Analyses of 100 Gbps Coherent System Performances

Pavel ŠKODA[1,2], *Jan RADIL*[2], *Josef VOJTĚCH*[2], *Miloslav HŮLA*[2]

[1]Department of Electromagnetic Field, Czech Technical University in Prague, Czech Republic
[2]Optical Networks Group, CESNET a.l.e., Czech Republic

pavel.skoda@cesnet.cz, jan.radil@cesnet.cz, josef.vojtech@cesnet.cz, m.hula@cesnet.cz

Abstract. *This paper presents the results of laboratory and field testing of coherent 100 Gbps system with DP-QPSK modulation. Several measurements were performed including power budget, nonlinear threshold, spectrum filtration, constellation diagram, interoperability with 10 Gbps lambdas and dispersion compensation type impact. Field tests addressed transmission of 100 Gbps signal as an Alien Wavelength through multivendor network, influence of photonic service parallel to 100 Gbps signal and performance of 100 Gbps system over single fiber bidirectional transmission lines. 100 Gbps system has been found extremely resilient to most classical impairments thanks to advances error coding and compatible with standard 10 Gbps NRZ lambdas and any type of dispersion compensation. The system was also working over single fiber bidirectional lines and in parallel with Photonic Service of time transfer. The paper also shows recent results of single hop test with 100 Gbps system in laboratory environment.*

Keywords

100 Gbps, DP-QPSK, field tests, dispersion compensation, photonic service.

1. Introduction

Optical coherent transmission formats open the new era of optical communications and allow following Shannon prediction of system capacity increase [1]. Although many experts were doubtful about universal modulation for 40 Gbps technology, in case of the successive 100 Gbps technology they seem to unite for one candidate [2], the Dual Polarization Quadrature Phase Shift Keying (DP-QPSK). This modulation was also employed by Alcatel-Lucent (ALU) and Oclaro into their 100 Gbps coherent platforms. New devices with optical coherent communication utilize powerful forward error coding mechanisms that considerably enhance transmission performance while digital processing eliminates the most of linear channel effects [3], [4]. One of the most important features questioned was interoperability with old 10 Gbps Non-Return-to-Zero (NRZ) modulation formats that require dispersion compensation through Dispersion Compensation Fibers (DCF) or Fiber Bragg Grating (FBG) modules [5], [6]. Also interoperability of coherent technology with new network applications or network equipment from different vendors is of wide interest [7][8].

First chapter describes test done with Alcatel-Lucent transmission system. Subchapters discuss laboratory tests, laboratory transmission line tests, constellation diagram measurements and transmission tests in production network CESNET2. Second chapter presents results from Oclaro testing at laboratory fibre lines and subchapters address the susceptibility of 100 Gbps system to slow OOK signals and its maximal single hop distance.

2. Alcatel-Lucent 100 Gbps System

2.1 Initial Laboratory Tests

The initial laboratory tests focused on identifying basic attributes of Alcatel-Lucent 100 Gbps Muxponder system. Non-regenerated reach, filtering susceptibility and nonlinear threshold tests will be discussed in this chapter. In the non-regenerated reach test a pseudorandom sequence from Bit Error Rate Tester (BERT) was multiplexed in Alcatel-Lucent system onto 100 Gbps DP-QPSK signal. 100 Gbps signal passed only variable attenuator before demultiplexing and retrieving pseudorandom sequence for BERT in order to obtain maximum attenuation that can be overcome without optical amplification. Thanks to Advanced Forward Error Coding (AFEC) embedded in ALU system, the system was able to overcome attenuation of almost 3 orders of magnitude (28.2 dB) without any amplification.

Filtration of optical spectra happens at many optical elements throughout every network. Also a slight misalignment of central wavelengths of optical elements is a common problem and therefore the resilience of system to the filtration effect is an important parameter. The variable attenuator was replaced by optical tunable filters. 100 Gbps signal was at first filtered by 100 GHz, 50 GHz and 30 GHz (full width at half maximum) filters that suppressed mainly spectrum sidebands. It is clear that the information is mainly carried in central band and the signal fits into 30 GHz channel. Then 30 GHz filtering was done asymmetrically by detuning filter spectrally from central frequency of 100 Gbps signal. There was no impact on transmission BER for our filtering schemes as long as filter detuning did not increase beyond 40 GHz. The AFEC performance was not monitored due to time constrains.

Once power in optical fiber increases over certain limit, nonlinear effects come into play. The most significant effect for 100 Gbps modulated signal in our setup is a self-phase modulation (SPM) that broadens signal spectrum while adding spurious phase modulation to signal. SPM is the result of nonlinear dependence of refractive index of optical fiber on optical power of a signal [8]. The optical filters were swop to booster amplifier and 100 km of G.652 fiber. Output power of the booster amplifier was increased from 10 dBm to 27 dBm. BERT didn't report any errors until the output power rose to 22 dBm. Optical spectra for several amplifier output powers are in Fig. 1. It can be seen that for powers over 20 dBm SPM induces considerable broadening of the main peak and masks the sidebands. Therefore amplifiers with high output power should be used with careful planning. We will limit output power of our booster amplifiers to 19 dBm for further tests. Measured results during laboratory tests are summarized in Tab. 1.

2.2 Experimental Transmission Line Tests

Experimental transmission line in optical laboratory had length of 600 km composing from both G.652 and G.655 fiber spans. Parameters of fiber spans can be found in Tab. 2. The test was set up using Dispersion Compensating Fibers (DCF) and long spans to explore performance of ALU system at conventional transmission links with DCFs that are in production network of CESNET. The initial setup with DCF as dispersion compensation was then replaced with Dispersion Compensating Modules (DCM) that are utilizing fiber Bragg Gratings (FBG) to prove that 100 Gbps technology can work together with standard systems.

Two 100 Gbps signals from ALU systems were combined with 12 standard 10G NRZ channels in multiplexer and sent to the first amplification stage. The spectrum after multiplexer is shown in Fig. 3. Double stage amplifiers with gain flattening feature were used in this experiment. All amplifiers except the first had dispersion compensating element in between their stages. The whole experimental transmission line can be seen at Fig. 2. Both 10 Gbps and 100 Gbps systems worked without errors with proper dispersion compensation. The setup with DCFs was working up to 844 ps of uncompensated dispersion without errors. Once some of DCF were changed for DCM, the error free operation was achieved only below 800 ps of uncompensated dispersion. So the conclusion drawn from this test is that FBGs have advantage in their length when compared to DCFs, but the dispersion must be compensated more accurately. This effect is probably caused by complicated dispersion compensating profile of FBGs.

2.3 Constellation Diagram Test

An eye diagram represents an effective way of displaying simple modulation schemes. A skilled engineer can easily judge signal quality and its parameters. More complex modulations like DP-QPSK are rather represented by constellation diagrams that show detected symbols in the complex plane. Dual Polarization Quadrature Phase Shift Keying (DP-QPSK) is a coherent modulation exploiting both phase and polarization to represent modulation symbols. Transceivers work at symbol rate of about 25 GBaud that translate to about 50 Gbps for four states QPSK in one polarization. Second polarization carries the same amount of information resulting in total throughput of about 100 Gbps.

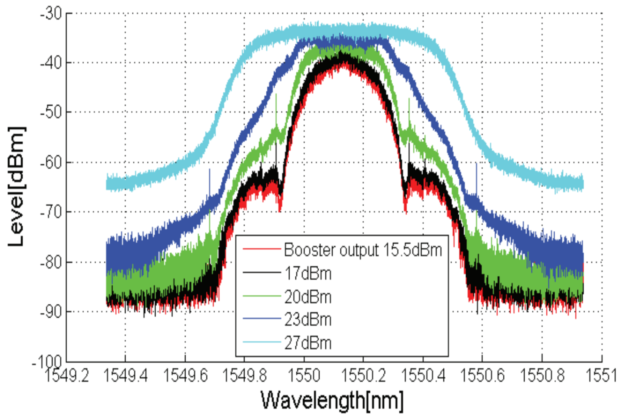

Fig. 1. Nonlinear spectrum broadening as a function of booster output power.

Test	Result	Comments
Power Budget	28.2 dB	without additional amplification
Filtration Effect	40 GHz	maximal filter detuning from signal center
Nonlinear threshold	22 dBm	of power booster output and 100km link

Tab. 1. Measured parameters of 100 Gbps ALU system.

ID	Type	Length [km]	Att [dB]	CD [ps/nm]
A1	G.652c	100,7	20,1	1611,2
A2	G.652c	103,7	20,7	1659,0
A3	G.652c	101,1	20,2	1618,0
B1	G.655	95,4	19,1	19,4
B2	G.655	100,3	20,1	401,2
B3	G.655	100,6	20,1	402,4

Tab. 2. Used fiber spans in laboratory experiment.

The optical coherent modulation analyzer PSO-200 from EXFO can detect and display various advanced optical modulation schemes. Analyzer is dedicated for coherent transceiver testing in production companies and therefore unable to correct transmission impairments. ALU transceiver was analyzed with PSO-200 and the clear constellation diagram of 100 Gbps DP-QPSK is shown in Fig. 4. The figure displays constellation diagrams for both orthogonal polarizations (X polarization in the top part and Y polarization in the bottom part) and related eye diagrams of demodulated bit streams at detector. As PSO-200 does not support forward error codes the displayed values represents modulation symbols rather than actual data. Fig. 4 displays the performance of PSO-200 in presence of 170 ps of uncompensated chromatic dispersion. The fact that real long haul fiber lines usually experience more noise from multiple amplifier stages and larger PMD than fiber spools prevented us from constellation analysis of real lines. It has to be highlighted that PSO-200 is not designed for system testing.

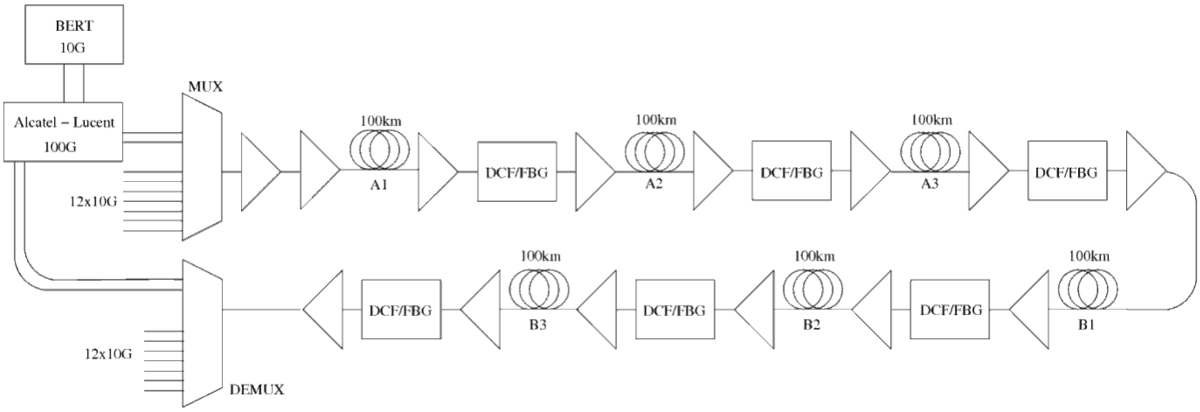

Fig. 2. Experimental setup of 600 km long transmission.

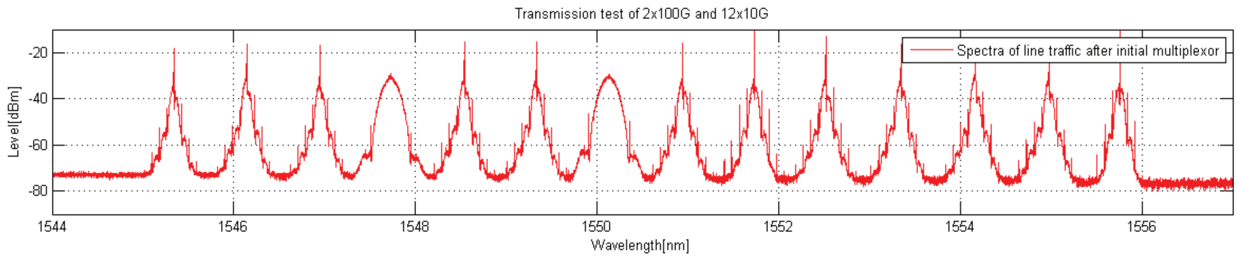

Fig. 3. Spectra of 2x100 Gbps and 12x10 Gbps after initial multiplexer.

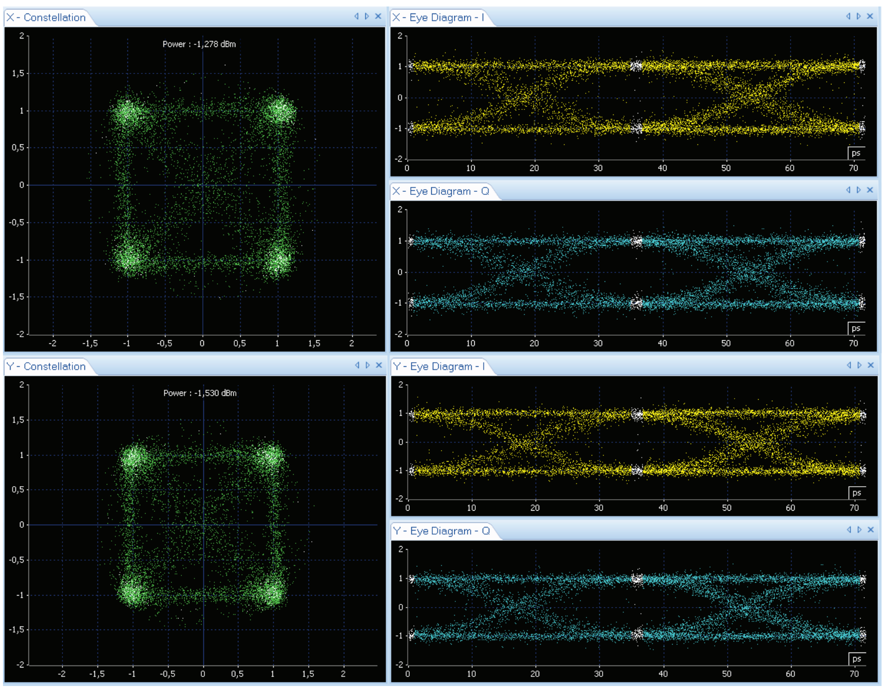

Fig. 4. Constellation diagram directly after transceiver 100 Gbps DP-QPSK.

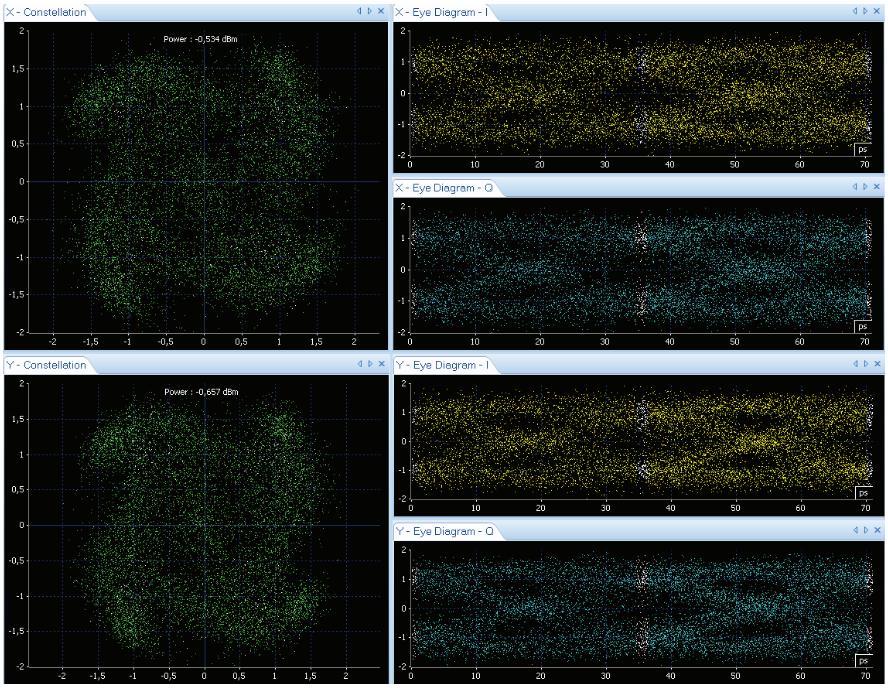

Fig. 5. Constellation diagram of 100 Gbps DP-QPSK modulation after 100 km of fiber with 170 ps uncompensated dispersion.

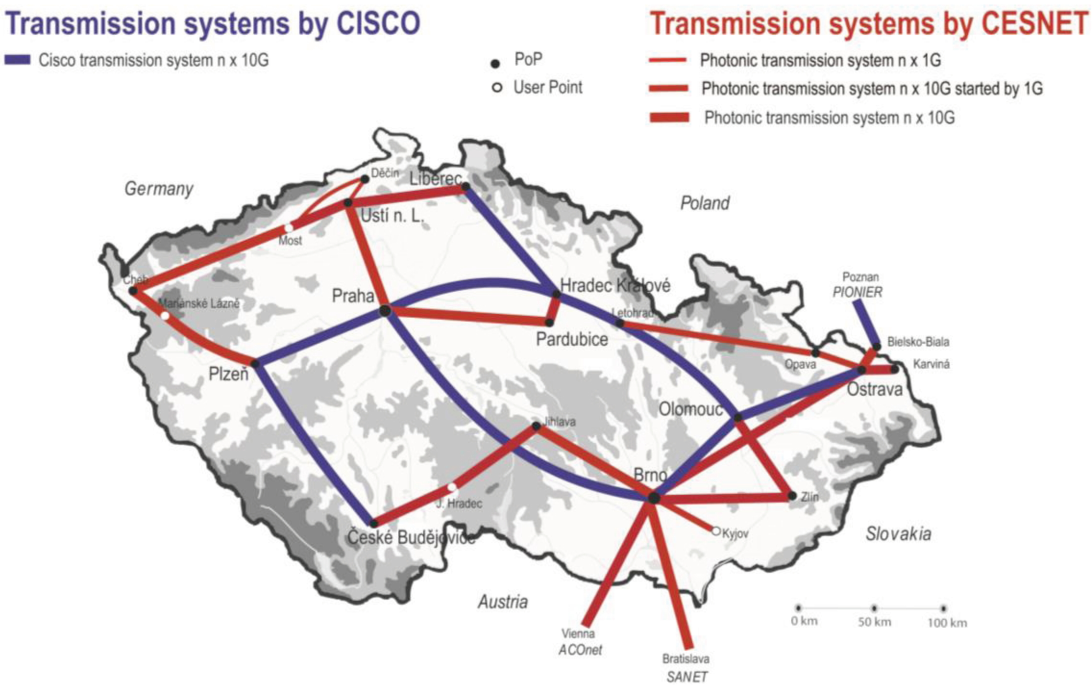

Fig. 6. Map of CESNET2 network where CISCO lines are marked blue and lines lighted by open systems are in red.

Test Scenario	DWDM Technology	Length [km]	Att [dB]	AFEC BER	10G BERT	Critical Spans [dB]	Specials
Praha-Hradec Králové-Ostrava-Hradec Králové-Praha	CISCO	1063	276	3,67E-04	0	22, 22	Distance > 1000 km
Praha-Hradec Králové-Olomouc-Brno-Praha	CISCO	778	208	4,44E-05	0	22, 22, 22	Concurrent photonic service
Praha-Brno-Wien-Brno-Praha	CISCO, CzechLight	1056	285	3,37E-03	2,60E-10	30, 31, 32, 34	Concurrent photonic service
Praha-Plzeň-Cheb-Most-Ústí nad Labem-Praha	CISCO, CzechLight	655	180	1,31E-03	0	34, 36, 36	Single Fiber Bidirectional Transmission

Tab. 3. ALU field tests summary.

3. Field Tests in CESNET 2 Live Network

Extensive laboratory tests were followed by several test scenarios in live network of CESNET 2 to verify interoperability of coherent 100 Gbps DP-QPSK system with standard 10 Gbps NRZ systems and special photonic services. Fig. 6 shows CESNET 2 network and highlights lines with Cisco DWDM in blue and Open DWDM transmission systems in red.

The first scenario used a loop over production lines equipped with Cisco ONS 15454 MSTP of total length of 1063 km by connecting Praha – Hradec Králové – Olomouc – Ostrava – Olomouc – Hradec Králové – Praha cities. Total overcame attenuation was 276 dB with two spans of 22 dB attenuation. Overall performance of the 100 Gbps system was measured by embedded AFEC performance and BERT running on one of multiplexed 10G channels. The 100 Gbps system was running smoothly with AFEC BER 3,67E-04.

The second scenario had shorter total distance of 778 km, but 100 Gbps signal was sent over the same line as a photonic service of precise atomic clock comparison (both 100 Gbps and photonic services were transmitted in the same fiber) [9]. The ring Praha – Hradec Králové – Olomouc – Brno – Praha (see Fig. 6) had 208 dB of attenuation and included also three spans with attenuation of 22 dB. The 100 Gbps system was errorless with AFEC corrected errors of BER 4,44E-05. During the test, the photonic service was in operation on the line Praha – Brno with no evidence of influence on each other.

The Third scenario was conducted over combination of Cisco DWDM and Open DWDM transmission systems on line Praha – Brno – Wien – Brno – Praha with concurrent transmission of photonic service of atomic clock comparison. The total length of line was 1056 km with 285 dB of attenuation and 4 spans of 22 dB plus another four critical spans of 30, 31, 32 and 34 dB. AFEC reported BER 3,37E-03 and 10 Gbps BERT measured BER of 2,60E-10. The main reason behind this effect is probably the reduction of signal quality at four critically long spans.

The fourth scenario was set over single fiber bidirectional transmission lines. The ring Praha – Plzeň – Cheb – Most – Ústí nad Labem – Praha included part of Cisco DWDM and part of Open DWDM transmission systems in total length of 655 km and 180 dB of attenuation. The ring had three critical spans of 35.5, 34, 35.5 dB. AFEC corrected 118e+9 errors over 15 minutes. Field tests are summarized in following Tab. 3. It can be seen that AFEC performance overcome BER of 1,31E-03 and is not detrimentally influenced by con-current photonic service for distances of 1000 km.

4. Oclaro 100 Gbps System

4.1 Slow OOK Signals Influence

Recently a 100 Gbps DP-QPSK transmission system from Oclaro has been tested on influence of slow On-Off Keying (OOK) signals at laboratory line 455 km long. The 100 Gbps system signal was enclosed between two slow OOK signals as can be seen in Fig. 7. We used modulated CW lasers, GBIC and XFP transceivers for signals of 100 MHz, 1 Gbps, 10 Gbps respectively. The misalignment of slow signals was due to more relaxed specification for GBIC transponders and wavelength offset of tunable laser. No provable detrimental effect of slow signals has been observed for our laboratory line. A small change in 100 Gbps system BER could be rather accounted also to power level fluctuation or wavelength offset of slow signals.

4.2 Single Hop Reach

100 Gbps systems are currently designed for backbone networks that are leading in the capacity requirements. It is sometimes beneficial to sacrifice some total reach of transmission system for larger distance between amplification stages. Therefore a single hop reach test was carried out in order to find out the maximum distance that can be overcome with our network equipment. A 10 Gbps OOK signal from BERT was muxponded in 100 Gbps system from Oclaro and sent to transmission line. The output powers of EDFA booster and pre-amplifiers were tuned to achieve maximal distance of 240 km. The addition of Raman Amplifier improved the single hop reach to 277.5 km, but the Raman amplifier added 700 mW of counter-propagating output power. Powers above 500 mW are dangerous to human eye and can lead to permanent degradation of optical fiber in case of faulty or dirty connectors.

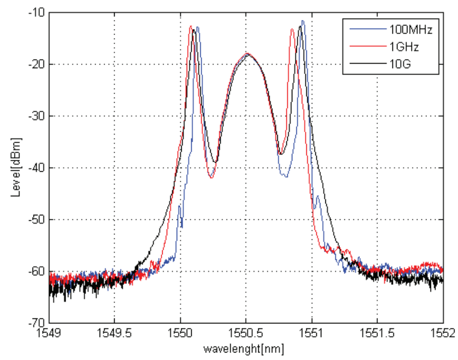

Fig. 7. Optical spectrum of 100 Gbps coherent signal enclosed by slow OOK.

5. Results of ALU and Oclaro Tests

Both ALU and Oclaro provided us with long haul muxponder transmission system using coherent DP-QPSK modulation of 100 Gbps bit rate. Although it would be interesting to compare performance of both systems, tests were carried out in very limited time and thus reflect interests at that time. Nevertheless we showed that some basic parameters of ALU system and found it very resilient to network impairments. Consecutive tests on experimental laboratory transmission line did not reveal any problems with DCF and DCM compensation and promoted DCM as superior technology for dispersion compensation. Constellation diagrams showed signal distortion under certain conditions and underlined power of digital signal processing during coherent detection.

Field tests in CESNET2 network verified the Alien Wavelength concept over systems from different vendors. ALU signal was propagated through CISCO DWDM and CzechLight DWDM transmission systems as an Alien Wavelength. Tests were done over several link lengths around 1000 km. The focus was at mutual influence with Photonic Service that is running between Prague and Vienna and single fiber transmission through part of CESNET2 network. Although links in production network of CESNET2 cannot be tuned to study detailed influences with live traffic, it can be seen from Tab. 3 that by number of critical spans with large attenuation and length of the link. So the drop in OSNR has the major impact on 100 Gbps signal. Nevertheless coherent signal does not have measurable influence on concurrent live traffic and Photonic Service in CESNET2 network.

The coherent signal from Oclaro 100 Gbps system uses the same modulation as ALU system with comparable coherent detection and digital signal processing. The influence of slow amplitude modulated signals on 100 Gbps coherent signal was under the measurement error given by power and frequency fluctuation of slow signal transceivers. In single hop test of 100 Gbps signal we overcome distance of 240 km with just EDFA amplifiers at endpoints of the link. Raman amplifiers acting as counter-propagating pump prolonged maximum single link length to 277 km.

6. Conclusion

We have tested two optical backbone 100 Gbps DWDM systems in laboratory and on production network. Although DWDM coherent transmission systems carry 100 Gbps over a single frequency, system are resilient to many network impairments as nonlinearities, filtration and inter-channel interference. These coherent systems can work over compensated networks with no measured influence from type of dispersion compensation. During comparison of DCF, FBG and uncompensated scenarios, no impact, but more attenuation according to DCF length, has been observed. FBG due to their lower insertion loss, nonlinear effects and delay should be preferred for chromatic dispersion compensation. Therefore new coherent systems can be deployed together with 10 Gbps NRZ transmission systems as long as the network will remain dispersion compensated.

ALU 100 Gbps Photonic Service Switch Platform verified to work with Cisco and CzechLight transmission systems in multivendor environment. The ALU 100 Gbps also proved to work over single fiber bidirectional transmission lines and in parallel with the Photonic Services of atomic clocks comparison.

Oclaro 100 Gbps systems also did not show any penalty in performance when surrounded by slow varying OOK signals. We achieved single hop reach of 100 Gbps system of 240 km for EDFA amplification and 277 km for combined Raman-EDFA amplification.

Acknowledgement

The research leading to these results has received funding from the European Community's Seventh Framework Program (FP7/2007-2013) under grant agreement nº 238875 (GÉANT).

This work was supported by the Ministry of Education, Youth and Sport of the Czech Republic as part of the CESNET Large Infrastructure project LM2010005 and by Technology Agency of the Czech Republic grant TA01011105.

References

[1] ESSIAMBRE, R.-J., KRAMER, G., WINZER, P. J., FOSCHINI, G. J., GOEBEL, B. Capacity limits of optical fiber networks. *Journal of Lightwave Technology*, 2010, vol. 28, no. 4, p. 662 - 701.

[2] ROBERTS, K., O'SULLIVAN, M., KUANG-TSAN WU, HAN SUN, AWADALLA, A., KRAUSE, D. J., LAPERLE, C. Performance of dual-polarization QPSK for optical transport systems. *Journal of Lightwave Technology*, 2009, vol. 27, no. 16, p. 3546 - 3559.

[3] WANG, J. et al. Optical data exchange of 100-Gbit/s DQPSK signals. *Optics Express*, 2010, vol. 18, no. 23, p. 23740 - 23745.

[4] MURATA, K. et al. 100-Gbit/s PDM-QPSK coherent receiver with wide dynamic range and excellent common-mode rejection ratio. *Optics Express*, 2011, vol. 19, no. 26, p. B125 - B130.

[5] RENAUDIER, J. et al. Investigation on WDM nonlinear impairments arising from the insertion of 100-Gb/s coherent PDM-QPSK over legacy optical networks. *IEEE Photonics Technology Letters*, 2009, vol. 21, no. 24, p. 1816 - 1818.

[6] BERTRAN-PARDO, O. et al. Overlaying 10 Gb/s legacy optical networks with 40 and 100 Gb/s coherent terminals. *Journal of Lightwave Technology*, 2012, vol. 30, no. 14, p. 2367 - 2375.

[7] BIRK, M. et al. Real-time single-carrier coherent 100 Gb/s PM-QPSK field trial. *Journal of Lightwave Technology*, 2011, vol. 29, no. 4, p. 417 - 425.

[8] BIRK, M. et al. Coherent 100 Gb/s PM-QPSK field trial. *IEEE Communications Magazine*, 2010, vol. 48, no. 7, p. 52 - 60.

[9] AGRAWAL, G. P. *Fiber-Optic Communication Systems*, 4th ed. New York (USA): Wiley, 2010.

[10] SMOTLACHA, V., KUNA, A., MACHE, W. Time transfer using fiber links. In *24th European Frequency and Time Forum (EFTF)*. Noordwijk (The Netherlands), 2010.