Live Native IP Data Carried End-to-End by 100 GE Router Interfaces and Single Carrier 100 G Transport System Over 1520-km Field Deployed Fiber

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***Abstract*—For the first time native IP data are carried end-to-end by 100 GE router interfaces and a 100 G optical transport system over 1520-km field deployed fiber. This is accomplished with multi-suppliers' 112-Gb/s single carrier real time coherent DP-QPSK DWDM transponder, 100 GE router cards, and 100 G CFP interfaces.**

***Index Terms*—100-Gb/s, 100 GE, coherent detection, DP-QPSK, field trial, IP data, optical transport, single carrier.**

I. Introduction

100-Gb/s Ethernet (100 GE) has been recognized as the next step in Ethernet evolution, since it is capable of carrying large amounts of traffic generated by emerging IP (Internet Protocol) applications such as peer-to-peer video, Web 2.0, and bandwidth-intensive services for medicine or government sectors [1]. This development is well aligned with the prediction that new data-centric applications continue to drive double digit traffic growth rates [2]. To carry the 100 GE data, DP-QPSK (Dual Polarization Quadrature Phase Shift Keying) with coherent detection has been recognized as the most desirable modulation format for 100 G transport with OTU4 (the 4th level Optical Transport Unit) [3]. Several 100-Gb/s DP-QPSK experiments have been reported with off-line processing [4]–[6]. While the off-line approach does not fully reflect a practical deployment scenario, it is nonetheless the first step towards an on-line, high-speed DSP (Digital Signal Processing) system, which is based on real-time sampling and processing of the incoming signal flow in hardware. There are also a number of reports on field trials of 100-Gb/s transport [7]–[9], [11], [12]. The field trials help the 100 G end users to set correct performance expectation of the ultra-high speed transport in real networks. Recently, real time native data transport with a dual-carrier DP-QPSK 100 G system has been accomplished. However in this paper, we report, to the best of our knowledge, the first field trial that realizes end-to-end native IP data 100 G transport with a single carrier modulation system and real time digital signal processing over a long-haul distance. In this trial, traffic between IP router high speed cards has been carried over DWDM transmission system of 19 amplifier spans with each span of 80-km field deployed fiber. The connection between IP router 100 GE cards and DWDM equipment is achieved via IEEE standard 100 G CFP interfaces. The interoperability between multi-equipment suppliers has been verified for the 100 G optical transport. The fact that four different companies were able to perform an end to end trial based on standardized components within a short duration underscores one of the biggest objectives of the 802.3ba Ethernet Task Force, that of interoperability of multi vendor equipment.

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II. Field Trial Configuration

The field experiment was carried out by combining a 100-Gb/s DWDM transport system, 100 GE IP router cards, 100 GBASE-LR4 CFP (Long-Range 100 G Form-Factor Pluggable) transceiver modules, and field deployed fibers. The 100-Gb/s DWDM system, NEC Spectralwave DWDM platform, contains a prototype of 100-Gb/s transponder. The DWDM system uses hybrid amplification, including both EDFAs (Erbium-Doped Fiber Amplifiers) and backward pumped distributed Raman amplifiers. The live native IP data in this trial are Ethernet testing data from a test set and encoded video signals. The native IP data are fed into a 10 GE interface in Juniper router T1600 [10]. Then the data are routed to the 100 GE cards in the same router. The 100 GE signal is then fed into the client port of the 100 G transponder. The connection between the 100 GE cards and the 100 G transponder is provided by Finisar 100 GBASE-LR4 CFP optical transceiver modules, which support an IEEE-compliant 4×25 G LAN WDM 103-Gb/s client link up to 10 kilometers of single mode fiber. The connection between the 100 GE cards and the 100 G transponder is also provided by NEC 100 GBASE-SR10 compliant client transceivers. The transmission line is composed of 19×80-km spans of standard single mode fiber (SSMF) interconnecting ROADMs (Reconfigurable Optical Add/Drop Multiplexers) and in-line amplifiers of the DWDM system.

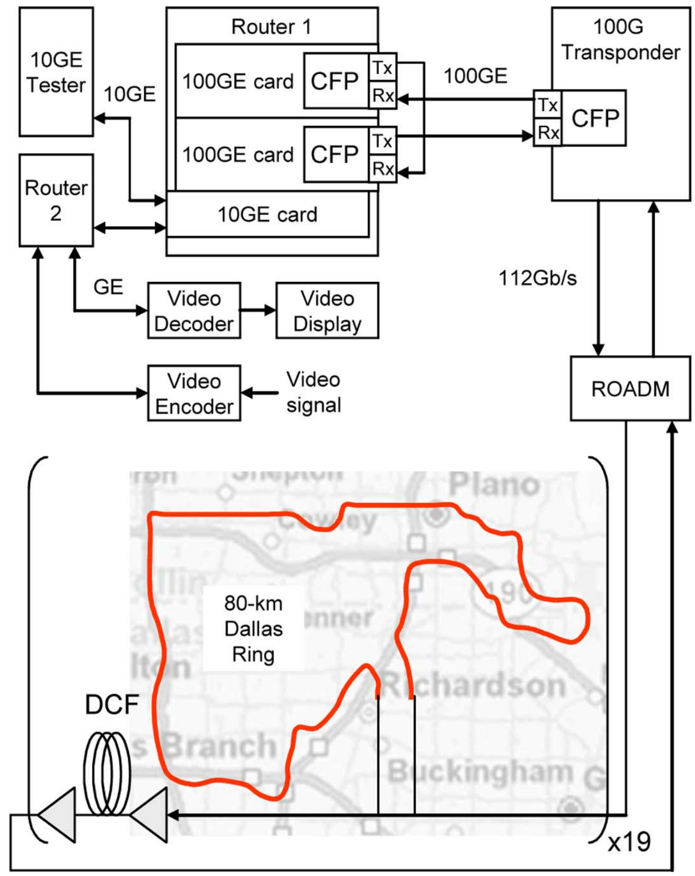

Fig. 1. Trial configuration for the end-to-end 100 GE data transport with single carrier DP-QPSK transmission.

There was dispersion compensation by DCF, since 100 G transponders were used on the existing DWDM platform.

The trial configuration is shown in Fig. 1. A 10 GE test set (Spirent model SPT-9000A) is used to generate 10 GE traffic for the router T1600 (Router 1) and to analyze the packet throughput. Another router (Router 2) is used to accept a GE (Gigabit Ethernet) signal containing a video signal via a video encoder and to send the video signal to a video display via a video decoder after the video signal traverses the trial path. Router 2 connects to Router 1 with another 10 GE link. The router T1600 routes both 10 GE data streams to one of the 100 GE cards and routes back the 10 GE data streams from the other 100 GE card to the corresponding 10 GE ports. The 100 G CFPs are used to connect 100 GE cards and the 100 G transponder. The transmitter port of the CFP in the first 100 GE card is connected to the receiver port of the CFP in the transponder and the receiver port of the second 100 GE card is connected to the transmitter port of the CFP in the transponder. The receiver port of the CFP in the first 100 GE card and the transmitter port of the CFP in the second 100 GE card are connected with a fiber jumper to close the loop. The 100 G transponder sends the 112-Gb/s optical signal to the long haul fiber route. Both directions of the inline bi-directional amplifiers have been used for the trial to save the equipment needed.

Fig. 2 shows details of the transmitter (a) and the receiver (b) of the 100 G transponder. The 100-Gb/s Ethernet (100 GbE) signal is received by the CFP interface circuit. The received signal is split and fed to two FEC (Forward Error Correction) chips for encoding. The two encoded data streams are multiplexed for data alignment and then converted into four lanes of 28-Gb/s signals with the gear-box circuit. In the transponder a differential coding scheme is adopted to avoid burst errors due to phase slips. The differential process is performed inside the gear-box. The four driving signals from the gear-box then are fed into two QPSK modulators, which are used for modulating continuous wave from a full-band tunable laser diode. The modulator outputs are multiplexed by the polarization beam combiner to generate the polarization-multiplexed QPSK signal. RZ carvers with 33% pulse width generation are used behind the QPSK modulators for long distance transmission. The transponder optics employs automatic control circuits, such as ABC (Automatic Bias Control), for long term stability.

At the receiver, polarization-diversity coherent optical front end with another tunable laser, which is used as a local oscillator, generates the electrical I-and-Q signals for two polarization axes. The four electrical signal outputs are digitized with the high-speed 8-bit ADC (Analog-to-Digital Converters) operating at 42 GSample/s. The clock is recovered with a tapped and polarization demultiplexed input signal. The sampled data is then processed by the DSP circuit and the 112-Gb/s output data are formed. In the FPGA (Field-Programmable Gate Array) based DSP part, a polarization-demultiplexing, carrier phase estimation, and decoder circuit are implemented. To achieve 112-Gb/s throughput, a parallel architecture is employed. At the

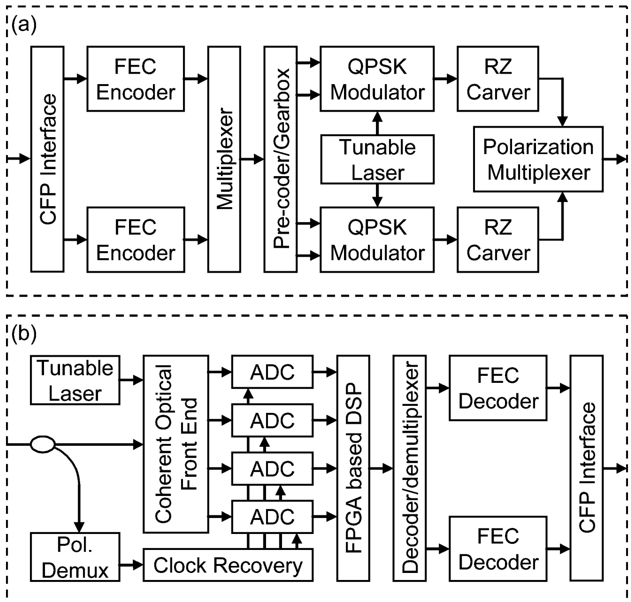

Fig. 2. Block diagram of the developed optical transponder with real-time digital signal processing, where (a) is the transmitter and (b) is the receiver.

input of the DSP circuit, data from ADCs are re-sampled to 1 sample-per-symbol by an anti -aliasing filter and resembler, and then demultiplexed in polarization. The polarization demultiplexing circuit, which is a butterfly filter, and 13 tab FIR (Finite Impulse Response) filters were implemented for the waveform equalization. After polarization demultiplexing, QPSK symbols are recovered by a carrier phase estimation algorithm with a digital phase loop and a symbol decision circuit. The recovered data are then differentially decoded. Its errors are corrected with the two FEC chips. The data are then reconstructed to the Ethernet signal at the CFP interface circuit. The FEC was a concatenated hard decision error correction code, which is widely used in the current system as an enhanced FEC.

Before the field trial the back-to-back performance of the transport system was evaluated. The test wavelength was selected as 1547.72 nm. The BER (Bit Error Rate) data were measured by changing the OSNR (Optical Signal-to-Noise Ratio). During the BER measurement optical noise was added at the receiver input. For the line performance test two pattern generators, which generated unframed $2^{23} - 1$ PRBS signals, were used in the gear-box and in the error detector at the DSP output, respectively. The BER with FEC was measured using the pattern generator and the error detector implemented at the CFP interface.

Fig. 3 shows architecture of the client transceiver module used for the trials. It supports reaches up to 10 km and is referred to as 100 GBASE-LR4. Also shown is the architecture extension to enable up to 40-km reach which is referred to as 100 GBASE-ER4. The two 4×25 G WDM optical interfaces are specified by the IEEE in [13]. The lane rate of the electrical interface is 10-Gb/s, determined by I/O rates in mainstream CMOS technologies used for the MAC (Media Access Controller) ICs (Integrated Circuits), which connects to the 100-Gb/s optical transceiver. The 10×10 G electrical interface is referred to as CAUI

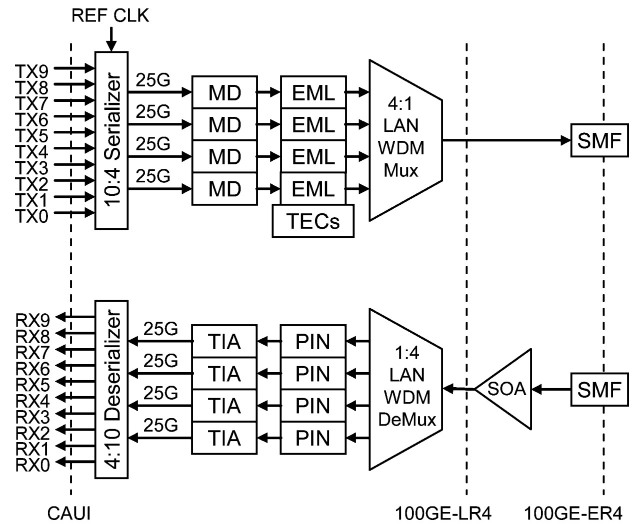

Fig. 3. 100 GBASE-LR4 and 100 GBASE-ER4 transceiver architecture.

(100-Gb/s Attachment Unit Interface) and is defined in [13]. The optical lane rate is 25-Gb/s and uses low cost NRZ (Non Return-to-Zero) modulation. The four lanes are wavelength division multiplexed (WDM) over a single fiber in each transmission direction. The exact optical lane grid is referred to as LAN WDM. It is located near the zero chromatic dispersion wavelength of standard SMF.

To translate between 10-Gb/s and 25-Gb/s lane rates requires 10:4 SerDes (Serializer and De-serializer) ICs, also referred to as gearbox ICs. The transmitter uses a quad MD (modulator driver) and quad EML (Electro-absorption Modulator Laser) with four different EML wavelengths combined in a WDM multiplexer (Mux). The receiver uses a WDM de-multiplexer (DeMux), quad PIN (p-intrinsic-n) photodiode, and quad TIA (Trans-Impedance Amplifier). A LA (Limiting Amplifier) function is required either in the TIA or SerDes ICs. For 40-km distances, the architecture uses an optional SOA (Semiconductor Optical Amplifier). 100-Gb/s SMF transceivers are packaged in the CFP module, as specified by the CFP MSA (Multi-Source Agreement) [14]. This is a pluggable form factor ($82 \times 145 \times 13.6$ mm) with SMF optical connectors in the front. To minimize cost, surface-mount components and PCB (Printed Circuit Board) transmission-line RF interconnect is used. First-generation transceivers use discrete optical components connected with fiber.

III. Results of Field Trial

The wavelength of the 112-Gb/s DP-QPSK signal is set at 1547.72 nm. The fiber used in the trial is in Dallas, Texas, area. Fiber span losses have a range of 18.3 dB to 20.2 dB with an averaged loss of 19.8 dB per span. The mean DGD (Differential Group Delay) per span has a range of 0.12 ps to 1.2 ps. The total mean DGD contributed by the transmission fiber is 3.2 ps. For a channel launch power of 0 dBm, the measured OSNR after 1 520 km transmission was 20.7 dB. IP packet throughput is measured at the 10 GE test set as shown in Fig. 1.

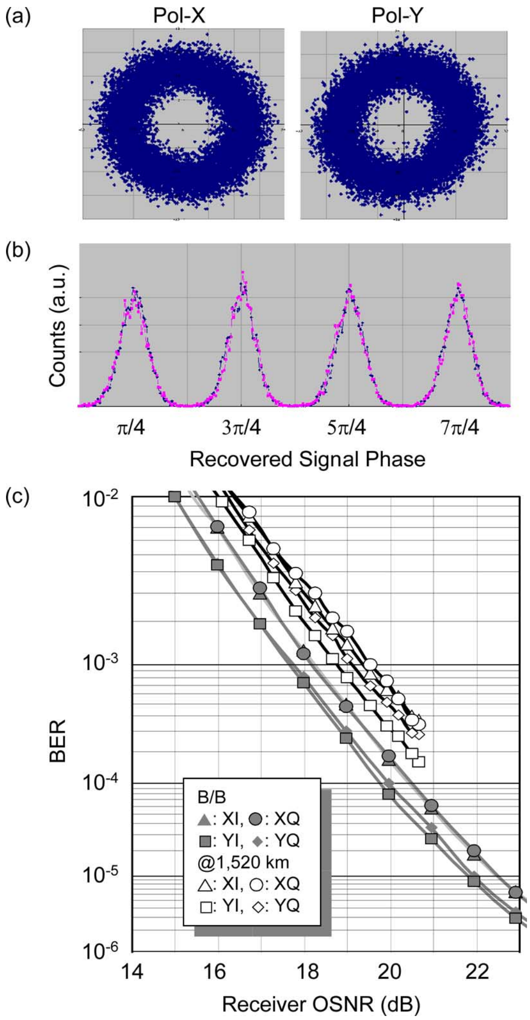

Fig. 4. Results of the trial—transport part: received phases of optical signal before digital signal processing (a), that after digital signal processing (b), and BER of the 112-Gb/s DP-QPSK transmitted signal (c).

The major trial results are shown in Figs. 4 and 5. The received DP-QPSK constellations after polarization demultiplexing based on the constant modulus algorithm are shown in Fig. 4(a). The recovered phase distributions after digital signal processing are shown in Fig. 4(b) (the blue curve is for Pol-X and the red one for Pol-Y). In Fig. 4(c), the BER of I and Q data streams of each polarization measured before FEC are plotted versus OSNR. The measured OSNR variation to achieve the same BER among four individual data streams is 0.7 dB. The curves with shaded markers in Fig. 4(c) indicate the back-to-back results serving as references. As shown in Fig. 4(c), BER less than 10^{-3} is achieved after 1 520-km transmission that indicates an error-free post-FEC operation. A comparison with the back-to-back results shows that the transmission penalty is less than 2 dB. Continuous error-free transmission was achieved by using FEC with an approximate 2 dB margin remaining.

Real time native IP traffic transport is characterized by measuring the packet flow statistics. The packet throughput of the 10 GE packet flow is measured with the 10 GE test set. The packet throughput has been measured with two types of the CFPs used in the trial. Each measurement lasts for about ten minutes and each set of data is averaged over three sets of raw data. The results are shown in Fig. 5(a). The packet size used in the trial is 1 500 bytes. The total number of packets sent in each measurement is about 500 millions. The packet throughput was 99.999997% for both CFPs (a better than expected result for prototype next-generation equipment). During the trial the video signal did not experience any degradation (see Fig. 5(b)).

(a) **Averaged Packet Throughput**

CFP Type	Finisar 100GBASE-LR4	NEC 100GBASE-SR10
Packet Size (Byte)	1500	1500
Packet Rate (P/s)	818062	818062
Total Packets Sent	496201353	496757867
Throughput	**99.999997%**	**99.999997%**

(b) **Decoded video signal carried by 100G IP packets**

Fig. 5. Results of the trial—packet part: the averaged IP packet throughput (a) and received video signal carried over by the end-to-end native IP data 100 G transport system (b).

IV. Conclusion

This field trial shows the feasibility of interoperability between multi-suppliers' equipment for 100 G transport. To the best of our knowledge, we have realized the first trial of end-to-end native IP data 100 G single carrier coherent detection transport on field deployed fiber over a long haul distance. Key elements in this trial included a 112-Gb/s DP-QPSK transponder with real-time digital signal processing, 100 GE router cards, 100 GBASE-LR4 CFP interfaces, and 1520-km reach-distance. This field trial, which fully emulated a practical near-term deployment scenario, has confirmed that all key elements needed for deployment of 100-Gb/s Ethernet technology are maturing.

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