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SEVENTH FRAMEWORK PROGRAMME

PROJECT: **FOX-C** CONTRACT NO.: **318415**

FLEXIBLE OPTICAL CROSS-CONNECT NODES

ENABLING NEXT-GENERATION FLEXIBLE OPTICAL NETWORKING

SPECIFIC TARGETED RESEARCH PROJECT (STREP)

INFORMATION & COMMUNICATION TECHNOLOGIES (ICT)

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3rd year Exploitation plans, dissemination activities and identification of standardization actions

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This deliverable summarizes the dissemination activities of the third year of the FOX-C project and also presents the final exploitation plans as well as the targeted standardization actions

Revision History

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1	1.0	Jordi Ferran, Jordi Lozano (WONE)	**30/11/15**
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3	3.0	Optronics	
	Comments:	**Adding Website statics, optronics exploitation plan**	
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	Comments:	**Complete W-onesys Exploitation part**	
5	5.0	Shalva	
	Comments:	**Complete Finisar Exploitation part**	
6	6.0	Jordi Ferran	
	Comments:	**Complete Standardization Part**	
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	Comments:	**Editing of 2.1 and corrections on section 3. Revision of the whole document**	
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	Comments:	**Correct a couple of unclear statements of Finisar and Orange**	
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	Comments:	**Exploitation Plan on Terabit transceivers**	
12	12.0	Jordi Ferran	**15/03/16**
	Comments:	**Move Wonesys Business plan to a confidential Annex**	

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Executive Summary

This deliverable reports on: (a) the project's dissemination activities during the third year, (b) the activities regarding exploitation of FOX-C results and (c) some remarks with respect to contributions to standards.

The dissemination activities during the third year of the project have mainly focused on the promotion of our important research outcomes to the scientific community. The key target was on the presentation of important technology aspects and examined solutions in major international conferences, attracting a significant number of researchers in the field. Significant effort was given in the continuous update of the project's website, containing news and important highlights from the research activities of the partners.

During this final year of the project, all industrial partners have presented their final exploitation plans related to FOX-C projects. Finisar has presented their view of WSS market with components forecast and their view on introduction of WSS with finer granularity towards2020-21. W-onesys, as a manufacturer of ROADM systems that integrate WSS, has assessed this trend and has defined the type of product, market and business model that could be offered in their portfolio: one Flexgrid-ROADM product oriented to the experimental optical networks market, typically implemented in research centres and universities. W-onesys, also presents a cost analysis according to the business model and five year sales projections and a business case has been prepared. Orange, also provide sits view on FOX-C technology after some studies have been made.

Different partners contributed towards the standardization effort. The first step it was to identify the topic related to FOX-C project that could be presented to ITU-T. Once the topic was identified, there were some discussions between Finisar and Orange to redact and support a proposal. Unfortunately, Finisar decided that they won't support standardization until a product has been developed and not just a prototype.

1 Dissemination activities

1.1 Website

The website of FOX-C project (www.ict-fox-c.eu) acts as a point of reference both for the external visitors and the consortium members. The content of the website is being regularly updated providing a description of the project concept and news on the performed activities to the external users. Partner OPTRONICS, as the FOX-C project coordinator, has established and maintained the FOX-C website sincethe first week of the project start.

The FOX-C website contains a public area with:

- News and events
- Publications
- Public Deliverables and open presentations
- Information about the consortium

The website contains a restricted area with access only to the FOX-C partners. This area enables the Consortium to manage the information dissemination between partners and contains a directory with the relevant files of the

- Working documents (Deliverables, Milestones and Task Detailed Work-Plans)
- Publications
- Plenary Meeting Information (presentations, minutes)
- Conference Call Information (presentations, minutes)
- Project Time plan
- Administration Information (Grant Agreement Documents, Templates)

Moreover, the website includes a specific area for the project reviewers. This area will assist during the annual reviewing processes by providing the reviewers all related files (periodic report, deliverables, publications etc.) that are necessary for completing the project periodic review.

The consortium identified that a well-maintained website is essential for the dissemination of the project activities and an easy and efficient way to provide a reference to the FOX-C project. For this reason, the consortium agreed to include the FOX-C website address in all public presentations.

FOX-C website statistics

The FOX-C website is registered to Google analytics service since the 10th of February 2014. Since then, all data collected by this tool is periodically analysed to monitor the project's exposure to the wider public. The website also includes a visitor counter, which has currently counted more than 22,000 visitors.

During the project's third and final year, when more results became available, the consortium increased its effort to promote the FOX-C project. Next figure presents the accumulated traffic of FOX-C website for the period from 10/2/2014to 16/12/2015. The figure also includes the traffic forecast for the third year based on the second year data (dashed line). This forecast is presented to highlight the significant traffic growth improvement that was achieved due to the success of the third year's dissemination activities. In particular, the results of the third year's efforts are more intensely reflected during the second half of the reporting period.

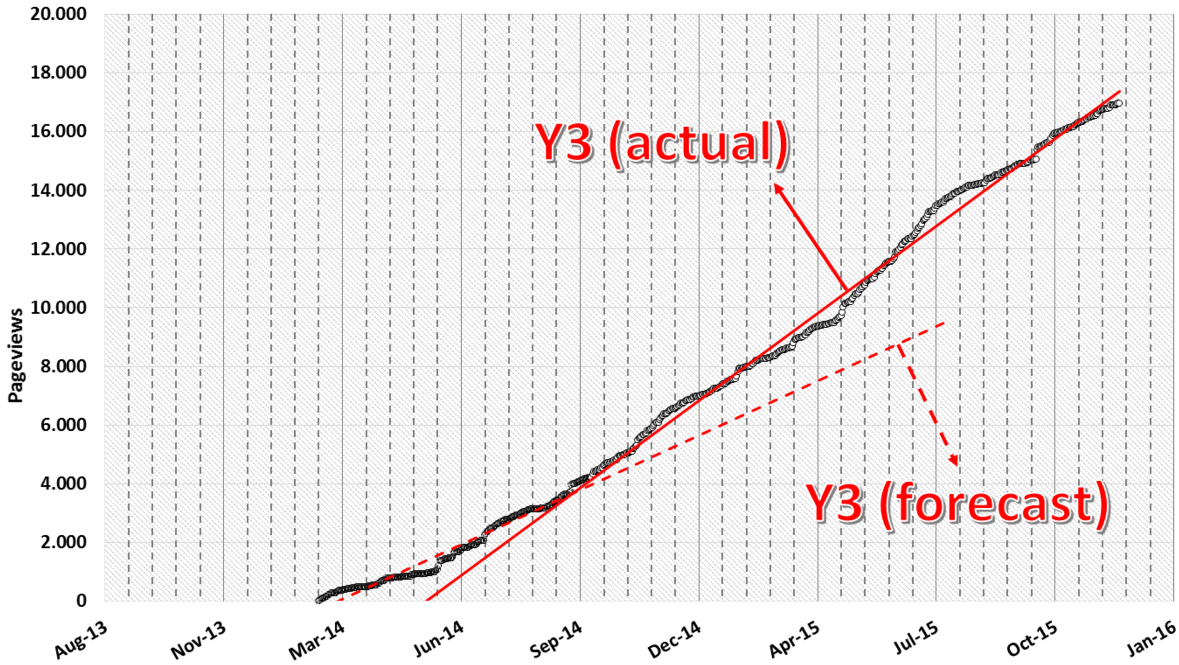

Figure 1.1: FOX-C website traffic. The figure highlights a significant increase of the interest during the third year of the project

Next figure presents the country origin of all unique users visited the website during the third reporting period of the project. The results indicate a significant increase of the interest to the project technologies to countries not direct related to the consortium members (USA, Brazil, China, Japan etc). In addition to that, the top 5 visiting countries is a strong indication that the project has attracted international interest.

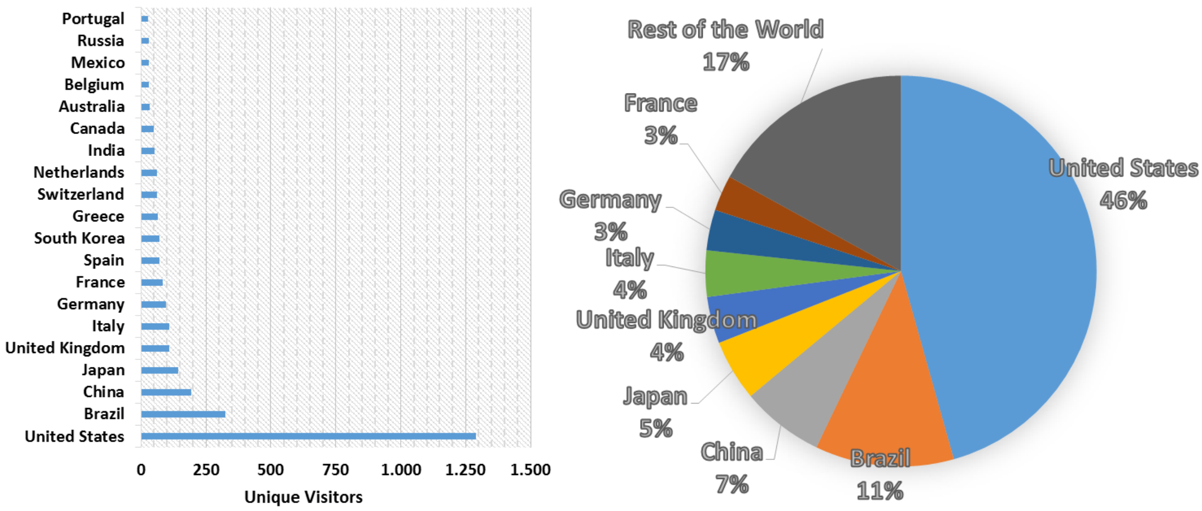

Figure 1.2: Top visiting Countries. Top 20 visiting Counties (left) and percentage distribution of users' country of origin (right)

At the end of the second reporting period a similar study showed a significant interest on the FOX-C project from Brazil (this was reported in deliverable D6.3). During the third year of the project the origin of the visitors was further investigated. The consortium managed to get introduced to some research groups and got invitations to one workshop and one conference, where Prof. Ioannis Tomkos presented the achievements of different EU projects including FOX-C project:

- IV International Workshop on Trends in Optical Technologies: Towards Terabit per second Optical Networking, May 27-28, 2015, Campinas, Brazil
- SBMO/IEEE MTT-S International Microwave and Optoelectronics Conference, October 29-November 01, Natal, Brazil

1.2 Dissemination activities

1.2.1 Scientific Publications

There is in total 79 scientific publications and 3 workshops along FOX-C project.

1.2.1.1 Journals

Type of Activity	**Details**	**Where**	**Date**	**Reporting Period**
Journal Publication	J. Zhao and H. Shams, "Fast dispersion estimation in coherent optical 16QAM fast OFDM systems," Optics Express, vol. 21, pp. 2500, 2013.	Optics Express	25/01/2013	Y1
Journal Publication	J. Zhao and A.D. Ellis, "Pilot tone design for dispersion estimation in coherent optical fast OFDM systems," Optics Communications, vol. 298-299, pp.75, 2013	Optics Communications	07/04/2013	Y1
Journal Publication	J. Zhao, "Intensity modulation full-field detection optical fast OFDM," OSA Journal of Optical Communications and Networking 2013, vol. 5, pp.465.	JOCN	18/04/2013	Y1
Journal Publication	R. Schmogrow, S. Ben-Ezra, P.C. Schindler, B. Nebendahl, C. Koos, W. Freude and J. Leuthold, "Pulse-shaping With Digital, Electrical, and Optical Filters – A Comparison," Journal of Lightwave Technology, Vol. 31, No. 15, 2013.	JLT	27/06/2013	Y1
Journal Publication	David Sinefeld, Shalva Ben-Ezra, and Dan M. Marom, "Nyquist-WDM filter shaping with a high-resolution colorless photonic spectral processor," Opt. Lett. 38, pp. 3268–3271, 2013.	Optics Letters	21/08/2013	Y1
Journal Publication	D. Hillerkuss, T. Schellinger, M. Jordan, C. Weimann, F. Parmigiani, B. Resan, K. Weingarten, S. Ben-Ezra, B. Nebendahl, C. Koos, W. Freude, and J. Leuthold, "High-quality optical frequency comb by spectral	Photonics Journal	04/09/2013	Y1

	slicing of SPM broadened pulses," IEEE Photonics Journal, vol. 5, 2013.			
Journal Publication	M. Sorokina, S. Sygletos, A. D. Ellis, and S.K. Turitsyn, "Optimal packing for cascaded regenerative transmission based on phase sensitive amplifiers," Opt. Express 21, 31201-31211 (2013)	Optics Express	11/12/ 2013	Y2
Journal Publication	R. Schmogrow, M. Meyer, P.C. Schindler, B. Nebendahl, M. Dreschmann, J. Meyer, A. Josten, D. Hillerkuss, S. Ben-Ezra, J. Becker, C. Koos, W. Freude, and J. Leuthold, "Real-time Nyquistsignaling with dynamic precision and flexible non-integer oversampling," Optics Express, Vol. 22, Issue 1, pp. 193-209 (2014)	Optics Express	02/01/ 2014	Y2
Journal Publication	S.T. Le, T.Kanesan, E. Giacoumidis, N.J. Doran, A.D. Ellis, "Quasi-pilot aided phase noise estimation for coherent optical OFDM systems," Photonics Technology Letters, Vol. 26, No. 5, pp 504-507 (2014).	Photonics Technology Letters	17/01/ 2014	Y2
Journal Publication	T. Kanesan, S. T. Le, D. Roque, and A. D. Ellis, "Non-rectangular perfect reconstruction pulse shaping based ICI reduction in CO-OFDM," Optics Express 22, 1749-1759 (2014).	Optics Express	17/01/ 2014	Y2
Journal Publication	R. Schmogrow, B. Nebendahl, A. Josten, P.C. Schindler, C. Koos, W. Freude, and J. Leuthold, "Timing, carrier frequency and phase recovery for OFDM and Nyquist signals using a mean modulus algorithm," Optics Express, Vol. 22, Issue 8, pp. 9344-9359 (2014)	Optics Express	10/04/ 2014	Y2
Journal Publication	P. C. Schindler, R. Schmogrow, S. Wolf, B. Baeuerle, B. Nebendahl, C. Koos, W. Freude, and J. Leuthold, "Full flex-grid asynchronous multiplexing demonstrated with Nyquist pulse-shaping," Optics Express, Vol. 22, Issue 9, pp. 10923-10937 (2014)	Optics Express	29/04/ 2014	Y2
Journal Publication	E. Giacoumidis, M. A. Jarajreh, S. Sygletos, S. T. Le, F. Farjady, A. Tsokanos, A. Hamié, E.Pincemin, Y. Jaouën, A. D. Ellis, and N. J. Doran, "Dual-polarization multi-band optical OFDM transmission and transceiver limitations for up to 500 Gb/s uncompensated long-haul links," Optics	Optics Express	30/04/ 2014	Y2

	Express, Vol. 22, No. 9, pp 10975-10986, (2014).			
Journal Publication	E. Pincemin, M. Song, J. Karaki, O. Zia-Chahabi, T. Guillossou, D. Grot, G. Thouenon, C. Betoule, R. Clavier, A. Poudoulec, M. Van der Keur, Y. Jaou¨en, R. Le Bidan, T. Le Gall, P. Gravey, M. Morvan, B. Dumas-Feris, M. L. Moulinard, and G. Froc, "Multi-Band OFDM Transmission at 100 Gbps With Sub-Band Optical Switching," Journal of Lightwave Technology, Vol. 32, No. 12, JUNE 15, 2014.	JLT	07/05/ 2014	Y2
Journal Publication	X. Ouyang and J. Zhao, "Single-tap equalization for fast OFDM signals under generic linear channels," IEEE Communications Letters, vol. 18, pp. 1319-1322, 2014.	Communication Letters	06/06/ 2014	Y2
Journal Publication	E. Giacoumidis, I. Aldaya, M.A. Jarajreh, A. Tsokanos, S.T. Le, F. Farjady, A.D. Ellis, and N.J. Doran, "Volterra-based Reconfigurable Nonlinear Equalizer for Dual-Polarization and Multi-Band Coherent OFDM," Photonics Technology Letters, Vol. 26, No. 14, pp 1383, (2014)	Photonics Technology Letters	15/07/ 2014	Y2
Journal Publication	S.L.Lee, M.E.McCarthy, E. Gaikoumidid, K.J.Blow, N.J.Doran, A.D.Ellis, "Comparison of bit error rate estimation methods for QPSK OFDM Transmission," Photonics Technology Letters, Vol. 26, No. 22, pp 2244-2247 (2014).	Photonics Technology Letters	04/09/ 2014	Y2
Journal Publication	J. Zhao, "Multi-tap equalization for performance improvement in optical fast OFDM systems," IEEE Photonics Technology Letters, Vol. 27, No. 1, 42-45, Jan. 2015	Photonics Technology Letters	08/10/ 2014	Y2
Journal Publication	X. Ouyang and J. Zhao, "Channel estimation in DFT-based offset-QAM OFDM systems," Optics Express, Vol. 22, No. 21, pp. 25651-25662 (2014)	Optics Express	14/10/ 2014	Y2
Journal Publication	S. Sygletos, S. Fabbri, E. Giacoumidis, M. Sorokina, D. M. Marom, M.F.C. Stephens, D. Klonidis, I. Tomkos, and A. D. Ellis, "Numerical investigation of all-optical add-drop multiplexing for spectrally overlapping OFDM signals," Optics Express, Vol. 23, No. 5, pp. 5888-5897 (2015)	Optics Express	25/02/ 2015	Y3

Journal Publication	X. Ouyang, H. Zhang, Y. Chen, S. Alam, M. N. Petrovich, F. Poletti, D. J. Richardson, F. C. G. Gunning, J. Zhao, "Experimental Demonstration of Improved Equalization Algorithm for IM/DD Fast OFDM," IEEE Photonics Technology Letters, Vol.27 no.16, Aug. 2015	Photonics Technology Letters	10/06/2015	Y3
Journal Publication	J. Zhao and P. D. Townsend, "Dispersion tolerance enhancement using an improved offset-QAM OFDM scheme," Optics Express, Vol.23 no.13, pp 17638-17652 (2015)	Optics Express	26/06/2015	Y3
Journal Publication	X. Ouyang, W. Jia, P. Gunning, P.D. Townsend and J. Zhao, "Experimental demonstration and field-trial of an improved optical fast OFDM scheme using intensity-modulation and full-field detection," Journal of Lightwave Technology, Journal of Lightwave Technology, vol. 33, pp. 4353, 2015.	JLT	17/08/2015	Y3
Journal Publication	D. Hillerkuss, & J. Leuthold, "Software-Defined Transceivers in Dynamic Access Networks". Journal of Lightwave Technology, PP(99), 1–1. http://doi.org/10.1109/JLT.2015.2470089(2015).	JLT	26/08/2015	Y3
Journal Publication	P. S. Khodashenas, J. M. Rivas-Moscoso, B. Shariati, D. M. Marom, D. Klonidis and I. Tomkos, "Investigation of Spectrum Granularity for Performance Optimization of Flexible NyquistWDM-Based Optical Networks," Journal of Lightwave TechnologyVol. 33, No. 23, 4767 - 4774, 2015.	JLT	13/10/2015	Y3
Journal Publication (Invited)	I. Tomkos, S. Azodolmolky, J. Sole-Pareta, D. Careglio, E. Palkopoulou, "A Tutorial on the Flexible Optical Networking Paradigm: State-of-the-Art, Trends, and Research Challenges," (invited paper), Proceedings of the IEEE, September 2014.	Proc. IEEE	02/06/2014	Y2
Journal Publication (Invited)	D. Klonidis, I. Tomkos, et. al., "Spectrally and spatially flexible optical network planning and operations," (invited paper), IEEE Communications Magazine, Vol. 53, No. 2, 69 – 78,Feb 2015.	Communications Magazine	19/02/2015	Y2

Journal Publication (Invited)	J. Zhao, "DFT-based optical offset-QAM OFDM: analytical, numerical, and experimental studies," Springer Photonic Network Communications, DOI 10.1007/s11107-015-0545-8, (invited) 2015.	Photonic Network Communications	23/08/2015	Y3
Seminar	Next Generation Packet-Optical Networks	TERA SANTA	07/11/2012	Y1
Special Session	ICTON 2013 ASTRON/FOX-C Special Session on "Physical Layer Technologies for Flexible/Elastic Optical Networks"	ICTON	23/06/2013	Y1

1.2.1.2 Conferences

Type of Activity	Details	Where	Date	Reporting Period
Conference Publication	D. Sinefeld, D. M. Marom, S. Ben-Ezra, "Adaptive spectral filtering for Nyquist-WDM generation with an LCoS-based photonic spectral processor," IEEE 27th Convention of Electrical & Electronics Engineers in Israel (IEEEI), 2012.	IEEEI	14/11/2012	Y1
Conference Publication	R. Schmogrow, M. Meyer, P.C. Schindler, A. Josten, S. Ben-Ezra, C. Koos, W. Freude and J. Leuthold, "252 Gbit/s Real-Time Nyquist Pulse Generation by Reducing the Oversampling Factor to 1.33," OTu2I.1, OFC/NFOEC 2013.	OFC/NFOEC	17/03/2013	Y1
Conference Publication	D. Sinefeld, S. Ben-Ezra, D. M. Marom, "Adaptive spectral filtering for Nyquist-WDM generation with extremely high resolution photonic spectral processor," OFC/NFOEC 2013.	OFC/NFOEC	17/03/2013	Y1
Conference Publication	H. Shams and J. Zhao, "First investigation of fast OFDM radio over fibre system at 60 GHz using direct laser modulation," IEEE Conference on Lasers and Electro-Optics Europe (CLEO-Europe), May 2013, paper CI-5.5.	CLEO-Europe	12/05/2013	Y1
Conference Publication	H. Wang and J. Zhao, "Performance comparison between offset-QAM CoWDM and Nyquist WDM," OSA Signal Processing in Photonic Communications (SPPCom) July 2013, paper SPM3D.2.	SPPCom	14/07/2013	Y1
Conference Publication	J. Zhao, "DFT-based offset-QAM OFDM with arbitrary orthogonal waveform generation," European Conference on Optical Communications Sep. 2013, paper P.3.10.	ECOC	22/09/2013	Y1

Conference Publication	J. Zhao, "Improved performance of optical F-OFDM over conventional OFDM for residual frequency offset compensation," European Conference on Optical Communications Sep. 2013, paper P.3.11.	ECOC	22/09/2013	Y1
Conference Publication	R. Rudnick, D. Sinefeld, O. Golani and D. M. Marom, "One GHz Resolution Arrayed Wavguide Grating Filter with LCoS Phase Compensation," Optical Fibre Conference (OFC 2014), San Francisco, CA, Mar. 2014.	OFC	09/03/2014	Y2
Conference Publication	S. Le, T. Kanesan, M.E. McCarthy, E. Giacoumids, I.D. Phillips, M. Stephens, M. Tan, N.J. Doran, A.D. Ellis, S.K. Turitsyn, "Experimental Demonstration of Data-dependent Pilot-aided Phase Noise Estimation for CO-OFDM," OFC 2014, paper Tu3G4, (2014).	OFC	09/03/2014	Y2
Conference Publication	I.D. Phillips, M. Tan, M. Stephens, M.E. McCarthy, E. Giacoumids, S. Sygletos, P. Rosa, S. Fabbri, S. Le, T. Kanesan, S.K. Turitsyn, N.J. Doran, P. Harper, A.D. Ellis, "Exceeding the Nonlinear-Shannon Limit using Raman Laser Based Amplification and Optical Phase Conjugation," OFC 2014, Paper M3C1, (2014).	OFC	09/03/2014	Y2
Conference Publication	M.E.McCarthy, S.Sygletos, M.F.C. Stephens, N. Mac Suibhne, I.D.Phillips, P.Harper, N.J.Doran, A.D.Ellis, "Challenges of Developing Non-linear Devices to Exceed the Linear Shannon Limit," Proc ICTON 2014, paper ICTON XV.2 (2014).	ICTON	06/07/2014	Y2
Conference Publication	A. D. Ellis, M. E. McCarthy, D. Lavery, N. Mac Suibhne, S. Sygletos, S. Savory, P. Bayvel and P. Harper, "Real Time 100 Gbit/s Electrical Nyquist WDM Transmitter," Proc ICTON 2014, paper VI.4, (2014).	ICTON	06/07/2014	Y2
Conference Publication	M. Song, E. Pincemin, D. Grot, T. Guillossou, Y. Jaouën, and R. Le Bidan, "Robustness of Coherent 100 Gbps QPSK and 200 Gbps 16QAM-OFDM to Practical Implementation Impairments," OSA Signal Processing in Photonic Communications (SPPCom) July 2014, paper SM3E.5	SPPCom	13/07/2014	Y2
Conference Publication	X. Ouyang and J. Zhao, "Performance characterization of optical offset-QAM OFDM for fibre transmission," 9th International Symposium on Communication Systems, Networks, and Digital Signal Processing, 2014.	CSNDSP	23/07/2014	Y2
Conference Publication	R. Rudnick, A. Tolmachev, D. Sinefeld, O. Golani, S. Ben-Ezra, M. Nazarathy, D. M. Marom, "Sub-Banded / Single-Sub-Carrier Drop-Demux and Flexible Spectral Shaping with a Fine Resolution	ECOC	21/09/2014	Y2

	Photonic Processor," 40th European Conference on Optical Communications (ECOC), Cannes, France 2014, paper PD.4.1			
Conference Publication	M. E. McCarthy, N. Mac Suibhne, S. T. Le, P. Harper, and A. D. Ellis,"High Spectral Efficiency Transmission Emulation for Non-Linear Transmission Performance Estimation for High Order Modulation Formats", 40th European Conference on Optical Communications (ECOC), Cannes, France 2014.	ECOC	21/09/ 2014	Y2
Conference Publication	S. Sygletos, S. J. Fabbri, E. Giacoumidis, M. Sorokina, D. Marom, M. F. C. Stephens, D. Klonidis, I. Tomkos and A. D. Ellis,"A Novel Architecture for All-Optical Add-Drop Multiplexing of OFDM Signals", 40th European Conference on Optical Communications (ECOC), Cannes, France 2014.	ECOC	21/09/ 2014	Y2
Conference Publication	S. Sygletos, M. E. McCarthy, S. J. Fabbri, M. Sorokina, M. F. C. Stephens, I. D. Phillips, E. Giacoumidis, N. M. Suibhne, P. Harper, N. J. Doran, S. K. Turitsyn, A. D. Ellis, "Multichannel Regeneration of Dual Quadrature Signals", 40th European Conference on Optical Communications (ECOC), Cannes, France 2014.	ECOC	21/09/ 2014	Y2
Conference Publication	S.J. Fabbri, S. Sygletos, E. Pincemin, K. Sugden, A.D. Ellis,"First Experimental Demonstration of Terabit Interferometric Drop, Add and Extract Multiplexer," 40th European Conference on Optical Communications (ECOC), Cannes, France 2014.	ECOC	21/09/ 2014	Y2
Conference Publication	S. T. Le, E. Giacoumidis, N. Doran, A. D. Ellis and S. K. Turitsyn,"Phase-conjugated Subcarrier Coding for Fibre Nonlinearity Mitigation in CO-OFDM Transmission", 40th European Conference on Optical Communications (ECOC), Cannes, France 2014.	ECOC	21/09/ 2014	Y2
Conference Publication	S. T. Le, M. E. McCarthy, N. Mac Suibhne, A. D. Ellis and S. K. Turitsyn,"Phase-conjugated Pilots for Fibre Nonlinearity Compensation in CO-OFDM Transmission", 40th European Conference on Optical Communications (ECOC), Cannes, France 2014.	ECOC	21/09/ 2014	Y2
Conference Publication	P. Torres-Ferrera, J. M. Rivas-Moscoso, D. Klonidis, D. M. Marom, R. Gutiérrez-Castrejón, and I. Tomkos, "Filtering effects of cascaded flex-grid ROADMs with high spectral resolution filters on the transmission of Nyquist and quasi-Nyquist WDM super-channels," Proc. ICOCN 2014, in press.	ICOCN	09/11/ 2014	Y2

Conference Publication	P. S. Khodashenas, J. M. Rivas-Moscoso, D. Klonidis, D. M. Marom, and I. Tomkos, "Evaluating the Optimum Filter Resolution and Sub-Channel Spectrum Granularity for Flexible Super-Channels," Optical Fibre Conference (OFC) 2015, Los Angeles, CA, paper W1I.5.	OFC	22/03/ 2015	Y3
Conference Publication	B. Baeuerle, A. Josten, F. C. Abrecht, E. Dornbierer, J. Boesser, M. Dreschmann, … D. Hillerkuss, "Multiplier-Free, Carrier-Phase Recovery for Real-Time Receivers Using Processing in Polar Coordinates," In Optical Fibre Communication Conference (p. W1E.2). Los Angeles, California: Optical Society of America. http://doi.org/10.1364/OFC.2015.W1E.2(2015)	OFC	22/03/ 2015	Y3
Conference Publication	D. Hillerkuss and J. Leuthold, "Software-Defined Transceivers for Dynamic Access Networks", In Optical Fibre Communication Conference (p. Tu2E.4). Los Angeles, California: OSA. http://doi.org/10.1364/OFC.2015.Tu2E.4(2015)	OFC	22/03/ 2015	Y3
Conference Publication	P. S. Khodashenas, M. B. Shariati, J. M. Rivas-Moscoso, D. Klonidis, J. Comellas and I. Tomkos, "Impact of Filter Sharpness on the Performance of Elastic Optical Networks," IEEE International Conference on Communications (ICC), 2015, pp. 6810-6815.	ICC	08/06/ 2015	Y3
Conference Publication	B. Baeuerle, A. Josten, F. Abrecht, E. Dornbierer, D. Hillerkuss and J. Leuthold, "Blind Real-Time Multi-Format Carrier Recovery for Flexible Optical Networks," (SPPCom) July 2015	SPPCom	27/06/ 2015	Y3
Conference Publication	A. Josten, B. Baeuerle, E. Dornbierer, J. Boesser, F. Abrecht, D. Hillerkuss, & J. Leuthold, "Multiplier-Free Real-Time Timing Recovery Algorithm in the Frequency Domain Based on Modified Godard,"in Advanced Photonics 2015 (p. SpS4D.2). Boston, Massachusetts: Optical Society of America. Retrieved from http://www.osapublishing.org/abstract.cfm?URI=SPPCom-2015-SpS4D.2(2015)	SPPCom	27/06/ 2015	Y3
Conference Publication	I. Tomkos, P. S. Khodashenas, J. M. Rivas-Moscoso and D. Klonidis, "Switching and Routing for Spatially and Spectrally Flexible Elastic Optical Networking," IEEE HPSR 2015 Tutorial, Budapest.	HPSR	01/07/ 2015	Y3
Conference Publication	P. S. Khodashenas, J. M. Rivas-Moscoso, D. Klonidis, G. Thouénon, C. Betoule, E. Pincemin and I. Tomkos, "Techno-Economic Analysis of Flexi-Grid	PS	22/09/ 2015	Y3

	Networks with All-Optical Add/Drop Capability," Proc. PS 2015, ThIII2-2.			
Conference Publication	G. Thouénon, C. Betoule, P. S. Khodashenas, J. M. Rivas-Moscoso, D. Klonidis, E. Le Rouzic and E. Pincemin, "Electrical v/s Optical Aggregation in Multi-layer Optical Transport Networks," Proc. PS 2015, WeIII1-2.	PS	22/09/ 2015	Y3
Conference Publication	G. Thouénon, C. Betoule, E. Pincemin, P. S. Khodashenas, J. M. Rivas-Moscoso and I. Tomkos, "All-Optical vs. Electrical aggregations CAPEX comparisons in a fully-flexible multi-layer transport network," Proc. ECOC 2015, We.4.5.4.	ECOC	28/09/ 2015	Y3
Conference Publication	P. S. Khodashenas, J. M. Rivas-Moscoso, D. Klonidis, G. Thouénon, C. Betoule and I. Tomkos, "Impairment-aware Resource Allocation over Flexi-grid Network with All-Optical Add/Drop Capability," Proc. ECOC 2015, P.6.13.	ECOC	28/09/ 2015	Y3
Conference Publication	Y. Yu, W. Wang, P.D. Townsend, J. Zhao, "Modified phase-conjugate twin wave schemes for spectral efficiency enhancement," Proc. ECOC 2015, We.2.6.5, 2015.	ECOC	28/09/ 2015	Y3
Conference Publication	J. Zhao and L.K. Chen, "Improved offset-QAM OFDM scheme with enhanced dispersion tolerance," Asian Communications and Photonics Conference, paper ASu1F.3, 2015.	ACP	19/11/ 2015	Y3
Conference Publication	R. Rudnick, L. Pascar, B. Frenkel, and D. M. Marom, "Polarization Diverse Fine Resolution Photonic Spectral Processor," In Optical Fibre Communication Conference, Anaheim, California.	OFC	20/03/ 2016	Y3
Conference Publication	F. Ferreira, N. M. Suibhne, C. Sánchez, S. Sygletos, A. Ellis, "Advantages of Strong Mode Coupling for Suppression of Nonlinear Distortion in Few-Mode Fibres," In Optical Fibre Communication Conference (p. Tu2E.3). Anaheim, California.	OFC	20/03/ 2016	Y3
Conference Publication (Invited)	E.Pincemin, M. Song, Y.Loussouarn, G.Thouenon, C.Betoule, "Towards 400G/1T flexible optical transport networks," International Conference on Transparent Optical Networks (ICTON), paper WeD3.5, 23-27 June 2013.	ICTON	23/06/ 2013	Y1
Conference Publication (Invited)	D. M. Marom, D.Sinefeld, O.Golani, N.Goldshtein, R.Zektzer and R.Rudnick, "High Resolution Optical Spectral Filtering Technology: Reaching the sub-GHz Resolution Range," International Conference on Transparent Optical Networks (ICTON) 2013.	ICTON	23/06/ 2013	Y1

Conference Publication (Invited)	J. Zhao, M. Li, and L.K. Chen, "Joint symbol synchronization and dispersion estimation in 16QAM optical fast OFDM," Opto-Electronics and Communications Conference (OECC) July 2013. (invited), paper WR3-1.	OECC/PS	30/06/ 2013	Y1
Conference Publication (Invited)	J. Zhao and A.D. Ellis "Designs of coherent optical fast OFDM and performance comparison to conventional OFDM," OSA Signal Processing in Photonic Communications (SPPCom) July 2013 (invited), paper SPT2D.1.	SPPCom	14/07/ 2013	Y1
Conference Publication (Invited)	E. Pincemin, M. Song, J. Karaki, A. Poudoullec, N. Nicolas, M. Van der Keur, Y. Jaouen, P. Gravey, M. Morvan and G. Froc, "Multi-band OFDM Transmission with Sub-band Optical Switching," European Conference on Optical Communications Sep. 2013, Paper Th2.A.1.	ECOC	22/09/ 2013	Y1
Conference Publication (Invited)	D. Klonidis, S. Sygletos, D.M. Marom, A. Ellis, E. Pincemin, C. Betoule, G. Thouenon, D. Hillerkuss, B. Baeuerle, A. Josten, J. Leuthold, J. Zhao, S. Ben-Ezra, J.F. Ferran, M. Angelou, G. Papastergiou, P. Zakynthinos and I. Tomkos "Enabling transparent technologies for the development of highly granular flexible optical cross-connects," International Conference on Transparent Optical Networks (ICTON), (invited), July 6-10, 2014.	ICTON	06/07/ 2014	Y2
Conference Publication (Invited)	C. Betoule, G. Thouenon, E. Pincemin, D. Klonidis, I. Tomkos, "Impact of optical flexibility and sub-band switching on multi-layer transport network architectures," (invited paper), ICTON 2014.	ICTON	06/07/ 2014	Y2
Conference Publication (Invited)	I. Tomkos, D. Klonidis, Ch. Kachris, P.Zakynthinos, J.M. Rivas-Moscoso, P. Khodashenas, "Spectrally and Spatially Flexible Optical Networking," (Invited paper), International Conference on Optical Communications and Networks (ICOCN), Nov 2014.	ICOCN	09/11/ 2014	Y2
Conference Publication (Invited)	J. Zhao, "Offset-QAM multicarrier technology for optical systems and networks," the 13th International Conference on Optical Communications and Networks, (invited).	ICOCN	09/11/ 2014	Y2
Conference Publication (Invited)	J. M. Rivas-Moscoso, S. Ben-Ezra, P. S. Khodashenas, D. M. Marom, D. Klonidis, P. Zakynthinos and I. Tomkos, "Cost and Power Consumption Model for Flexible Super-channel Transmission with All-Optical Sub-channel Add/Drop Capability" (invited) ICTON 2015, paper Th.B2.5.	ICTON	05/07/ 2015	Y3

Conference Publication (Invited)	P. S. Khodashenas, J. M. Rivas-Moscoso, D. Klonidis, D. Marom and I. Tomkos, "Evaluating the Performance of Ultra-fine Spectrum Granularity Flexible Optical Networks," (invited) ICTON 2015, paper We.B1.4.	ICTON	05/07/ 2015	Y3

1.2.1.3 Workshops and conference sessions

Type of Activity	Details	Where	Date	Reporting Period
Workshop	Architectures and control for elastic optical networks	European Conference on Optical Communications (ECOC) 2013, London, UK	22/09/2013	Y1
Workshop	Workshop on Spatially or/and Spectrally Flexible Core Optical Networks	European Conference on Networks and Communications (EUCNC) 2014, Bologna, Italy	23/06/2014	Y2
Workshop	Photonic Switching Systems in support of Spatially and Spectrally Flexible Optical Networking	Photonics in Switching (PS) 2015, Florence, Italy	22/09/2015	Y3

2 Exploitation Activities

This section provides a market analysis related to the overall FOX-C concept and the developed solutions within the project. In the second part the final foreseen exploitation activities and the generated business plans for the industrial partner are presented.

2.1 Market analysis

The potential implementation roadmap for the FOX-C concept has been analysed and presented in deliverable D2.4. The extracted trends are based on the current data traffic increase widely acceptable by major operators and vendors and also consider the currently dominant solutions utilised for legacy communication systems. These trends are important for the industry to identify their strategic position in the market in the upcoming years, and therefore are further analysed in the following sections.

2.1.1 Relative technology cost projection

Based on the studies in D2.4 using the 51-node France Telecom national network, the relative total equipment cost was evaluated for a FOX-C enabled elastic optical network providing All Optical Traffic Grooming (AOTG) capabilities. The estimated cost has been compared to that of a legacy SLR scenario that uses 100G single-carrier signals with DP-QPSK modulation over 50GHz ITU-T grid (i.e. the currently dominant standard) and a more forward looking MLR scenario which allows modulation format adaptation to the required OSNR, thus providing superior flexibility and scalability in spectrum allocation and resource utilization. For these studies an annual traffic increase of 35% in the network was assumed over actual total network traffic of 16Tb/s measured for 2015. The obtained results are presented in Figure2.1. (In this figure, the dotted projection line shows the trend of the total equipment cost if the spectrum per fibre per link were unlimited. It is noted that the deployment of systems in parallel would have an additional cost increase.)

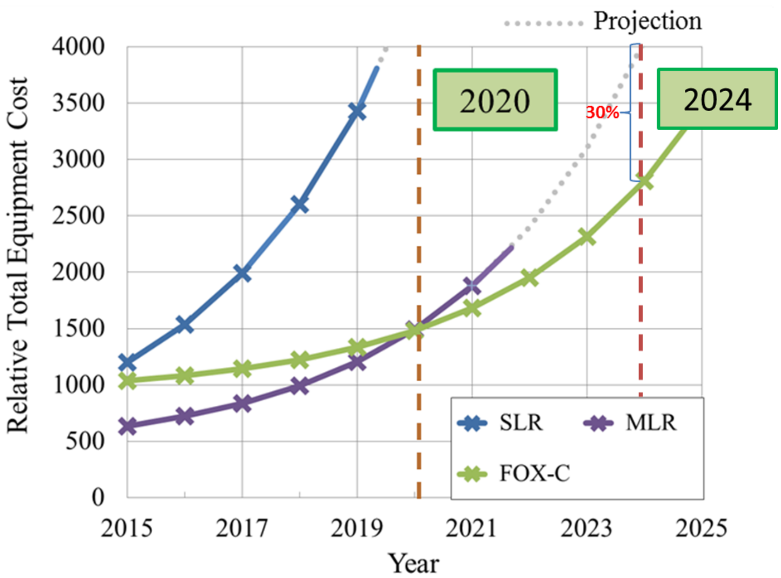

Figure2.1: Relative total equipment cost of SLR, MLR and FOX-C scenarios as a function of traffic increase in upcoming years. The 2020 vertical line shows the year in which the break-even point between MLR and FOX-C solutions is reached. The 2024 vertical line shows the year in which a 30% cost benefit is achieved for the FOX-C case compared to the MLR case.

Based on this study it is observed first that the scaling cost and therefore the required investment in support of the SLR solution is large and will become unaffordable within the next 4-5 years if the overall traffic will keep increasing at the same rate. This actually agrees with a number of relevant studies denoting upcoming capacity crunch and the need to move to elastic optical networking. Next by comparing the FOX-C solution with the MLR case it is derived that the total equipment cost for the FOX-C solution equates the cost of the MLR solution in 2020 and from then on it becomes more cost effective. A commonly acceptable business strategy followed by operators defines that a 30% improvement is necessary in order to derive enough benefits and start considering the deployment of a new solution in their networks. Of course in practice this depends on various other financial parameters as well as the overall market situation. Based on this empirical rule it is observed that the FOX-C solution can achieve a 30% cost reduction from 2024 onwards. It is noted though that the 30% improvement was calculated with respect to a cost projection assuming unlimited spectrum per fibre per link. Therefore, an increase in the costs for the MLR solution should be expected (since additional investment to extend the fibre operating bandwidth through e.g. L-band EDFAs or Raman amplification would be required). Similarly, in the cost model presented in deliverable D2.3,a cost premium for newly created technology is assumed, but we envisage that the cost of new components (such as 1×20 WSS and the HSR filter) will scale down as a consequence of technology maturity. This implies that the break-even point and the year from which a good business case is expected have been conservatively underestimated here.

2.1.2 Commercial availability

The commercial availability of the FOX-C node solution as a function of the research outcomes of this project and the market needs has been evaluated by Finisar and represented in the graph of Figure 2.2. This graph summarizes all the available switching node technologies that are used or expected to be used in networks and for which there are commercially available products. The technologies are also ranked in terms of implementation complexity while also the start year of their availability is denoted.

From this graph it is important to highlight that the 1st generation of the WSS family of products initiated around year 2005 with the first 1x9 WSS elements. This solution had started becoming the dominant market solution in switching at around 2010 and onwards. At that time and once this technology was widely accepted, the 2nd generation of WSS emerged, offering higher port count elements (1x20 WSS) and also Flex-grid and CDC-F structures, in order to meet the current trends of flexible optical networks.

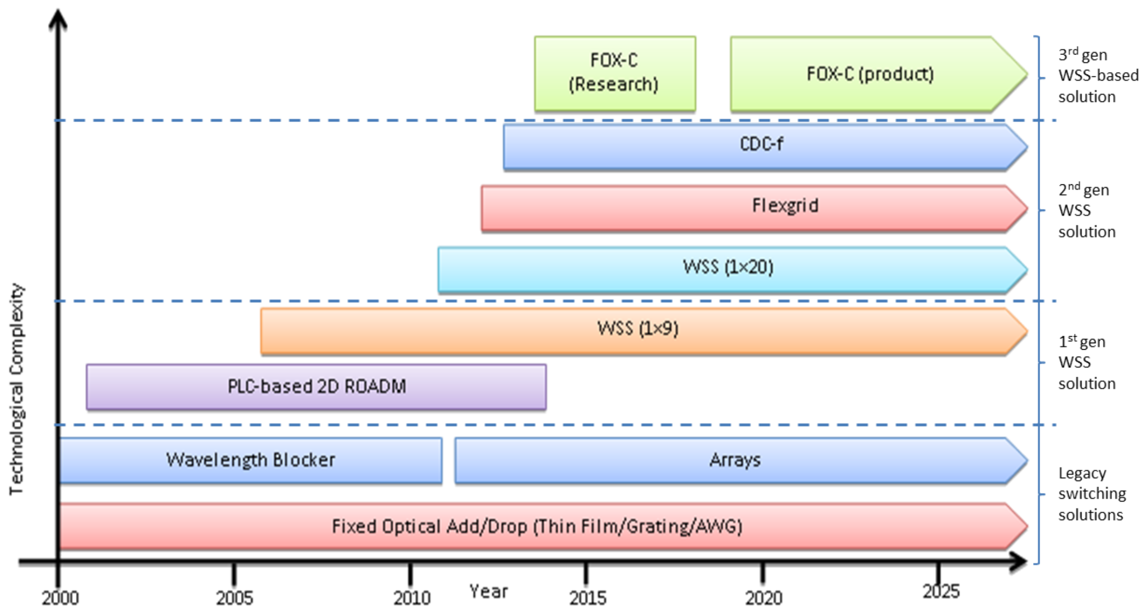

Figure 2.2 – FOX-C technology availability with respect to other switching node technologies, (according to data provided by Finisar).

The FOX-C ultra-fine switching granularity solution comes as a natural evolution step denoting potentially the 3rd generation of WSS-based nodes with the added feature of All Optical Traffic Grooming (AOTG) which will relax the network from costly OEO and OTN based approaches while offer optimised resource allocation options. Since the initial research ends with the end of the FOX-C project, a period of 3-5 years is required until the development of the first node prototypes and then the first commercially available products respectively. This places the potential commercial availability of the FOX-C switching node at around 2020 to 2021, which coincides with the time when the AOTG-based networking approach of FOX-C project start showing cost benefits with respect to the MLR solutions.

2.1.3 Market growth

The optical communications infrastructure serves as the backbone of our connected society, and just as the Internet continues to grow, so do optical transport networks. The latest Cisco VNI Global IP Forecast predicts traffic will grow three-fold by the end of this decade, based on overall 23% CAGR of Internet traffic (see Figure 2.3-left). The most significant growth originates from mobile data, due to the proliferation of smart phones and the transition to 5G cellular service. The optical communication infrastructure has to continue to grow in lockstep for delivering this content. Unfortunately, the optical communication market is characterized by cyclical behaviour, driven by technology cycles and periodic over-builds (see Figure 2.3-right). On the long term, the traffic and the infrastructure grow hand-in-hand, however the optical backbone wildly undulates about the traffic growth rate.(Note that traffic growth in Figure 2.3-right is larger than Internet traffic growth reported in Figure 2.3-left, due to contribution of managed IP traffic.) We are currently within the cycle of 100G coherent DWDM technology deployments, with deployments offering (again) over-capacity compared to traffic growth, hence a correction is to be expected. By 2019, 100G will make up 95% of telecom optical transceiver transmission capacity (Figure 2.4-left), covering both long haul and proliferating into the metro segment with hundreds of thousands of ports shipped (Figure 2.4-right). Following this correction, the next technology cycle will emerge—we believe around 2020-2021—which will be based on multi-carrier super-channel transceivers offering payloads between 400 Gbps and 1 Tbps. The transport of these super-channels be may be augmented by the FOX-C developed technology for add-drop of complete super-channels and subcarriers within using fine resolution filter. These technologies fall under the WDM ROADM segment of the optical communication infrastructure, which is the fastest growing optical transport segment, outstripping the overall WDM market, which will reach $10.8 billion by 2020 (Figure 2.5). Note that WSS revenue represents ~4% of this market, hence projected to reach $400-450M by 2020.These WSS include all current product variants, including FlexGrid WSS, and M×N WSS for CDC ROADM applications. Fine resolution WSS, a possible outcome of the FOX-C project, may be deployed in the subsequent technology cycle beginning in 2020.

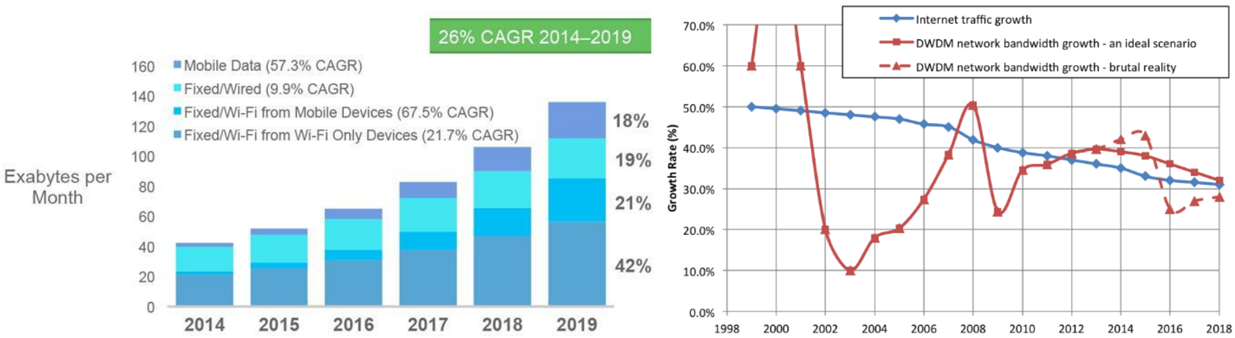

Figure 2.3 – Left: Projected growth of the Internet. Source: Cisco VNI Global IP Traffic Forecast, 2014-2019. Right: Cyclic deployment of DWDM bandwidth versus Internet traffic growth. Source: LightCounting Market Research.

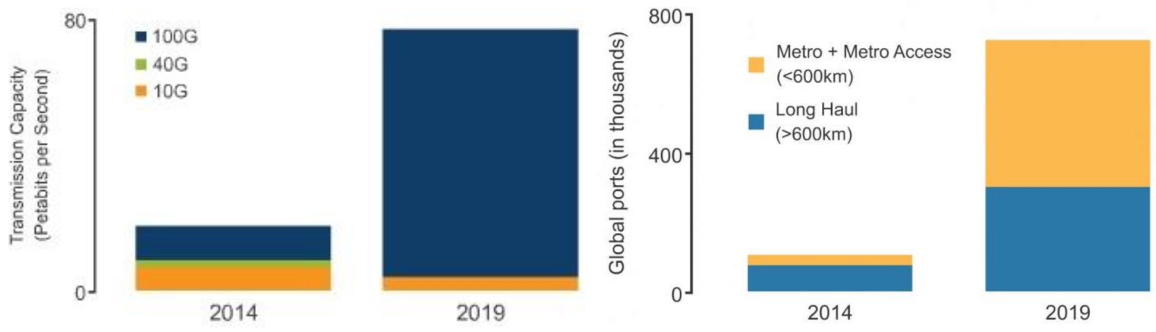

Figure 2.4 – Left: Transmission capacity by deployed transceiver rates. Source: Infonetics Research "10G/40G/100G Telecom Optics: Biannual Market Sizeand Forecasts Report," April 2015. Right: Global ports of 100G deployment. Source: Infonetics Research "100G+ Coherent Optical Equipment Ports: Annual Market Share, Size and Forecasts,"July 2015.

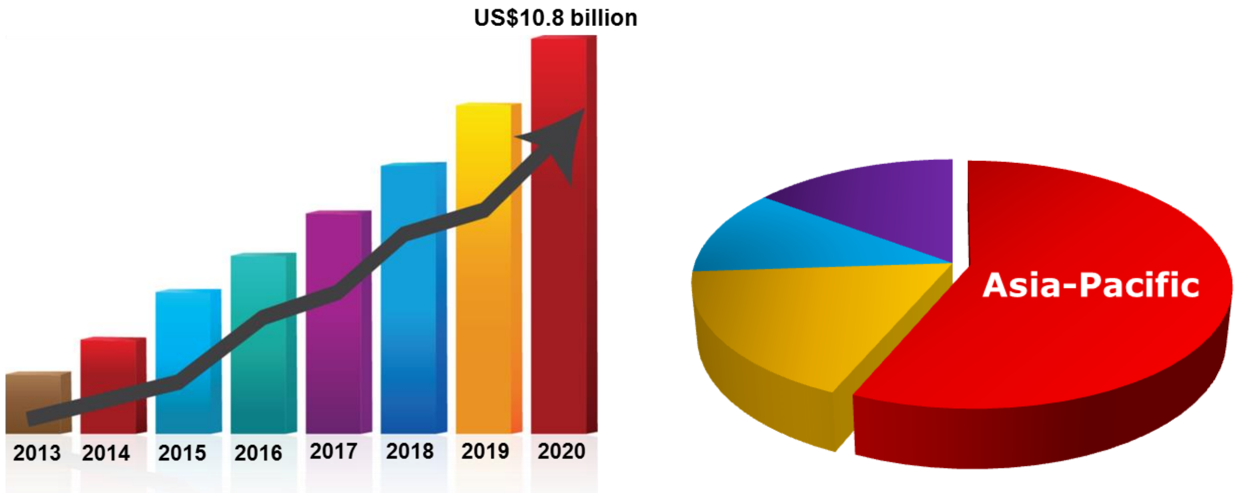

Figure 2.5– Left: WDM ROADM equipment revenue. Right: Regional breakdown, with Asia-Pacific being the largest and fastest growing regional market. Source: Global Industry Analysts, April 2015.

2.2 Exploitation Plan activities and Business plan

2.2.1 FINISAR: HSR-based node. Exploitation Activities/Strategy

ROADM is a system that allows flexible, precise, and remote selection of wavelengths transiting a given intermediate node on network for dropping or adding. ROADM components allow access to any wavelength passing through node. This can be done for adding or modifying the data before transmitting to the next node. ROADM components also allows interconnection of multiple intersecting networks at optical level preventing the expense and complexity of O/E/O conversions to setting up interconnection. The key factor contributing to growth of WSS component market is the growing demand for dynamic ROADMs. However, product cost and quality are some of the major challenges faced by this industry that can hinder its growth rate. Growth of WSS market slowed down during past few months as a result of excessive supply chain inventory; however, this market is expected to resume growth in the near future as a result of surging demand for technologically improved components.

Market Segmentation:

ROADM market divided into four types of modules: PLC Based ROADMs, Blocker Based ROADMs, Wavelength Selective Switches (WSS), and Edge ROADMs (ER)supporting different segments of network and based on following applications: Degree Two Node, Degree Three Node and Multiple Degree Node.

WSS:

Third-generation ROADMs technology based on the wavelength selective switch (WSS) — that has quickly become the "gold standard." The market segment Finisar is one of the major player is a fast moving WSS market. The WSS component market has had a tough 2 years, with revenue hitting nearly $100M quarterly in2H10 only to collapse to $60M quarterly in 2H12. First we thought this pause was a result of excessive supply chain inventory compounded by slower ROADM equipment growth. Revenue for WDM ROADM-based optical equipment (not components) was $4.5B in CY13, 11% higher than CY12; and $2.4B in 2H13, 5% higher than 2H12. By CY18, revenue will total $8.4B, corresponding to a CAGR of 13%; this is the fastest growing optical transport segment, outstripping the growth of the overall WDM market and benefiting from a capex mix shift from SONET/SDH to WDM. The WSS volume is more cyclical than the end WDM equipment. Though the market has been flat for the past 2 years, significant grow his ahead, tied to increased deployment of new 100G coherent systems and the start of the rollout of Colourless, Directionless, and in some cases Contentionless(CDC) ROADMs at the end of 2014. The cyclical surge was achieved through CY15.This cyclical surge was combined with introduction of new generation WSS products mainly addressing two issues: Flexibility with 12.5GHz grid and high density integration supporting shelf slot height utilization policy. According the cyclical behaviour of the WSS market, the 5-6 year is determined as a WSS product cycle period. Taking this number in account, the best timing to introduce next generation WSS product supporting finer granularity will be around 2020-2021. This assumption strengthened by the fact that the next generation transmission systems should be based on Nyquist reshaped sub-carriers where ultra-fine resolution and sharp rise and fall behaviour at the filter edges should provide measurable benefit from such WSS devices.

Dual-stage switching

Add/drop functionality demonstrated by FOX-C project is based on a dual-stage optical switching implementation that allows all-optically adding, dropping and switching variable bandwidth tributaries with an ultra-fine spectrum resolution from/to ultra-high capacity super-channel. Finisar as a leader in WSS market with market share of 40% utilize opportunity provided by the FOX-C project in two levels: first to develop next generation WSS lab prototype and demonstrate to the key customers the capability of fine resolution WSS over existing WSS in resolution by factor eight. Finisar to commercialize this product will need to put additional development effort from the lab concept to the product. This process will cost additional few millions of US dollars.

For the promotion of the dual stage filtering concept, Finisar's main interest is in the development and industrialization of the high-port count WSS with1GHzresolution, identified as the key driver for the two stage FOX-C solution.

WSS Deployment Model

Let's look at how WSS modules are used by carriers in their networks as they deploy WDM ROADM equipment, and how that translates into WSS utilization. To construct a ROADM node that could ultimately optically switch 8 fibres, a carrier would install a brand new chassis that included 8x1 and 1x8 WSSs. When first installed in 2010, this node must only support 4fibres, so four8x1 and four1x8 WSS components are needed. Then in 2011, the carrier needs to support an additional fibre and adds line cards with additional 1x8 and 8x1 WSSs. As more fibres need to be interfaced, more WSSs are installed.

Therefore, WSS component volume is a function of new equipment node installations as well as when more degrees are added to existing nodes. WSS as a percentage of WDM ROADM equipment revenue is low when nodes are first installed, as the revenue derived from the WSS components is small compared with the revenue from a new chassis installation. As support for additional degrees is added at existing nodes, the marginal revenue generated has a much higher bill of materials from WSS components.

At this point all future WSS designs are gridless and abandon the 100GHz grid, and future trends are the introduction of WSSs with degree counts in excess of 1x9, and the use of M×N switches designed to reduce the complexity of colourless and directionless ROADM architectures.

Verizon operates what we believe is the largest WDM ROADM network in the world, with over 4,000ROADM nodes with an average degree count of 3.5. They are installing 8x1 based WSSs today, expecting they will need additional degrees per node. The demand for larger WSSs with degree counts in the 20s comes from their use on the drop side, while interoperating with smaller WSSs which feed the line side.

ROADM Subsystem Vendors

The equipment vendor's decision to use a subsystem vendor instead of design/build from discrete optical components is a function of the equipment maker's size and experience and their short-term cost targets. Larger companies, such as Verizon that seek cutting-edge optical technology will outsource their optical designs to subsystem vendors. JDSU and Finisar offer subsystems that integrate their in-house WSS and amplifiers which can be built smaller and with tighter optical specifications than those assembled from discrete components.

Finisar and JDSU are major players in this subsystem market sharing market with few small vendors. Finisar will use development technology to extend this product family by implementing fine resolution WSS into these subsystems.

Market value

By graph below the 1x5 and larger WSS market will approach 200M$ in 2018 and according the last market indicators will reach 250M$ in 2020. Finisar will introduce new fine resolution WSS as available product for selected costumers on 2020 reflecting 5M$ US dollars in sale. After product general availability the sales will grow reaching 35% of market share replacing existing relatively low resolution WSS.

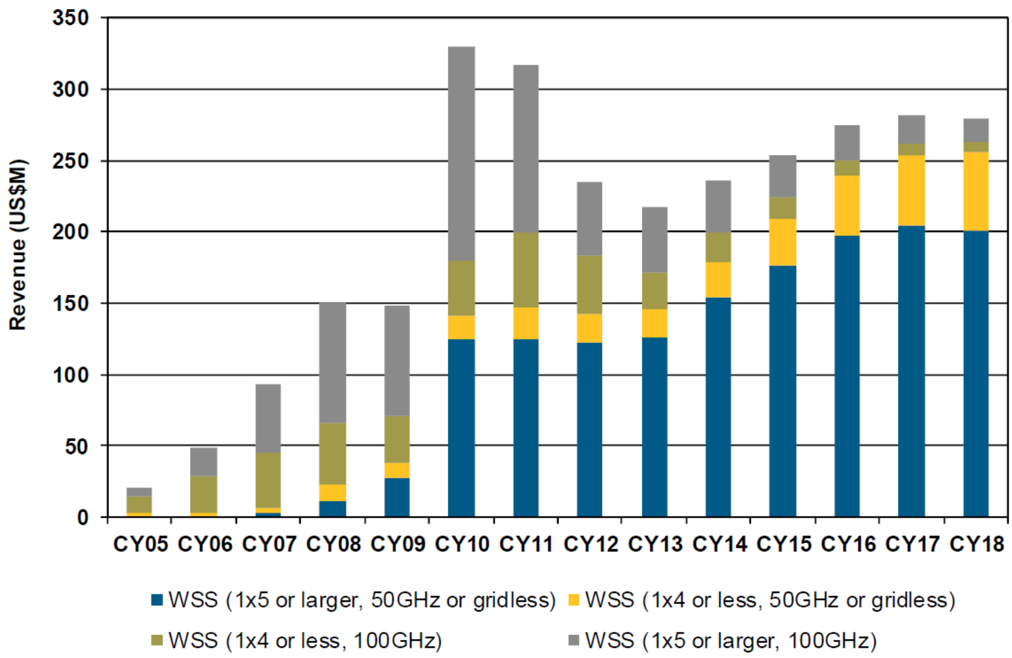

Figure 2.6 – WSS market growth. Source: Infonetics Research "ROADM Components: Biannual Market Share, Size and Forecasts," April 2014.

2.2.2 ORANGE: Possible adoption of the FOX-C scheme and under which requirements

Each time network operators have to upgrade optical transport networks towards higher capacity, the question of under-utilization of the fibre network resource is set for a while. Until now, there is no other choice than using an electrical OTN based switching layer between the IP packet layer and the optical WDM transmission layer in order to optimize the filling of optical channels. OTN switching adds a new aggregation technology to the architecture of multi-layer transport networks, which represents excess-cost and adds complexity to network operations.

On the other hand, we know (and it has been well detailed in [1]) that the traffic is very heterogeneously spread over the networks. Some links are very loaded while at least half of the network links are not optimally filled.

Network operators have to face an unavoidable migration towards higher capacity to support the observed 35% per year of traffic increase while exploiting as long as possible its physical (fibre) and system (WDM) infrastructure. Indeed, in a context where the standard single-mode fibre (SSMF) is approaching its capacity limit and a "capacity crunch" is announced for 2023 [2], it is crucial to fill optimally the existing optical channels. Even if some academic and industrial research laboratories all around the world are presently strongly involved in the study of spatial division multiplexing (SDM) solutions (through implementation of few-mode and/or multi-core fibres) to increase the traffic transported by an optical fibre, it has to be said that these technologies are not sufficiently mature and lack standardization to be deployed in the next years. Furthermore, the impressive cost of the replacement of a complete fibre infrastructure encourages network operators to optimize the already deployed fibre infrastructure, by increasing the capacity carried by WDM channel while filling as much as possible the fibre bandwidth (~35 nm).

The flexible optical networking concept is an interesting solution to meet these requirements in a medium term future. It allows both the optical channel capacity and its spectrum occupancy to be adjusted to the exact traffic demand to carry on the network, and thus it reduces any network resource over-dimensioning and wasting.

The FOX-C project has allowed to materialize the concept thanks to the design, development and test of innovative and future-proof flexible ROADM. The design adopted in the project is based on a dual-stage optical switching implementation that allows to all-optically add, drop and switch variable bandwidth tributaries with an ultra-fine spectrum resolution from/to ultra-high capacity super-channel. By doing that, the FOX-C node offers capabilities to manage the high diversity of traffic demands to be carried on real transport networks, from the very low granularity of 10Gbps towards the very high capacity demands of 1Tbps.

Multiple networking studies have been carried out during the project to analyze the benefits in terms of cost (mainly CAPEX) and resource efficiency of the FOX-C node utilization, through various real transport network deployment scenarios. Both a realistic national backbone and metro-regional networks have been considered with their associated traffic matrices. Let's note that traffic matrices considered are coming from real data and have been extrapolated to future years to simulate the traffic evolution. All these results have been thoroughly presented in [3] and [4].

In all the use cases analysed, the all-optical traffic grooming (AOTG) aggregation solution developed in the FOX-C project has always greatly outperformed the electrical OTN-based aggregation solution due to the fact that electronic OTN adds significant additional cost (today, the solutions provided by suppliers are not integrated on the ROADM yet, and a more integrated OTN-WDM solution should probably reduce the gap). Moreover, the OTN enhances fixed optical channel fill-in but doesn't improve at all the spectrum efficiency. With the AOTG solutions, the number of fibres required to carry a given traffic volume is always lesser than with conventional solutions.

The benefits of using FOX-C solutions in terms of cost, power consumption and spectrum efficiency have been extensively proven in [3] and [4]. CAPEX comparisons through one of our real multi-layer national scale networks showed a clear advantage to prefer the AOTG solution to the currently used technologies. Actually, FOX-C solution presents global CAPEX gain higher than 36%. This result is also confirmed by longer term scenarios which handle higher traffic volumes (provided that the level of optical aggregation inside the super-channel remains well-adapted to the average bit rate per demands). Said in other words, we prove that optical aggregation may have detrimental effects on the global network cost. More precisely, if we only favour the aggregation or the capacity fill-in optimization, we have advantages to prefer the most dense modulation format. As an example, if we quasi-systematically use the 16-QAM modulation format instead of the DP-QPSK one, we double the capacity carried by the optical channel but we reduce its optical reach, from 2000 km to more or less 400 km. In such a case, we can generate much more costly electrical regeneration on the network, what is exactly the contrary expected with the massive deployment of ROADM. So, it is necessary to find the best trade-off between aggregation level and global network cost.

In a metro-regional network scenario, the advantages of FOX-C approach are also very valuable. Compared to the national backbone network use case, the context is a little bit different because metro-regional networks are generally based on rather low-cost WDM systems supporting lesser channels (up to 40 wavelengths) each carrying 10 Gbps. Moreover, contrary to the backbone network, in such regional networks the traffic is clearly distributed over all nodes in a Hub&Spoke manner. It means that two nodes concentrate all the traffic coming from all remaining nodes. Since the coherent 100 Gbps DP-QPSK technology, just deployed on the core networks, is seen as the next step, it was interesting to analyse the FOX-C solution in this context. Results on the global multi-layer CAPEX analysis show that the AOTG solution is always more interesting than migrating the whole network towards the 100Gbps solution. AOTG becomes the most competitive solution allowing at least 30% cost saving on average with respect to the trend to deploy 100Gbps once the traffic volume gets through a given threshold.

On this metro-regional use case, we have predicted the first fibre saturation after the fourth year, which also corresponds to the year when the FOX-C solution allows the cheapest global multi-layer network cost (14% of cost savings, and becomes more and more competitive as time goes by).

On the national scale use case, we have noticed that it is preferable to wait five years before starting to deploy the FOX-C solution. In this case, we expect 65% and 45% CAPEX cost can be saved with respect to the scenario where we keep the current 100 Gbps WDM systems working on a fixed-grid (50 GHz ITU grid) and with respect to the scenario where the FOX-C solution is deployed over a greenfield network, respectively. In any case for Orange, the best way to use the FOX-C solution consists in doubling the currently deployed optical fibre infrastructure with new fibre managing the flexible spectrum. It is all the more interesting than it is what we are used to do each time we have introduced a new technology on our networks. Let’s note that since incumbent operators generally own its fibre infrastructure, many “dark” fibres are often available in underground deployed cables, and it only consists in lightening new optical fibres within. The additional flex-grid infrastructure allows to take advantage of the optical flexibility and to manage efficiently the additional traffic demands.

These results are encouraging. Indeed, the FOX-C solution is not really needed before 4 or 5 years. This is the time frame that seems necessary for the industry to transform the high resolution optical filter developed in the project from a lab prototype to an integrated photonics device usable in a commercial wavelength selective switch product. Since at first sight all ROADM deployed may require supporting the flexible optical networking concept in the future, important volumes and competitive costs can be seriously envisaged thanks to mass production effect. During this development period, network operators have to prepare the adoption of the flexible optical networking concept. The way optical channels of flexible capacity are managed has important impacts on operational processes. Moreover, if the AOTG concept solves multi-layer complexity by reducing the number of layers on the network architecture, it also adds new complexity that should be managed by more automation on the network. Before being deployed, the solution will have to be integrated into the network control layer.

2.2.3 W-ONESYS: WSS SystemExploitation Activities/Strategy

W-onesys will use the synergies of FOX-C project to develop a new product based on Flexgrid WSS of Finisar. This new product called **PS-FG-WSS** will be added to W-onesys portfolio and it will be compatible with the existing W-onesys Platforms.

In the first part of this section, we will describe all steps planned by W-onesys to develop an industrial product. In the second part of this section, we will present a complete business case and also some sensitive cases. Market analysis done in 2.1 shows that ROADM for coming years will be based on Flexible technology; in particular, those implemented with 1x5Flexgrid WSS or larger. Initial PS-FG-WSS will be based on 1x9 Flexgrid WSS.

A company like W-onesys has not enough resources to target more than 1% of global market. So, the strategy of W-onesys will be to target the European Experimental Optical Networks. This market is based on Gridless ROADM technology for Universities and Research Centers. PS-FG-WSS will be used to test and validate control planes like SDN, GMPLS or network developments.

2.2.3.1 PS-FG-WSS development

The final goal of W-onesys is to industrialize a CDC–ROADM based on 1x9 gridless WSS. Two different steps have been designed for this purpose.

In the first phase, we build a prototype that is planned to be used in FOX-C final tests at Orange Labs. This process of industrialization has several actions like (some of them already done) schematics design and layouts (PCBs), analysis of manufacturing costs, analysis of supply chain (suppliers, manufacturing phases, optimizing production time, batch production optimization, delivery time, etc.) by the estimated number of units that can be sold in the markets considered.

In the second phase, we release a final version of the product based on results of first prototype. W-onesys has planned to obtain a first reference for this product in an optical experimental network. UPC (Universitat Politecnica de Catalunya) has already shown some interest in acquiring a 3-degree Gridless ROADM. UPC has planned to use this ROADM to test SDN control plane developed at the university.

The first prototype of PS-FG-WSS has already been developed and used in final testing in Orange labs in Lannion. (A more detailed description of this product can be found at W-onesys website http://www.W-onesys.com/?page_id=152). Next figure shows the developed card

Figure 2.7: PS-FG-WSS card

A Local Craft Terminal to manage PS-FG-WSS has also been developed. Next figure shows a screenshot of control GUI.

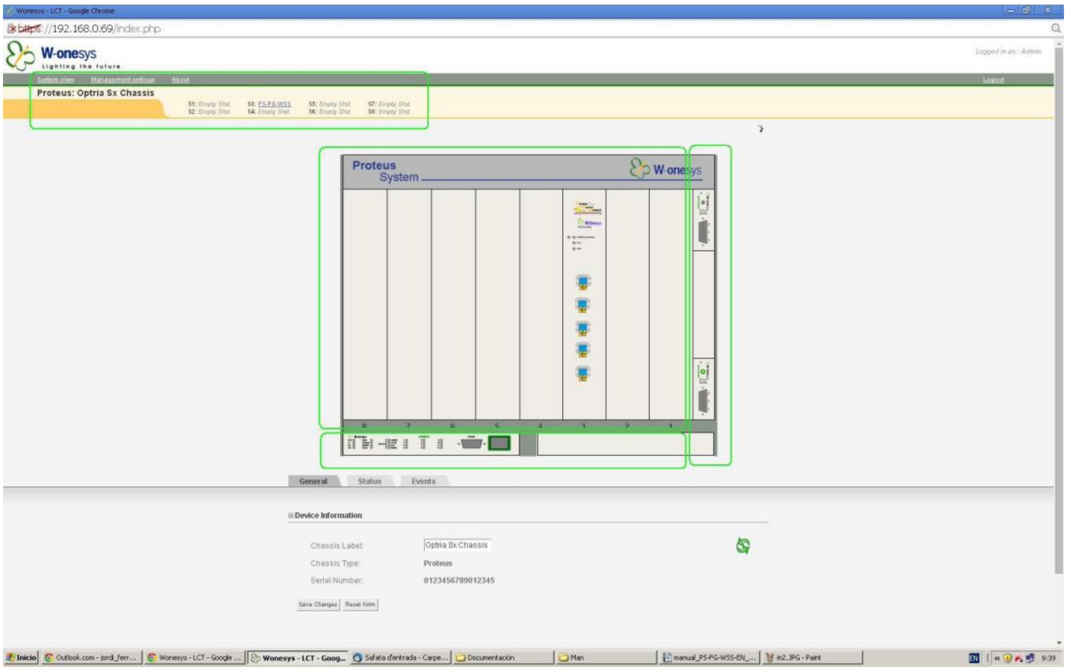

Figure 2.8: Local Craft Terminal to Control PS-FG-WSS

2.2.4 OPTRONICS Exploitation Activities/Strategy

Even though Optronics did not have any technical contribution to the FOX-C project, they plan to exploit the current capabilities and knowledge that was developed in this project. After gaining significant knowledge and experience on the FOX-C technologies, Optronics can now offer high level consulting services to OTE (incumbent operator) and Wind. The Greek operators have already been informed about the FOX-C project as well as the current developments at the various occasions (workshops, exhibitions, and personal communications) during the project's lifetime. Optronics could arrange for a pilot project on a small scale to evaluate the overall system performance, provided that sample systems will be available.

2.2.5 HUJI new opportunities for developed FOX-C technologies

One of the key hardware developments of the FOX-C project was a fine resolution optical filter, with the ability to resolve sub-1 GHz spectral features within a 200 GHz wide window and apply arbitrary filter shapes. At the onset of the project it was unclear whether this is technically feasible due to the stringent accuracy requirements of the arrayed waveguide grating. The FOX-C developments verified we can control the phases of the AWG consistently and repeatedly using the optoelectronic approach (with a secondary LCoS SLM serving to set the phases). This capability can now be extended along several new promising routes, as listed below.

Some of the straight-forward applications are those already relying upon high frequency utilization. These include radar systems that require special processing such as nulling a jamming signal or employing a swept frequency source and tracking filters of high fidelity, avionics and electronic warfare such as frequency-hopping communications, and 5G optical signal distribution to remote antennas where a fine resolution optical demultiplexing filter can separate the signal to different antennas towers or to different antenna elements of a single tower.

The eventual filtering system developed within FOX-C consisted of two LCoS SLM elements; the first adjusted the phase errors in the image plane of the waveguide array and the second filtered the spectrally dispersed frequency components by imparting to each unique amplitude and phase. However, we can synthesize arbitrary filtering functions by encoding in the time delays of the waveguides themselves, instead of in the spectrally-resolved plane (see Figure2.8-a). This is an indirect method, which relies on FIR (finite impulse response) filter synthesis techniques. But once the filter taps are determined (both amplitude and phase can be encoded per delay), then we can quickly adapt the system to operate as tapped delay line (see Figure 2.8-b). Each waveguide has an inscribed path length difference for setting the delay. The reflective SLM can set any phase delay $(0,2\pi)$ and any amplitude $(0,1)$ to each imaged waveguide, hence setting the multiplier to the specific delay. This allows us to encode any filtering function directly in the optical domain. Using this technique we have the number of taps set by the number of waveguide arms, and the delay element is now the inverse of the FSR. Since we are backtracking through the AWG without inversion (i.e. not imaging with the long waveguide imaged onto the short one, as happens in the developed FOX-C implementation), then the path length difference is doubled. Hence if we used FOX-C's 200GHz FSR AWG, it would be reduced to 100 GHz. Arbitrary filters can still be synthesized, with the resolution actually improving (100 GHz/nr of waveguides = 100 GHz / 250 = 0.4 GHz). This could still be used for sub-band channel selection, as in FOX-C, or as any other filter designed to correct for the impairments experienced in a transmission system.

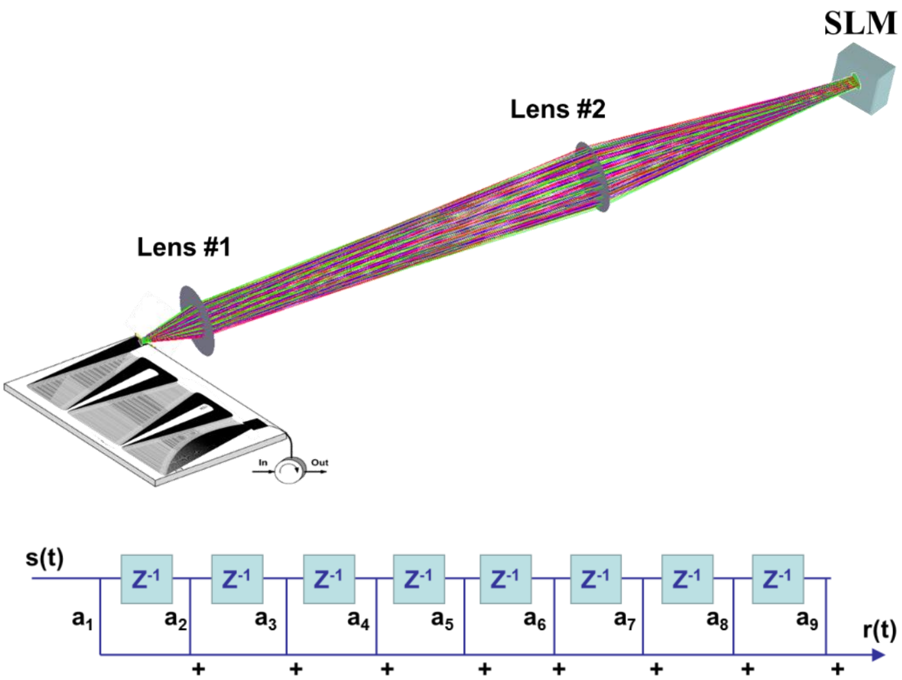

Figure 2.9: Filter synthesis functionality by directly modulating the AWG arms. (a) Proposed optical arrangement of imaging AWG output onto LCoS and back-reflecting after modulation. (b) Equivalent model as a tapped delay line.

We can take the technology even further, by considering the challenge of MIMO processing of SDM channels. Here a set of channels has been co-transmitted in a media that experiences mode-mixing. The received information is scrambled, and needs to be unravelled using signal processing. This is usually delegated to the digital signal processing domain. But large-scale DSP, as would be required for high bit rate SDM communication is currently beyond the ability of real-time implementation, and even it was it would be expensive and power hungry. However, we can extend the above implementation to handle multiple input, multiple output cases all in the optical domain (see Figure 2.9). Here we would have a delay of multiple ns (by the waveguide arms), equivalent to hundreds of delayed pulses, and would be required to set the 'multipliers matrix' between the input and output sets to undo the mode mixing. This could potentially completely replace the digital MIMO processing. There is an open question on the update rate required from the modulating elements. We used LCoS SLM technology which has ~ms update rates. It is unclear whether this technology solution provides sufficient speed to track the rate of change experienced in an SDM transmission system. As is known from deployed PMD compensating elements in SMF deployments, the rate of change is probably a little faster.

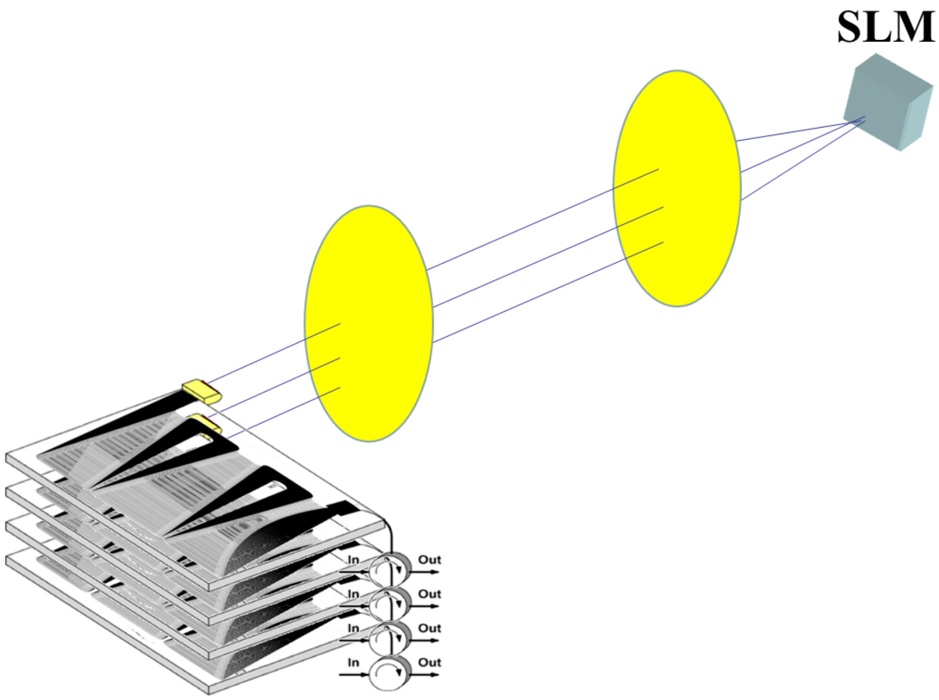

Figure 2.10: Multiple input, multiple output filtering arrangement which can be used for unravelling mode mixing in SDM transmission in the optical domain.

3 Standardization Activities

The final standardization plan in FOX-C was defined by partner Orange Labs (FT). The plan considered first the identification of the potential fields were FOX-C could contribute based on the generated research outcomes, and then the coordinated contribution between primarily FT and Finisar(and with the assistance of W-onesys) to relevant standardization bodies. The coordinated contribution in particular between a worldwide optical components vendor and a leading operator was identified to be essential for the actual initiation of relevant standardization discussions in ITU-T.

On the first stage of standardization plan, it was necessary to identify those FOX-C concepts that could be presented to ITU-T. In order to conclude on the best topics, there have been several internal discussions and exchange of ideas not just among the industrial partners Finisar, FT and W-onesys but also the technology owners HUJI, ASTON and AIT. One of the main restrictions was that the proposed topics should not address completely novel fields of research but fields showing an incremental step towards the FOX-C networking solutions and with respect to the current standards. The possible topics identified are the following:

a) Finer granularity WDM grid.
    - The actual ITU-T granularity is at 12.5GHz, while the FOX-C concept denotes finer granularities which could optimally reach 3.125GHz (as studied in D2.3) and be supported by the HSR filter element. The targeted proposal though was for 6.25 GHz, succumbing to the traditional spectral halving trend in ITU-T.

b) Flexible grid allocation.
    - FOX-C allows having a flexible grid allocation which could have significant impact on the spectrum utilization efficiency. Some part related to flexible allocation of resources (wavelength, spectrum format, etc.) could be also a potential topic for standardization.

c) Transceiver solutions.
    - There has been significant work on this field in the project, by investigating different modulation formats and developing the processing and evaluation algorithms. Therefore, a potential field could focus on the standardization of new coherent transceivers.

d) Node solutions.
    - FOX-C introduced the two stage add and drop scheme offering all optical traffic grooming capabilities within a super-channel. Moreover, designs have been extracted and studied for both flexible OADM and multi-degree OXC nodes. This new architecture and the related functionality could be presented for standardization.

e) Higher rate.
    - On ITU-T there are ongoing talks about next higher rate (OTU-5). The FOX-C findings in transceivers and data switching requirements could have a potential impact on the decisions for the new higher rate standard at 400Gbps or 1Tbps.

From all these topics, the FOX-C partners decided that the “Finer granularity WDM grid” could be the most possible topic to influence standards. A key reason for that is the direct involvement of both FT and Finisar in the relevant ITU-T study group. Moreover, it was identified as the essential first step in standardization in order to promote later the network related and node design options that arise from the optimum use of a finer grid.

Once the topic has been agreed among the FOX-C consortium, partners Finisar and Orange have initiated detailed discussions, with the presence of WONE, HUJI, ASTON and AIT. Finisar has engaged in discussions the design group from Finisar Australia who participate directly in the standards.

Unfortunately, after several rounds of discussions it was decided by Finisar not to support a possible standard for which they only have a lab prototype. According to their strategy, they are allowed to promote new standards only when they have a new full product or at least the final working and tested prototype ready to transition towards manufacturing. However, since the finer granularity switching concept is within their potential targets a relevant contribution will most probably be pursued in the near future.

4 Annex 1. Exploitation plan of terabit transceivers

Market view for FOX-C transceivers

This chapter gives an overview of the main business drivers for the introduction, in a mid-/long-term time scale, of high speed 400G/1T transceivers in the metro/core optical networks which could be addressed by the FOX-C technology.

Traffic on carrier backbone networks is growing exponentially, driving global momentum for wide-scale commercial 100G deployments that are currently underway, while resulting in growing interest for optical transport deployments beyond 100G (i.e. 200/400G initially and the 1T).

To meet the increasing traffic demands, the next big upgrade of service provider networks will be at 400G transport. Today both service providers and their equipment suppliers are preparing for this transition. Manufacturers of OTN boxes, optical packet platforms and core routers are finding ways to scale up to 400G transports. There have been (or are underway) numerous 400G trials worldwide, mostly on networks carrying live 100G traffic.

Firm	Equipment		Service Provider Trials	
Alcatel-Lucent	Photonic Service Switch		Nextgen (Australia) France Telecom (France) SaskTel (Canada)	Shaw Communications (Canada) Telefonica Espana (Spain) Zain (Saudi Arabia)
Ciena	Ciena 6500		British Telecom (UK)	Sprint (US)
Cisco	NCS Platform			
Coriant	FlexiGrid	hiT 7100/7300	Netia (Poland)	Telekom Austria (Austria)
Cyan	Z-Series		GlobalConnect (Denmark)	
Ericsson	MHL 3000 Smart Service Routers 8000		Telefonica Espana	
Fujitsu & NEC	--		NTT (Japan)	Verizon (US)
Huawei	NE5000E Router Various WDM/OTN boxes		EXATEL (Poland) Jazztel (Spain) KPN (The Netherlands)	Mobily (Saudi Arabia) True (Thailand) Telefonica Chile (Chile)
Infinera	DTN-X		DANTE (pan-European)	TeliaSonera (Scandinavia)
Juniper	MX Routers		Possibly Verizon (US)	
TE SubCom			Submarine trial	
Xtera	Nu-Wave Optima	NXT	Verizon (US)	
ZTE	ZXONE 8000		Deutsche Telekom (German)	Scandinavian trial

Soon the conditions will be then mature to evolve the optical interfaces toward 400Gb/s transmission and even to start activities to cope with higher rates such as 1 Tb/s: 1 Tb/s would better match such great traffic growth driven by service differentiation and evolution, and would address the usual 10x rate increase of Ethernet (considering packet technology is becoming the dominant technology in optical networks). 400Gb/s is to be considered an intermediate step toward 1 Tb/s. There are already few signs about 1Tb/s field trials, including Ericsson-Telstra, Huawei-Vodafone, Verizon-NEC and Infinera-TeliaSonera, ECI-DFN, etc.

In the following paragraphs we try to give quantitative forecasts for the optical market that can be addressed by FOX-C.

The revenue from the different DWDM market segments is currently dominated by the 10G and 100G interfaces with the latter surpassing the share of 10G/40G during late 2015, as shown in the figure below.

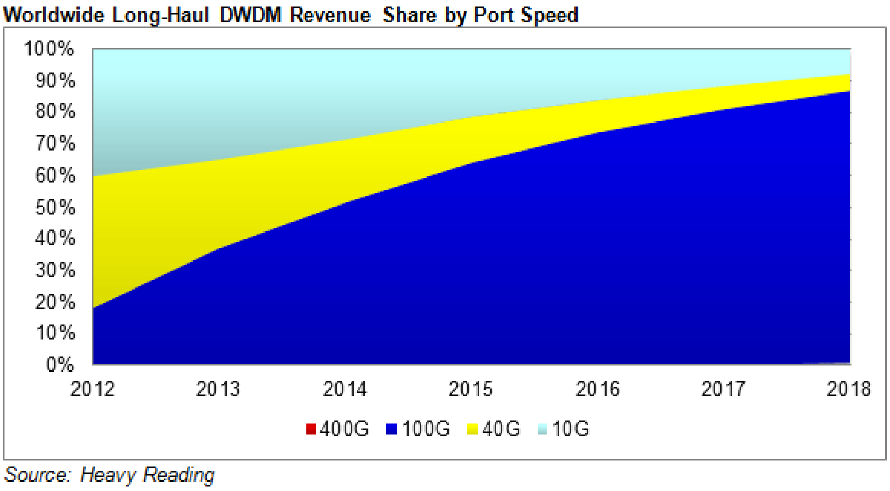

Figure 4.1: Market shares for 10G/40G/100G/400G transport

Therefore even if 200G/400G will come to market in a couple of years, the initial revenues will be low (coming mainly from niche applications) due to large deployments of cost effective 100G interfaces (also available for the metro market thanks to photonic integration). 400G and 1T will delay to become dominant for some more years (until 2019-2020). Of course the actual future numbers for 400G/1T market penetration will be influenced by the global network strategy adopted which depends on technology costs but also on the growth expectation of different operators. The following figure tries to quantify these expectations.

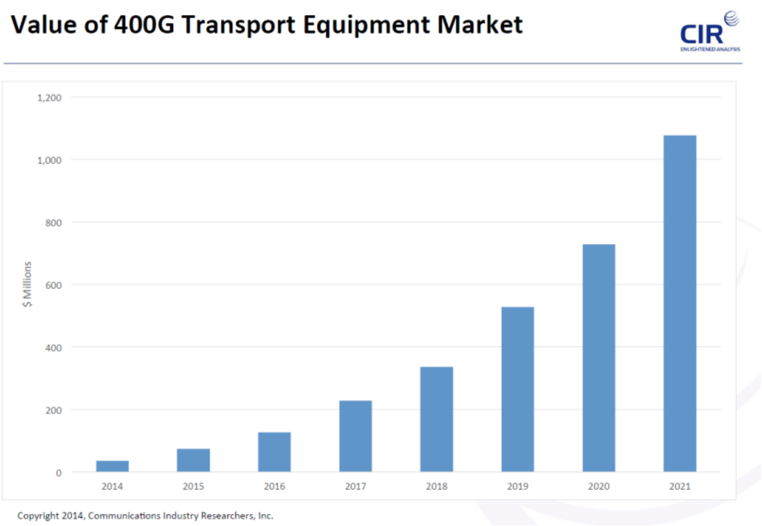

Figure 4.2: Evolution of beyond 100G transport equipment market

Analyzing all trends above, one can therefore conclude that the market opportunity for 400G and 1T transceivers will be realized in the next 3-5 years (for deployments of some significant scale). That time-frame is well aligned with the potential exploitation of FOX-C project results on flexible transceivers.

Industry standards and market outlook for 100G transceivers

In Figure 4.3 we show a design of a single-carrier transceiver based on the Optical Internetworking Forum (OIF) implementation agreements for 100G polarization multiplexed quadrature modulated transmitter and intradyne coherent receiver; i.e. OIF-PMQ-TX-01.1 [7] and OIF-DPC-RX-01.2 [8], respectively. This transceiver design is basically the industry standard today and what equipment vendors are based their implementations on for single line rate (SLR) and multiple line rate (MLR) 100G transceivers.

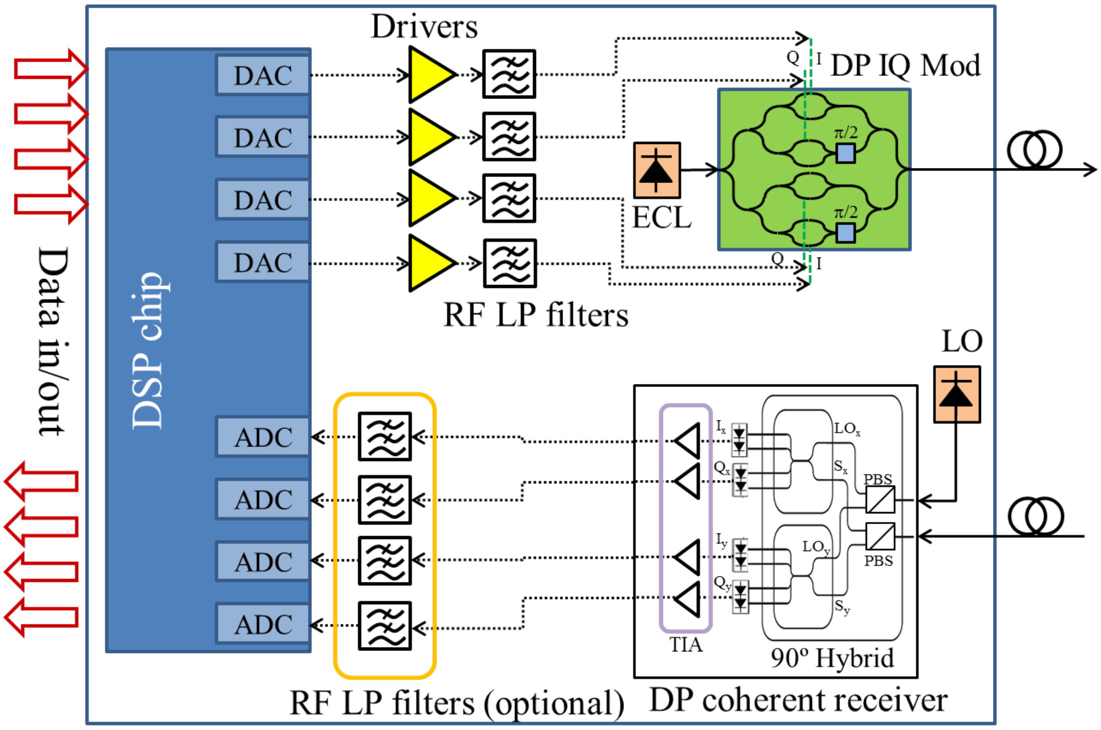

Figure 4.3: *Design of a single-carrier 100G transceiver for SLR and MLR*

This 100G transceiver consists of:

- a DSP chip (implemented on 40nm CMOS technology)
- four low frequency RF power dividers
- four DAC/ADC
- a four-port RF amplifier as modulator drivers
- four RF LP filters after the modulator drivers to remove the aliasing components (these can be dispensed with if the sampling rate of the DSP chip is sufficiently high in comparison with the electrical bandwidth)
- four optional RF LP filters that can be used in front of the ADCs, depending on the sampling rate and electrical bandwidth of the ADCs, to remove unwanted spectral components (an increased sampling rate of the ADCs would allow getting rid of the aliasing spectra in the DSP, but it would come at the price of increasing the amount of data to be processed at the receiver).

- one polarisation-multiplexed IQ modulator
- two narrow-line width lasers (one at the transmitter and the other one at the receiver)
- one integrated, dual-polarization coherent receiver, including a 90º hybrid, four balanced photodiodes and four trans-impedance amplifiers (TIA)

From this 100G transceiver the most costly and power consuming element that actually determines the performance of the entire transceiver is the DSP. The DSP cost can vary currently from 20% to >50% of the 100G transceiver cost depending on whether or not systems vendors have in-house DSP chip development capability (see Table 4-1). Those vendors that have in-house DSP capability, they can slash the prices due to the reduced transceiver fabrication costs that they can realize.

Table 4-1 DSP chi ownership

	In-house DSP	3rd party DSP/Module	
Vendors	Alcatel-Lucent Ciena Cisco Huawei Infinera	ADVA Coriant ECI Fujitsu NEC Xtera	BTI Cyan Ericsson Huawei Transmode ZTE
Shipment	85% of hardware shipped to date	NEL-based discrete designs and Acacia modules	

(Source: Infonetics Research, 2014)

Other factors that might enable a transceiver cost/power consumption reduction or/and an improved transmission performance, are related primarily with:

- The potential to move towards low-power 20-nm (or even 16nm) ASIC implementations
- Improved NL-effect compensation DSP algorithms
- Robust cycle-slip mitigation

100G coherent PDM-QPSK pluggable interfaces are promised to realize big market success. System designers are interested to move to pluggable transceivers for 100G coherent applications to take advantage of the “pay as you grow” benefits and are urging for smaller transceivers in order to increase the bandwidth density. The CFP2 form-factor has thus become very attractive, but faces the problem that the current technology cannot integrate all the necessary transceiver elements for a 100G coherent transceiver within either the footprint or the electrical power budget of a CFP2.

A first solution to the problem was to define a new type of coherent transceiver, the CFP2-ACO (analog coherent optics) [9], which remove the DSP ASIC from the module and places it on the line card. Its footprint is therefore reduced and it requires less power than alternative options such as the CFP or the OIF MSA, but reduces flexibility since CFP2-ACO can only be plugged into line card slots specifically designed for this transceiver technology. The CFP2-ACO transceiver has been recently announced or already released by several vendors (e.g. Fujitsu [10], NEC [11], Oclaro [12]) and is expected to be increasingly commonplace from 2016 onward. The CFP4-ACO, exhibiting further footprint and power reduction, is forecast to be released after 2018.

The CFP2-DCO (digital coherent optics), which does incorporate the DSP chip (thereby solving the flexibility problem of the CFP2-ACO), could be released in late 2017, but this depends on competition from the ACO solution. In this scenario, market opportunities among system vendors without in-house ASIC capability need to be found. Recently, NTT, in collaboration with Broadcom Corporation, has started shipping the first 20-nm low-power coherent DSP, NLD0640 Gen2 LP-DSP. This makes merchant Silicon DSP solution available for all manufacturers and enables interoperability among multi-source pluggable coherent optics using lower-cost technologies such as compound semiconductor and silicon photonics [13]. NTT demonstrated successful interoperability of the new NLD0640 Gen2 LP-DSP not only with multi-source CFP2-ACOs but also with CFP-DCOs employing their own in-house DSP ASIC [14].

Regarding bit rates beyond 100G, 200G/400G DWDM transceivers, seeking 100G DCO compatibility, are now in production. According to the OIF white paper OIF-Tech-Options-400G-01.0 [15], single-carrier transceiver implementations are the preferred solutions for short-haul and metro applications, with baud rates ranging between 42.7 and 64 GBaud and high-level modulation formats (16QAM and above) with 50 to 75 GHz channel spacing, achieving spectral efficiencies above 5.3 bit/s/Hz. Compared with multi-carrier solutions, single-carrier solutions provide the benefit of a simple structure, easy wavelength allocation and network management, smaller size, lower power dissipation, and lower cost. The real challenge is the ADC due to the high requirements regarding bandwidth and effective number of bits (ENOB) for multi-level modulation. The ASIC design is also very difficult. Considering 8-bits quantization, the throughput would reach 4 Tb/s, in real time. Large-scale parallel process and fine clock control is required. At ECOC 2015, NTT announced the shipment of the industry-first 20nm CMOS coherent DSP providing 200 Gb/s 16QAM DSP for metro-access [16].

The work of FOX-C partners on DSP can be used to improve the future generation of DSP implementations enabling better transmission performance but also improved power efficiency so that advanced ACO & DCO CFP2/4 transceivers could be realized.

Through the project, the FOX-C partners have worked on various DSP algorithms to reduce the complexity and thus power consumption. These DSP algorithms include phase estimation in optical fast OFDM and offset-QAM OFDM, filtering and synchronization in Nyquist FDM etc. The work of partners includes not only system-level design but also register level design to provide direct information regarding required multipliers, lookup tables etc and power consumption, to evaluate the possibility of real product realization. The team has also studied the influence of different parameters of electronic and optical analogue components, including frequency responses and device linearity, and investigated solutions to relax the required specifications. This investigation enables the developed technologies well prepared for integrating into the CFP2 with minimized device-related penalty.

During the FOX-C project special timing recovery which works on less than two samples per symbol was developed. This enables non-integer oversampling with lower than two samples per symbol digital coherent receivers. This can increase data throughput/ symbol rate with static sampling rate. On the other side if the symbol rate stays static we can reduce the ADC sampling rate. This results in a reduced net bit throughput on the DSP chip and ultimately reduces chip utilization and therefore power consumption.

We also developed a new carrier recovery. We used polar coordinates processing in order to reduce complexity. This means we can reduce chip utilization and power consumption which allows even to implement this algorithm on a FPGA chip for prototyping purposes. However we have to sacrifice performance. Furthermore the algorithm is implemented for 4QAM, 8QAM, and 16QAM which allows for the dynamic adaption through operation for different transmission scenarios. The design has been optimized for a symbol rate of 28 GBd which delivers available data rates of 100G, 150G and 200G for a polarization diverse coherent optical receiver processed in real-time.

Our findings reduce the complexity of current DSP algorithms and by this enable the next generation of DSP chips to be more power efficient by allowing higher spectral efficiencies and data throughput.

Industry standards and market outlook for 400G/1Tb transceivers

Even though higher bit rates per transceiver can be achieved in a single-carrier configuration by increasing the modulation level (thereby increasing the spectral efficiency, at the price of reducing the transmission reach) and the baud rate (which results in increased non-linear impairments and component requirements), as we proved in FOX-C project, the most viable solution is to resort to multi-carrier super-channel transmission, whereby the signal is divided into sub-channel constituents at a lower baud rate and modulation level by means of compact multiplexing techniques such as NWDM or OFDM.

Table 4-2 summarises several 400G transceiver implementations for short-haul (SH), metro, long-haul (LH) and ultra-long-haul (ULH) applications according to OIF-Tech-Options-400G-01.0 [15], including the DAC/ADC requirements and the maximum achievable reach.

Table 4-2 *Potential 400G architectures in the state of the art. (Distances reported are either based on the state of the art demonstrations [7] or from OIF contributions 3:OIF2014.030.00, 4:OIF2015.030.01, 5:OIF2015.100.00, 6:OIF2015.037.01, 7:OIF2014.031.00 [15])*

	Modulation	Symbol Rate (Gbaud)	#sub-channels	DAC Options[1]	ADC Options[1]	State of the art Distance (km)[2]
SH (~100 km, 50 GHz)	64QAM	42.7	1	1x4 80 GSa/s, 6.5 bits, 25 GHz[3]	1x4 80 GSa/s, 6.5 bits, 25 GHz[3]	300[Buchali 14]
	16QAM	64	1	1x4 88 GSa/s, 16 GHz[Rios-Muller 14]	1x4 90 GSa/s, 25 GHz[Rios-Muller 14]	6600[Rios-Muller 14]
Metro (<1000 km, 75/100 GHz, 10x ROADM)	16QAM	32	2	2x4 64 GSa/s, 16 GHz[4]	2x4 80 GSa/s, 33 GHz[4]	1800[4]
	16QAM	64	1	1x4 88 GSa/s, 16 GHz[Rios-Muller 14]	1x4 80 GSa/s, 33 GHz[Rios-Muller 14]	6600[Rios-Muller 14]
	64QAM	14.2	3	3x4 32 GSa/s, 6.5 bits, 10 GHz[5]	3x4 32 GSa/s, 6.5 bits, 10 GHz[5]	600[5]
	MB-OFDM (16QAM)	8	8	8x4 12 GSa/s, 10 GHz[Pincemin 14]	8x4 50 GSa/s, 5 GHz[Pincemin 14]	1000[Pincemin 14]
LH (~2000 km, optional ROADM)	QPSK	64	2	2x4 90 GSa/s, 5 bits, 20 GHz[6]	2x4 90 GSa/s, 5 bits, 20 GHz[6]	6577[Wang 15]
	QPSK	32	4	4x4 64 GSa/s, 14 GHz[7]	4x4 80 GSa/s, 33 GHz[7]	2975[7]
	16QAM	16	4	4x4 32 GSa/s, 5 bits, 10 GHz[3]	2x4 64 GSa/s, 5 bits, 17 GHz[3]	630[3]
ULH (>2000 km)	QPSK	32	4	4x4 64 GSa/s, 14 GHz[7]	4x4 80 GSa/s, 33 GHz[7]	2975[7]
	8QAM	42.7	2	2x4 64 GSa/s, 16 GHz[4]	2x4 80 GSa/s, 33 GHz[4]	6787[SZhang 14]
	16QAM	21	3	3x4 40 GSa/s, 6 bits, 11 GHz[5]	3x4 40 GSa/s, 6 bits, 11 GHz[5]	5000[5]

Σφάλμα! Το αρχείο προέλευσης της αναφοράς δεν βρέθηκε. shows in turn the OSNR requirements for ifferent modulation formats and net bit rates per carrier. We observe that single-carrier implementations require not only higher electrical bandwidth (>25 GHz) and ENOB (>6), but also OSNR above 22dB for BER equal to 10^{-3}. For multi-carrier implementations, on the other hand, these requirements can be relaxed depending on the actual architecture, e.g. to reduce the OSNR required for a particular modulation format, the baud rate needs to be reduced (see **Σφάλμα! Το αρχείο προέλευσης της αναφοράς δεν βρέθηκε.**). In any case, moving to 400G solutions faces a trade-off between spectral efficiency and reach flexibility.

Table 4-3 ***OSNR requirements (theory) for 400G modulation format options. Achievable OSNR without decreasing net bit rate is highlighted in bold text. The net bit rate shown is per carrier [15]***

Modulation Format	Net Bit Rate (Gb/s)	Symbol Rate (Gbaud)	Shaping	BW (GHz)	Grid (GHz)	SE (bit/s/Hz)	OSNR BER=10^{-3}	OSNR BER=10^{-2}
PDM-QPSK	100	28	NRZ	56	50	2	**12**	9.8
	100	32	Nyquist	35	50	2	12.6	**10.4**
	200	56	NRZ	112	100	2	**15**	12.8
	200	64	Nyquist	70	75	2.66	15.6	**13.4**
PDM-8QAM	100	18.7	NRZ	37.3	50	2	**13.8**	11.4
	100	21.3	Nyquist	23.4	25	4	14.3	**12**
	200	37.3	NRZ	74.6	100	2	**16.8**	14.4
	200	42.7	Nyquist	47	50	4	17.4	**15**
PDM-16QAM	100	16	Nyquist	17.6	25	4	16.2	**13.8**
	200	32	Nyquist	35.2	50	4	19.2	**16.8**
	400	64	Nyquist	70.4	75	5.33	22.2	**19.8**
PDM-64QAM	200	21.3	Nyquist	23.4	25	8	23.4	**20.8**
	400	42.7	Nyquist	47	50	8	26.4	**23.8**

If higher modulation levels are employed, reduced transmission reach is unavoidable because these high-order QAMs require higher OSNR, and are more sensitive to laser phase noise (e.g. 16QAM is 4-fold more sensitive than QPSK) and to fibre non-linear effects, in particular to non-linear phase noise. Similarly, the higher the QAM order, the lower the tolerance to narrow optical filtering due to ROADM cascading is [15].

Equipment suppliers seem today to converge towards 400G super-channels composed of 2 sub-carriers carrying each 200G PDM-16QAM in 75 GHz bandwidth. When compared to 100G PDM-QPSK, the 2x200G PDM-16QAM requires 7 dB higher OSNR, which represents a reduction by a factor of ~5 of the maximum transmission distance [15]. Table 4-4 summarizes the main features of the 400G solutions proposed by equipment suppliers. 32 Gbaud seems to be the best trade-off to increase the spectral efficiency without stressing too much the electronics (DAC/ADC/RF drivers) or the transmission performance [15]. Another solution to the reach/spectral efficiency trade-off could be the use of hybrid Raman/EDFA amplification with improved noise figure.

Table 4-4 400G WDM transmission solutions compared to 100G [15]. The table on the right shows the results obtained during the FOX-C project

Modulation	QPSK	16QAM	16QAM	8QAM	QPSK	QPSK
Overall Data Rate (Gb/s)	100	400	400	400	400	400
Symbol Rate (Gbaud) with FEC	32	32	64	43	64	32
Number of sub-channels	1	2	1	2	2	4
Nyquist filtering	No	Yes	Yes	Yes	Yes	Yes
Data rate per sub-channel (Gb/s)	100	200	400	200	200	100
Channel occupancy (GHz)	50	75	75	100	150	150
SE (bit/s/Hz)	2	5.33	5.33	4	2.66	2.66
Required OSNR at BER=10^{-2}	12.5	19.5	22.5	18.5	13.4	12.5
Maximum transmission reach* (km)	~2000	~400	~200	~500	~600	~2000
HW implementation penalty		++	+++	+++	++	+

16QAM
1000
15
10
Yes
100
20
5.13
16
>1000

From the network operators point of view, the reach for LH should be >2,000 km, and the reach for metro and regional ranging between 100-1,000 km. Furthermore, a 4x100G implementation is perceived to be more flexible than a 2x200G or 1x400G. Regarding the 2x200G PDM-16QAM implementation at 32 Gbaud, it can be fitted in a 75 GHz spectral slot according to ITU-T G694.1 flex-grid, but there are concerns about the filtering penalties arising from transmission over cascaded ROADMs, since ~10 ROADMs are required.

Finally, regarding standardization –and on account of the great number of proposed 400G solutions (cf. Table 4-2 and Table 4-3), it is important that the “modulation format soup” that “killed” the 40G data-rate should not be reproduced at 400G. Similarly, a 400G client physical interface needs to be standardized. IEEE 802.3 launched the 400GbE task force (IEEE 802.3bs [17]) in March 2014. The 802.3bs study group has converged to a common transmission technology (PAM-4) for applications 400GBASE-DR4, LR4, FR4, with the following specifications:

- DR4: 4 parallel duplex SMF, each carrying 100G, at 56Gbaud/s PAM-4, 500m
- LR8: 1 duplex SMF with 8×50G LANWDM wavelengths, each carrying 28Gbaud/s PAM-4, 10km
- FR8: same technology of LR8, de-spec’d for 2km reach

According to the IEEE 802.3bs 400GbE Task Force timeline adopted in September 2015, the standard is expected in December 2017 [17].

Within the FOX-C project we have come up with new 400G/1T super-channel implementations of transceiver solutions, implementing either electrical multiplexing schemes, such as eOFDM and NFDM or optical multiplexing schemes, such as Nyquist WDM with optical filtering (NWDM) and all-optical OFDM. Based on the carriers’ needs summarized above, we focused on N×100G configurations at 32GBaud (where N is the number of sub-channels) to provide greater flexibility and the transmission reaches required by LH/ULH applications. The developed offset-QAM OFDM technology from the UCC team can address the transmission reach/spectral efficiency tradeoff by supporting larger dispersion value (i.e. longer distance) without adding the cyclic prefix overhead (i.e. higher spectral efficiency). The suppressed spectral tails also mitigate the crosstalk to adjacent sub-channels, thus facilitating flexible sub-channel add/drop in metro/long-haul optical networks. On the other hand, optical fast OFDM uses real operations, which can reduce the DSP complexity and power consumption. Therefore, this solution is more promising to compete in the market of short-reach or access networks (<80 km). Comparison of Terabit super-channel transmission over 1000km between MB-OFDM and NWDM. NWDM transceiver extended with NFDM. Implementation of real-time capable algorithm for multi-format Nyquist signals with varying roll-off factors and oversampling factors below two samples per symbol. The hardware implementations have been optimized for lowest complexity in order to reduce power consumption.

Our industry partners in FOX-C have identified important technology enablers (i.e. Nyquist FDM/WDM, multi-band OFDM, offset-QAM OFDM, fast OFDM etc.) addressed by the FOX-C project developments which can be directly exploited for the definition of future high speed transceivers.

We developed receiver real-time digital signal processing techniques to cover non-integer oversampling. This allows, compared to standard 2 sample per symbol receivers, the increase of the symbol rate while keeping the sampling frequency constant. This results in a higher data throughput. Or can keep the data throughput and so the symbol rate and reduce the sampling frequency. This reduces the power consumption and chip occupation but still reaches the same symbol rates as before. A key to enable this technique is our modified Godard timing recovery. Here, we exploit the reduced complexity when resampling in the frequency domain. Our technique realizes timing estimation and correction in the frequency domain without multiplications.

The coherent transmission problem of having a frequency and phase offset between transmitting and receiving laser, we solved with an innovative solution than allowed the carrier recovery without the need of multiplications. Since multiplications are a rather expensive signal processing step this allows to reduce the chip occupation and so the power consumption.

For the FOX-C project we realized a super-channel with 1Tb/s with OFDM and NWDM, transmission up to 1000km. Here, we realized signal generation with different symbol rate and excess bandwidth. With these parameters we are able to realize different super-channel realizations. It is important to tune these parameters to have reliable transmission under different channel realizations. Nonlinear impairments can be handled by changing the symbol rate and the channel spacing.

NFDM investigations with different number of subcarriers were realized during the project. The NWDM transceivers have been extended with the capability of NFDM transmission. NFDM allows digital subcarrier multiplexing. We demonstrated NFDM generation with different amount of subcarriers. A varying number of subcarrier allows for control of the symbol duration. The industry also announced their interests in NFDM techniques and plan to include it in their next product generation [18]. We plan to further investigate the advantages of NFDM under different system impairments like NL tolerances, filtering and bandwidth limitations of electronic devices. Furthermore, a comparison between the MB-OFDM and NFDM concerning transmission and NL tolerances will follow.

The FOX-C research teams of ETHZ and UCC plan to interact with the technology transfer offices of the Universities to explore the possible ways that the know-how developed within FOX-C can be utilized towards licensing by equipment vendors and/or network operators, as well as towards the possible creation of relevant start-up companies. The UCC team has positioned the suitable market segments for the developed technologies, i.e. flexible metro market for the offset-QAM OFDM technology, and short-reach transmission for the optical fast OFDM technology. On one hand, the team will continue to implement the technologies into prototypes, such as real-time demonstration module, and acquire the relevant support/knowledge on ASIC design and choice of optical components. Commercially, the team will refine the target market segment, and analyze the market size/growth rate as well as competitive technologies in the target market. The team will work together with the technology transfer office to explore the route to market (IP licensing or a start-up). At the same time, the team plans to meet system/subsystem vendors that are potentially interested in the technologies to acquire their feedback and adjust relevant technical specifications, as well as end-user companies to understand the transceiver market needs. Once through the initial phase, if the outcome is positive, the team will continue the commercialization process. In the case of licensing, the team will collaborate with the target companies to generate real products and move the technologies into the market. For the start-up option, the team will refine the market growth, analyze possible supply chain, project finance and seek funding, e.g. Venture Capitalist, to support the next-stage commercialization.

In general, it is not possible to file a patent on already published material. But in general we have an internal discussion whether we should bring our results into a patent first and then publish the results into a scientific article. Especially before we published the material about the timing and carrier recovery, we elaborated about above, we were close to filing a patent but after a patent search we decided to not take this step. But this in general says that the patent office of ETH is open for our results and suggestions and we will take this opportunity for the next results that are up to come.

5 References

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