the explosive growth of data communication at a speed of 30% /year. According to Cisco, Global mobile data traffic will increase sevenfold between 2016 and 2021, at a compound annual growth rate of 47 percent from 2016 to 2021, reaching 49.0 exabytes per month by 2021. All this traffic is eventually handled by data centers

This not only counteracts activities on carbon footprint reduction, it also creates a growing concern for Data Center management regarding cost, cooling and performance. Many solutions are being developed, but the most efficient way is to find a solution in the data communication itself.

The FP7 EU project ADDAPT ("Adaptive Data and Power Aware Transceivers for Optical Communications") has developed a transceiver

concept to reduce energy. As one of the participants, the founder of Cool Optics Pieter van Leeuwen, is developing this concept further into an energy management solution including the network stack. Additional applications are in the areas of latency reduction and optical switching.

How?

This ADDAPT transceiver concept is based on adaptable lanes to save energy. This is done by switching to sleeping mode in 2 nanosec during idle time, from which it can recover in 10 nanosec. It performs at up to 56 Gbps using NRZ modulation and is adaptable between 7 Gbps to 56 Gbps. It consumes 4pJ/bit while 'on', and virtually zero while in sleeping mode.

Energy consumption in the network stack is much higher compared to that in the transceiver. Enabled by the ADDAPT concept, Cool Optics is developing an extended solution to control energy consumption in the complete network stack. This includes the data hub IC's in the server, the network stack IC's, the switches and the transceivers. This can reduce the energy bill and the Carbon Footprint by up to 15%. This solution is based on the Cool Optics "Lock and Link"^{TM} control technology, idle time prediction algorithm ITPA^{TM} on a nanosecond timeframe and energy management on the daily pattern DEMP^{TM}.

Bit Error Rate (BER) is an important factor influencing latency in data communication. The upcoming 56 Gbps/PAM-4 standard has a BER of < 10^{-5}. This low BER requires Forward Error Correction (FEC) which not only introduces appr. 0.1 µsec latency but also 40% more energy consumption and chip area. In the Cool Optics technology BER will be 10^{-12} and therefore does not need FEC, saving 0.1 µsec latency, chip area and energy.

One of the new innovative technologies under development is Optical Switching. It has inherent advantages in latency and energy. However, other than packet switching, each optical switching action disrupts the data communication. Restarting after each switch causes a startup latency in a µsec time frame. The Cool-optics "Lock and Link"^{TM} technology is being designed to start and stop the data stream in a controlled way within a nanosec timeframe. Cool Optics technology therefore can be an enabling technology for Optical Switching.

Issues and Benefits

Data Center issues:

- follow the roadmap on data speed and volume
- lower OPEX by Energy cost savings, carbon footprint reduction
- lower CAPEX by less cooling and power equipment
- reduction of floor space

The Cool Optics solutions will be able to reduce energy consumption of the data communication devices by up to 60%. This will also result in a reduction of cooling and power supplies and will enable device suppliers to reduce their form factor and consequently expensive data center floor space. It will improve performance by reducing latency and it will help the development of Optical Switching.

System and OEM industry issues:

- better throughput performance
- higher performance in the network bandwidth
- less cooling features and smaller power supply

The Cool Optics solution energy will save 60% energy in the network stack, (typical 100 mW/Gbps), and a reduction of 20 mW/Gbps (present technology) to potentially 1 mW/Gbps in the transceiver. The latter allows for smaller modules (µQSFP), doubling the number of slots in the backplane, improving the overall throughput of the backplane by a factor of four.

Over time, the Cool Optics Lock and Link^{TM} technology will enable the OEM industry to

develop Optical Switching solutions, bringing an even larger performance increase.

The network IC industry issues:

- improve the energy efficiency of IC's
- provide those solutions at affordable cost levels,
- follow the speed demands of the market.

The Cool Optics solutions will be able to meet these demands with an energy reduction of 20 – 80% (average 60%) depending on network load. Costs of ICs are to a large extend determined by area of the IC. The area for the Cool Optics solution is smaller because of a simpler (de)modulator and no need for FEC (Forward Error Correction).

More information: pieter.vanleeuwen@cool-optics.nl

Mobile: +31 6 1320 6814

Eindhoven, The Netherlands

Cool Optics non-confidential document (2017) © Cool Optics, Eindhoven, NL

7.9.3 Savings by ADDAPT's adaptivity compared to Deep Sleep and Fast Wake

In WP3 we did some investigation by building a simulation model that shows the relation between on and off time, and network load. 100% means: 100% savings compared to 'no switch off during idle'. The longer the switch on/off time, the less time the link is in low power mode, and the less energy savings. You can easily see the difference in savings potential between the adapt performance and the 'fast-wake' or 'deep sleep' approach. Cool Optics found a way to integrate ADDAPT transceiver in Ethernet, and controlling start and stop, including correct Ethernet handling, on a fast and efficient way. The results are shown in the following graph.

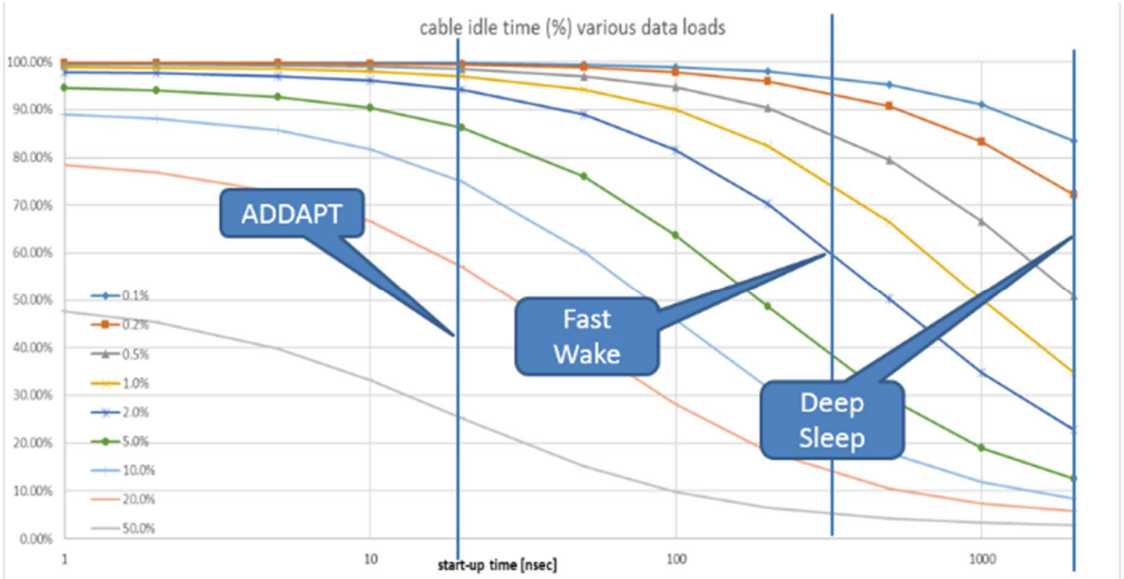


Figure 5: Energy saving over time for different adaptive approaches.

8 References

Reference	Description
[ADDAPT]	Grant Agreement no 619197 for Collaborative Project, Annex 1 – "Description of Work"
[D2.2], [D2.3], [D2.4], [D2.5]	Deliverable reports in the ADDAPT project on "Market study, evaluation of applications and product specifications"
[1]	Cisco Visual Networking Index: Forecast and Methodology, 2013–2018
[2]	Lambert, Sofie, et al. «Worldwide electricity consumption of communication networks.» *Optics express* 20.26 (2012): B513-B524.
[3]	Modrzejewski, Remigiusz, et al. "Energy efficient content distribution in an ISP network." Proc, IEEE Global Communications Conference (GLOBECOM'13). 2013.
[4]	Chiaraviglio, Luca, Marco Mellia, and Fabio Neri. "Minimizing ISP network energy cost: formulation and solutions." IEEE/ACM Transactions on Networking (TON) 20.2 (2012): 463-476.
[5]	Tejasvi Anand et al. "A 7Gbps Rapid On/Off Embedded-Clock Serial-Link Transceiver with 20ns Power-On Time, 740µW Off-State Power for Energy-Proportional Links in 65nm CMOS", published at 2015 IEEE International Solid-State Circuits Conference.
[6]	WHITE PAPER: "WP-ECONET". Power Saving Features in Mellanox Products, 2013
[7]	Workinggroup 802.3bs. Bhatt_3bs_01a_0714 by Vipul Bhatt, Inphi, July 2014.
[8]	Workinggroup 802.3bs. Ghiasi_3bs_01b_0514. Ali Ghiasi, Ghiasi Quantum LLC, May 2014
[9]	Workinggroup 802.3bs. Stassar_3bs_01b_0914. Peter Stassar, Huawai, Chris Cole, Finisar. September 2014
[10]	Workinggroup 802.3bs. motions_3bs_01_0115. Motions / Strawpolls, Jan 2015 Interim, Recorded by Kent Lusted, Intel
[11]	Infiniband Trade Association. InfiniBand Architecture, Specification Volume 1, Release 1.3, March 2015.
[12]	Ethernet specification as described in IEEE 802.3, maintained and innovated by IEEE.
[WP40GbE]	The Market Need for40 Gigabit Ethernet. White Paper 2012, Cisco, Gautam Chanda

9 Acronyms

Acronym	Definition
100GbE	100 Gigabit per second Ethernet
40GbE	40 Gigabit per second Ethernet
AM	Alignment Marker. A special block within Ethernet, used to align the lanes to each other. The alignment markers shall be inserted after every 16383 66-bit blocks on each PCS lane.
ATM	Asynchronous Transfer Mode (ATM) is, standards for carriage of a complete range of user traffic, including voice, data, and video signals" [1]. ATM is a core protocol used over the SONET/SDH backbone of the public switched telephone network (PSTN) and Integrated Services Digital Network (ISDN), but its use is declining.
AUI	The Ethernet expression for "Attachment Unit Interface", the interface between two physically separated devices. This may be between two IC's, or between the Ethernet board and the Ethernet cable module. Many variants of AUI exist, indicated with one or two capitals in front of "AUI". Examples are CDAUI, GAUI, XLAUI, CAUI,…The AUI interface is sometimes used as a conceptual interface to describe functionality between two (sub)layers, and may or may not be physically instantiated.
CLEO	Conference on Lasers and Electro-Optics
DBC	Data Center Bridging. An Ethernet specification for the data-center environment
DLL	Data Link Layer. The network layer takes care of packaging data into packets. It furnishes transmission protocol knowledge and management and handles errors in the physical layer, flow control and frame synchronization. An example for Ethernet is described in IEEE 802.3 Clause 80.
ECOC	European Conference on Optical Communications
EEE	Energy Efficient Ethernet. A substandard developed under IEEE 802.3az, and described in Clause 78.
EoS or EoSDH	Ethernet over SDH. Refers to a set of protocols which allow Ethernet traffic to be carried over synchronous digital hierarchy networks in an efficient and flexible way. The same functions are available using SONET (a predominantly North American standard).
HPC	High Performance Computing (supercomputing)
IA	Implementation Agreement
IBA	Infiniband Architecture. The total framework that describes both on architectural level and on detailed level the Infiniband Architecture. The IBA is maintained and published by the IBTA
IBTA	Infiniband Trade Association. Association of several organisations maintaining, and innovating the IBA. Some members of IBTA make products that have features of IBTA implemented.
IEEE	Institute of Electrical and Electronics Engineers. It amongst others standardized the Ethernet protocols
iWARP	The Internet Wide Area RDMA Protocol (iWARP) is a computer networking protocol for transferring data efficiently. It is sometimes referred to simply as "RDMA", though RDMA is not a feature exclusive to iWARP.
KPI	Key Performance Indicator. An easy metric that shows a performance on a particular

Acronym	Definition
	subject.
LPI	Low Power Idle, the mode defined in EEE (Energy Efficient Ethernet) where the link is in a status of low power, no transmission.
LPI_signal	The signal that Ethernet uses to signal that LPI mode shall become active. There are two service primitives related to LPI signal: LP_IDLE.request LP_IDLE.indication. (for Deep Sleep it is more complex)
MMF	Multimode fiber
MSA	Multi-source agreements (MSAs) are not official standards organizations. Rather, they are agreements between equipment vendors when developing form factors for communications interfaces. Examples of MSA are QSFP, SFP, CXP, µQSFP
NCSA	National Centre for Supercomputing Applications, University of Illinois
OFA	Open Fabrics Alliance. Founded in June 2004 as the OpenIB Alliance, the Alliance was originally focused on developing a vendor-independent, Linux-based InfiniBand software stack. Today, the vision of the OpenFabrics Alliance is to deliver a unified, cross-platform, transport-independent software stack for RDMA and kernel bypass.
OFC	Optical Fibre Communication Conference and Exposition
PCS	Physical Coding Sublayer. A layer in the Ethernet PHY, where the bitstream is encoded (e.g. 64b/66b) and scrambled. (and in the receive path decoded and descrambled)
PD	A photodiode is a semiconductor device that converts light into current. The current is generated when photons are absorbed in the photodiode.
PHY	The physical network layer in communication stacks. Various examples exist, such as in Ethernet, for example in Clause 80.
PMA	Physical Medium Attachment. A sublayer in the PHY of Ethernet. PMA allows the PCS (specified in e.g. Clause 82 [12]) to connect in a media-independent way with a range of physical media.
PMD	Physical Medium Device, the devise that takes care of transforming electrical bitstreams into modulated signal over the medium at hand (coax, twisted pair, backplane, optical cable, …)
PoS	Packet over SDH, a way to transport (IP) packets over SDH / SONET
PPI	A typical Ethernet expression for Physical Parallel Interface. There are several PPI's: XLPPI, CPPI, similar to the variants of AUI. It is the interface between PMA and PMD and is e.g. the interface to which a QSFP is designed.
PUE	Power Use Effectiveness. A KPI developed by The Green Grid Association , a nonprofit, open industry consortium
QSFP	Quad Small Form-factor Pluggable. A compact, hot-pluggable transceiver used for data communications applications.
RAM	Rapid alignment marker. The RAM is used in Ethernet as an alternate method of alignment when operating in the deep sleep low power state. Rapid Alignment Markers (RAMs) function in a similar manner to the normal alignment markers.
RDMA	Remote Direct Memory Access
RoCE	RDMA over Converged Ethernet (RoCE) is a network protocol that allows remote direct memory access over an Ethernet network. RoCE is a link layer protocol and

Acronym	Definition
	hence allows communication between any two hosts in the same Ethernet broadcast domain. Although the RoCE protocol benefits from the characteristics of a converged Ethernet network, the protocol can also be used on a traditional or non-converged Ethernet network. [Wikipedia]
SAS	Serial Attached SCSI (SAS) is a point-to-point serial protocol that moves data to and from computer storage devices such as hard drives and tape drives
SATA	Serial ATA (SATA) is a computer bus interface that connects host bus adapters to mass storage devices such as hard disk drives and optical drives.
SCSI	Small Computer System Interface is a set of standards for physically connecting and transferring data between computers and peripheral devices. The SCSI standards define commands, protocols and electrical and optical interfaces. SCSI is most commonly used for hard disks and tape drives, but it can connect a wide range of other devices, including scanners and CD drives, although not all controllers can handle all devices.
SDH	Synchronous Digital Hierarchy, in telecommunications
SiPh	Silicon Photonics
SMF	Singlemode fiber
SMP	Internal IBM protocol between processor of the Power7 family
VCSEL	The vertical-cavity surface-emitting laser, or VCSEL is a type of semiconductor laser diode with laser beam emission perpendicular from the top surface, contrary to conventional edge-emitting semiconductor lasers (also in-plane lasers) which emit from surfaces formed by cleaving the individual chip out of a wafer.
WAN	Wide Area Network, in telecommunications