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Design and performance evaluation of PEA IP over DWDM core networks

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Abstract

This work demonstrates the design and performance evaluation of an IP over DWDM network of the PEA (Provincial Electricity Authority) in the stage of the transforming from a conventional network to a full DWDM. The most significant parameters taken into account for performance evaluation of a DWDM network are optical signal to noise ratio (OSNR) and bit error rate (BER). This study presents an advanced modulation technique for coherent polarization-multiplexed differential quadrature phase shift keying (CP-DQPSK) with Enhanced - FEC coding to improve OSNR and BER for longer distance transport of 100GE traffic without signal regeneration. The simulation results show that the coherent DQPSK offer approximately 4dB improvement in OSNR sensitivity compared to non-coherent DQPSK. The 10GE LAN PHY service and 100GE LAN PHY service with unrepeated testing have been reported for the test distances, 431.60 km and 350.99 km, with OSNR at destination 13 dB and 14 dB, and wavelength service availability of [illegible]7 % and 99.9999 %, respectively.

Keywords: PEA, IP over DWDM, OSNR, BER, CP-DQPSK, FEC

1. Introduction

The Provincial Electricity Authority (PEA), one of the state enterprises, has operated its [illegible] IT system covering the entire country for more than three decades. The system has not only served activities and operations of the organization but also provided the services to the private sector and other organizations. PEA has been running a variety of IT and communication technology systems, ranging from small in-house developed systems to large enterprise wide systems including extensive use of optical fiber throughout the country for telecommunication and data communication purposes [1]. There are a large number of vital operations for co[illegible] purposes (e.g., new video conferences, SAP, GIS [illegible] SCASA/DMS, smart grids, and cloud computing, among others) which is a significant key for continuous growth of IP traffic. The architecture of today's IP and transport core networks are strained by the need to transport terabits of traffic with stringent latency and reliability constraints. Furthermore, as the price per bit for equipment decreases with the present and future technology, there must be lower capital and operational cost than in the past [2-3]. The bandwidth requirements for those services need optical technologies for high capacity. This is certainly achieved with Dense Wavelength Division Multiplexing (DWDM) technology in which the multiple optical signals are each assigned a unique wavelength and then they are multiplexed into a single fiber core.

In this paper, we evaluate a real IP over DWDM network (PEA DWDM) with 227 physical nodes and more than 1,000 physical links covering all of Thailand (with the exceptions of Bangkok, Nonthaburi and Samut Prakran Provinces.). The challenges of design and performance evaluation of a large scale network are network costs and link availability to appropriately locate the physical nodes at the PEA office branches. The physical node location addresses of the PEA offices and electrical power substations vary in distance, from a few kilometers to many hundreds of kilometers. The topology of the PEA DWDM network is quite unique. Over distances of hundreds of kilometers, the physical links could not transport the 100GE LAN PHY without regeneration. One of our challenges is designing a network to transport the 100GE LAN PHY without regeneration.

There is a report giving experimental results of a DWDM transmission system that includes 70 channels on a 50 GHz grid. This uses a single carrier real time DSP implemented on an ASIC and real-time FEC performance. It also includes post-FEC measurements over 2000 km of uncompensated SMF on a commercial DWDM system [4]. Recently, DWDM transmission of coherent 8-ary PSK has been reported using PolMux-RZ-8PSK and single-ended digital coherent detection that demonstrates 8x114 Gbps DWDM transmission over 640 km of SSMF on a 25 GHz grid. This provides a record of spectral efficiency of 4.2 bit/s/Hz [5]. The demonstration in [6] studies a system at 10 Gbaud

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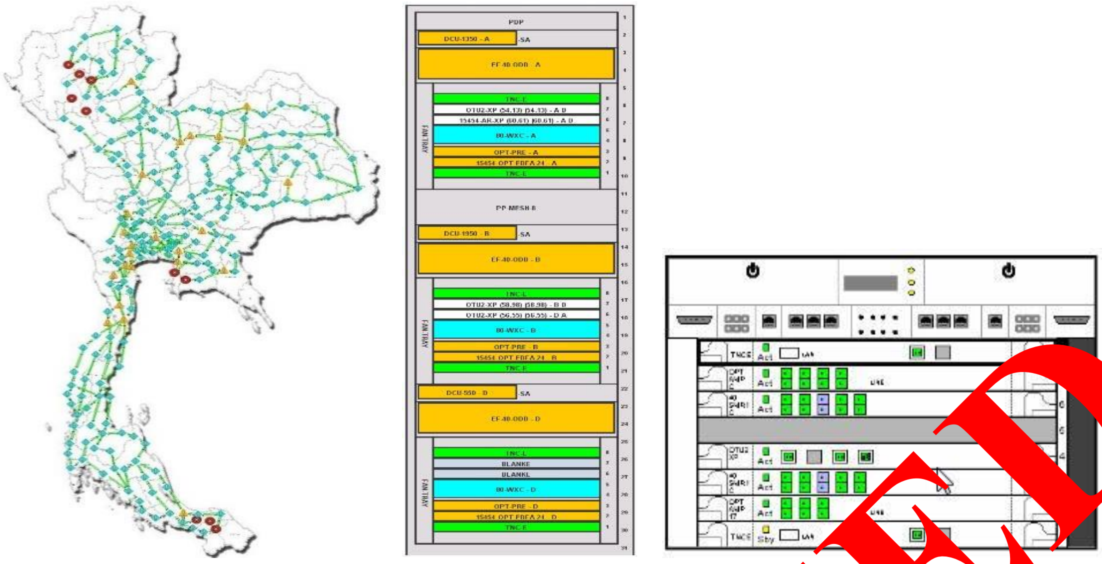


(a) Topology map (b) Rack equipment (c) Subrack eq[illegible]nt

Figure 1 Designed PEA's DWDM Network Topology and Equipment

shows that 8PSK with differential detection (D8PSK) has not been significantly explored for 100 GE. Although many current researchers are working on coherent systems, the various detection schemes show benefits for reducing the complexity of the receiver at a cost that is commercially acceptable in the short term. Polarization-Multiplexed QPSK has played a significant role as the format of choice for deploying DWDM systems with 100Gbps per channel commercial applications. Modulation formats including Optical Duobinary (ODB), Differential Phase Shift Keying (DPSK), Differential Quadrature Phase [illegible] Keying (DQPSK) and Polarization Multiplexed Quadr[illegible]e Phase Shift Keying (PM-QPSK) have been im[illegible]mented [illegible]n carrier networks. This also requires other factors [illegible] Dispersion (CD) and Polarizatio[illegible]de D[illegible]ion (PMD) tolerance. The benefits of [illegible]dditional per[illegible]nce and latency require that the CD to[illegible]e be further in[illegible]ased and the optical compensation [illegible]nit i[illegible]link can be eliminated. System designers must consid[illegible]ese requirements. Coherent polariza[illegible]ultiplexed d[illegible]ntial quadrature phase shift k[illegible]ing (CP-DQPSK) s[illegible]ows a significant modulation s[illegible] to m[illegible]et 100GE LAN PHY requirements. This is an impo[illegible]echnique [illegible]hat will be applied in the current study.

The [illegible] of this pa[illegible] as follows: Section 2 includes some back[illegible]und of the network model. Section 3 discusses [illegible] re[illegible] work. Methodology, design and imp[illegible]tation [illegible]ncluded in Section 4. In Sections 5 and 6, there [illegible] some descriptions of the experimental settings including [illegible] analyses of the experimental results. Finally, conclusions of the study are reported in Section 7.

2. Network model

The PEA DWDM network consists of 75 core and metro nodes, 1256 aggregation nodes, and 1755 physical links. The physical layer network is shown in Figure 1, where Figure 1(a) shows the topology map of the network, Figure 1(b) is shown the rack of equipment and the subrack of equipment is shown in Figure 1 (c). This is a schematic diagram of the complete network topology excluding complex details. The PEA DWDM core network consists of three typ[illegible]f nodes [7]. [illegible]DAM/Router node includes 24 n[illegible]es and installs the R[illegible]DM equipment as one unit of the [illegible] core router. The DWDM equipment connects to the IP Co[illegible]outer at 100 GE LAN PHY. It multiplexes the client sig[illegible]into the 100 GE LAN PHY channel using the Time-Divi[illegible]ultipl[illegible]ing (TDM) function.

3. Related works

[illegible]veral researchers have compared the performance of modulation formats and detection techniques. The various data rates define the proper modulation for the better network resource utilization. For example, at a low data rate such as 10 Gbps, the commonly used modulation is an on-off keying or NRZ modulation format. The higher data rates of 40/100 Gbps require advanced modulation schemes, such as differential quadrature phase shift keying (DQPSK), polarization multiplexed quadrature phase shift keying (PM-QPSK) and orthogonal quadrature phase shift keying (OQPSK) [8]. The spectral efficiency of the system can be obtained by polarization-multiplexed quadrature phase-shift keying (PM-QPSK) or quadrature amplitude modulation (PM-QAM) [9-11]. In [12], there is a confirmation that the conditions limiting the performance of long-haul broadband systems are the noise accumulated from amplified spontaneous emissions (ASE) and the generation of nonlinear interference (NLI) due to the Kerr effect in the fiber. Therefore, advanced modulation techniques including high spectral efficiency are required for long haul optical transmission systems and high transmission rates. Polarization-Multiplexed QPSK is an important technique that has been used in commercial DWDM systems with 10 Gbps per channel. Additionally, [13] showed that the influence of nonlinear effects in DWDM systems is decreased by the coherent detection optical channels. For optical fiber communication systems with high-speed (40 Gbps and greater), the FEC codes have also shown significant performance in order to provide the correction ability to compensate for serious transmission quality degradation. Referring trends in urban transmission systems, the requirement of the systems without repeaters has rapidly changed from 10 or 40 Gbps data rates to 100 Gbps. In the literature [14-17], there are reports of increasing 100G transmission for long distances without repeaters. It benefits from the powerful FEC coding to provide ultra-low loss and large effective area (A_{eff}) optical fiber. The optimized Raman/remote optically pumped amplifier (ROPA) architecture is also obtained.

We must focus on advanced modulation formats that include high spectral efficiency for serving long distance transmissions at high data rates. DQPSK shows superior performance. Therefore, it is suitable for higher order modulation techniques for optical transmission systems using IQ modulation [18-19].

A significant performance parameter of long-haul transmission channels is the optical signal to noise ratio (OSNR). Linear optical amplifiers are primarily used to reduce the OSNR. However, broadband noise is generated during the process of optical amplifier enhancement ASE.

The quality of optical signals is a significant key to the performance of optical communications including the matrices of the OSNR and the bit error rate (BER). An earlier study [20] examined various modulation formats for achieving a better BER. It also confirms that the data rates and quality of transmission improvement primarily depend on the modulation technique used.

In this paper, we focus on an advanced modulation technique, CP-DQPSK, and coherent detection with FEC to improve the data rate of a 100GE transponder card. We analyzed network performance using OSNR and BER values.

4. Methodology

4.1 Differential Quadrature Phase-Shift Keying (DQPSK)

4.1.1 Optical IQ modulator

An IQ modulator is used to provide multiple optical modulation using Mach-Zehnder modulators or phase modulators in parallel operation. A LiNbO3 interferometer [18, 20] presents an IQ modulator in a commercial transmission system. An IQ modulator has two parts, the in-phase arm (I) and a quadrature arm (Q). Referring to [20], there is phase difference of $\pi/2$ between the I and Q arms obtained from a simple optical phase modulator. The structure of an IQ modulator is shown in Figure 2(a). QPSK defines the absolute phase for each signal indicating the standard DQPSK phase types as 0°, 90°, -90° and 180° or -180°. The phase positions of QPSK are 45°, 135°, 225° and 315°.

Compared to BPSK, QPSK provides a doubled baud rate occupying the same bandwidth. Therefore, it is suitable for high data transmissions. The modulator providing the phase difference between two arms can be defined by the following expression:

$$\Delta\varphi_I(t) = \frac{u_I(t)}{v_\pi}\pi \cdot \Delta\varphi_Q(t) = \frac{u_I(t)}{v_\pi}\pi \quad (1)$$

where $\Delta\varphi_I(t)$ and $\Delta\varphi_Q(t)$ are the phases of the I and Q arms, respectively, $u_I(t)$ is applied voltage and v_π is the driving amplitude. The transfer function of an IQ modulator is:

$$\frac{E_{out}(t)}{E_{in}(t)} = \frac{1}{2}\cos\left(\frac{\Delta\varphi_I(t)}{2}\right) + j\frac{1}{2}\cos\left(\frac{\Delta\varphi_Q(t)}{2}\right) \quad (2)$$

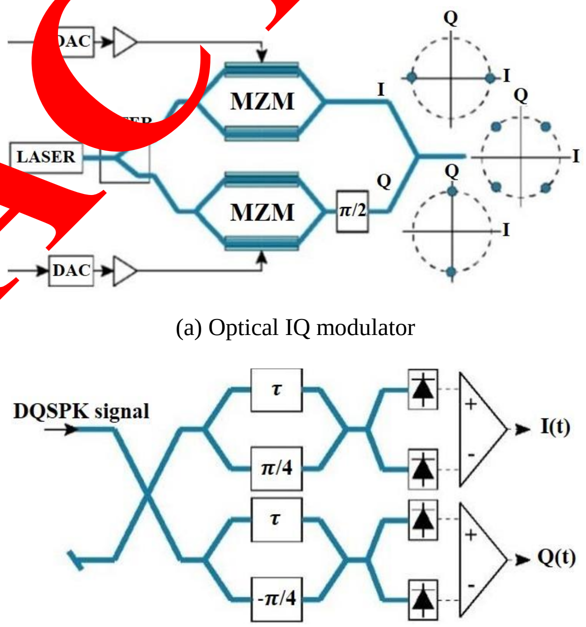
For an IQ modulator, the amplitude modulation as (3) and phase modulation as (4) are obtained from (1) and (2).

$$A_{IQM}(t) = \left|\frac{E_{out}(t)}{E_{in}(t)}\right| = \frac{1}{2}\sqrt{\cos^2\left(\frac{u_I(t)}{v_\pi}\pi\right) + \cos^2\left(\frac{u_Q(t)}{v_\pi}\pi\right)} \quad (3)$$

$$\varphi_{IQM}(t) = \arg\left[\cos^2\left(\frac{u_I(t)}{v_\pi}\pi\right) + \cos^2\left(\frac{u_Q(t)}{v_\pi}\pi\right)\right] \quad (4)$$

4.1.2 Optical IQ demodulator

Figure 2(b) shows the process of an optical IQ demodulator, including two 2DPSK receivers in parallel. An optical on bit delay line works with a [illegible] balanced photodiode in the two receivers. The data are differentially pre-coded at the transmitter end. The phase of the current transmitted signal can be compared to the phase of previously transmitted signal using restored phases provided by the IQ demodulator. Therefore, the phase of the previous signal must differ from that of the current signal. The phase difference between current and previous signal has four (4) cases: (1) Δθ = 0, (2) Δθ = π/2, (3) Δθ = -π/2, and (4) Δθ = π.



(a) Optical IQ modulator

(b) Optical IQ demodulator

Figure 2 Optical IQ modulator and demodulator

$$\sigma^2_{j,k} = \frac{\varphi^2_{j,k}\tau_{j,k}}{T_j}\left\{2_{P_1-P_2}\, h\exp\left(\frac{hT}{T_{j,k}}\right)\right\} \quad (5)$$

where

$$\varphi_{j,k} = \frac{2_{\gamma_j} P_{j,k}}{\alpha_j}, \tau_{j,k} = \frac{|D_j\Delta\lambda_j|}{\alpha_j}, \quad (6)$$

$$P_1 = \exp\left(-\frac{T_k}{\tau_{j,k}}\right) + \frac{T_k}{\tau_{j,k}} - 1, P_2 = \cosh\left(\frac{T_k}{\tau_{j,k}}\right) - 1 \quad (7)$$

where, α is an attenuation coefficient, D is a dispersion parameter, and γ is a nonlinear Kerr coefficient. T_k is the bit time of an OOK channel, $\Delta\lambda_j$ is the spectral separation of the DQPSK channel, and $P_{j,k}$ is the average power. The variance of the non-linear phase noise caused by cross-phase modulation (XPM) is obtained using the following expressions:

$$\sigma^2_{XMP} = \sum_{j=l}^{l} \sigma^2_{XMP,j} \quad (8)$$

$$\sigma^2_{XMP,j} = \sum_{k=1}^{w} c_k \sigma^2_{j,k} \quad (9)$$

where, C_k= 0 or 1, i.e., it represents whether OOK channel k is active or not, and w is expressed as the number of the wavelengths per channel. The phase-shift variance and ASE noise are expressed as:

$$\sigma^2_{ASE} = \frac{1}{\rho} \quad (10)$$

$$\rho = n.B_{ref} T.SNR_o \quad (11)$$

where, ρ is the SNR per symbol, n=2, B_{ref} represents reference bandwidth and T is the signal duration. The BER for a DQPSK is expressed as follows:

$$BER = \frac{3}{8} - \frac{\rho}{4}\exp^{-\rho} \sum_{m=1}^{\infty}\left[\frac{I_{m-1}}{2}\left(\frac{\rho}{2}\right) + \frac{I_{m+1}}{2}\left(\frac{\rho}{2}\right)\right] \times \frac{\sin\left(\frac{m\pi}{4}\right)}{m} \exp\left(-m^2\sigma_T^2/2\right) \quad (12)$$

$$\sigma^2_T = \sigma^2_{XMP} + \sigma^2_{ASE} \quad (13)$$

where, $I_k(x)$ indicates a k-[illegible] modified Bess[illegible] function, and σ_T^2 is the variance. The G[illegible]ian approximation is expressed as:

$$Q = \frac{\pi/4}{\sqrt{\frac{k}{2\rho}\left(\frac{\theta}{\sin\theta}\right) [illegible]}} \quad (14)$$

wh[illegible]ere, k [illegible]2 and the r[illegible]ainder of the expression is given

$$\theta = \frac{[illegible]}{k + 2\rho\sigma_T^2} \quad (15)$$

The net performance of the optical system is observed from the performance characteristics of each component (subsystem). To effectively design and implement a DWDM network, it is necessary to obtain the characteristics of the fiber links. The attenuation and dispersion characteristics of a fiber change during installation. They also define the maximum distance and bandwidth of the fiber. Measuring the optical parameters and testing for conformance are very important during the manufacture, installation and maintenance phases. Specifying a DWDM network usually requires determination of the BER and OSNR. Spectral analysis and link availability are also carefully considered.

OSNR shows a degree of impairment when an optical signal transits an optical transmission system that includes optical amplifiers. There are several methods to estimate the OSNR level in a coherent light transmission system. The spontaneous emission noise produced by the operation of optical amplifiers and the noise from the nonlinearity of optical fibers are used to calculate the actual OSNR value. The noise model of a coherent optical system can be expressed as:

$$\frac{1}{OSNR_{BER}} = \frac{1}{OSNR_{ASE}} + \frac{1}{OSNR_{NL}} \quad (16)$$

The terms in expression (16) indicate that a [illegible] line has linear and nonlinear [illegible]odes. The OSNR [illegible]ust be calculated for a wide range [illegible] inpu[illegible] signal [illegible]owers for the coherent optical syste[illegible] to eva[illegible] operati[illegible] modes. The influence of the pr[illegible]ucts of nonli[illegible] will increase while the input power i[illegible]ses. In this cas[illegible]e nonlinear effects in the fiber li[illegible]k gen[illegible] noise that can be expressed in the following form:

$$\frac{1}{OSNR_{NL}} = \eta.P^2 \quad (17)$$

whe[illegible] is [illegible]nlinear coefficient (assumed to be 20×10^{-3} mW[illegible]); $OSNR_{NL}$ is OSNR caused by nonlinear [illegible]ects. It must take into account the OSNR margin for [illegible]g optical systems. Expression (17) can take the following form:

$$OSNR = P_{in} - NF - 10\log(h\nu\Delta\nu) - 3 \quad (18)$$

4.2 Cisco Transport Planner (CTP)

Cisco Transport Planner software offers a useful tool to design optical networks with Cisco ONS 15454 MSTP products. This software requires network parameters as minimal information, such as site distance. CTP models the network generating a detailed BOM with ordering information. Designing optical networks demands verification of multiple network conditions, such as the optical budget limitations, platform architectural frameworks and restrictions. It provides a pattern to model and tests DWDM optical networks in a graphical design environment. The primary purpose of CTP is to validate and support design networks. CTP also provides searching capability for the best solution to a designed network using an optimization algorithm. A designed network must promise an optical budget and deal with overload cases to operate efficiently. An analysis of the optical budget and overload criteria evaluates the strength of the signal traversing the topology. If a design solution satisfies the constraints, it is a valid design. The optimization algorithms provide multiple solutions and verifies the constraints against those solutions. This requires that if the constraints are satisfied, the solution with the lowest *"cost-to-utilization ratio"* is selected as the optimal solution. Then, if the network design solution fails to satisfy all the constraints, we adjust the network parameters such as signal amplification and attenuation. To

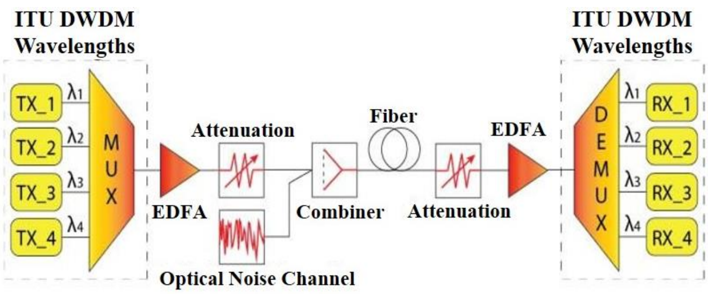


Figure 3 Block scheme of 4-channel DWDM

do a DWDM network design, in general, we enter the following parameters into the CTP [7]:

(1) The topology of the network: ring, linear or meshed.

(2) The number of network nodes.

(3) The distance between the nodes, the type of fiber linking the nodes, the losses for each span and the required End of Life (EOL) margin as per customer requirements.

(4) Service demands including the service type, the protection type and the number of channels between nodes.

(5) The type of equipment used at each node.

5. Experimental setup

DQPSK modulation was evaluated in three (3) scenarios:

(1) Using an IQ modulator in a 4-channel DWDM system, we used OptSim software to evaluate the performance.

(2) Using CTP software to design a DWDM netwo[illegible] with a 100GE CP-DQPSK transponder with FEC/EFE[illegible] and HG-FEC.

(3) Simulation to compare the OSNR values of coherent and non-coherent DQPSK.

5.1 Evaluate DQPSK modulation with [illegible] mod[illegible]

A. Simulation model description

Figure 3 shows the ex[illegible] simulation [illegible]del. The simulation scheme is [illegible]onstru[illegible] following a typical DWDM architectur[illegible] There are [illegible] DWDM channels (TX_1, TX_2, T[illegible]_3 and TX_4). [illegible] channel central frequencies an[illegible] spacings between adjacent channels are implemented [illegible] ITU-T G.694.1 recommendations. Channel spacing [illegible]fined as [illegible] GHz or 0.4 nm. Table 1 shows [illegible]nominal [illegible]el frequencies. The characteristics of the si[illegible]tion mod[illegible] also listed in Table 2. DWDM [illegible]nnels a[illegible] constructe[illegible] using a wavelength multiplexer [illegible] waveguide grating (AWG). The non[illegible]rity coefficient of an optical fiber is defined as 10 W[illegible] to observe the robustness of DWDM system.

B. Transm[illegible]tter description

An IQ transmitter includes two pseudorandom binary sequence (PRBS) generators PRBS_I and PRBS_Q, generating data at a 20 Gbps data rate. The two data sequences were pre-coded by the DQPSK conforming to DQPSK format. Then the pre-coded data are fed into NRZ modulator drivers and filtered with an electrical Bessel filter. The signal is modulated by an optical carrier. Figure 4(a) shows the modulator structures – NRZ-DQPSK. The description of an optical IQ modulator using NRZ-DQPSK is described in Section 4.

Table 1 Nominal channel freq[illegible]encies [illegible] a 4-channel DWDM

Channel	Nominal channel frequency (T[illegible]z)	Nomi[illegible]hanne[illegible] wavelen[illegible]m)
1	192.9[illegible]	1553.7[illegible]3
2	193.00	15[illegible].3288
3	[illegible]93.05	1[illegible]52.9264
4	[illegible]93.10	1553.5243

Table 2 Parameters of [illegible]hannel DWDM

Inp[illegible] EDFA optical power	12 dBm
Fi[illegible]r distance	100 km
F[illegible]r attenuation	0.2 dB/km
F[illegible]dispersion	16 ps/nm/km
No[illegible]rity co[illegible]fficient	10 $W^{-1}km^{-1}$
Output [illegible] optical power	20 dBm
Noise spectral density	1.5 dB

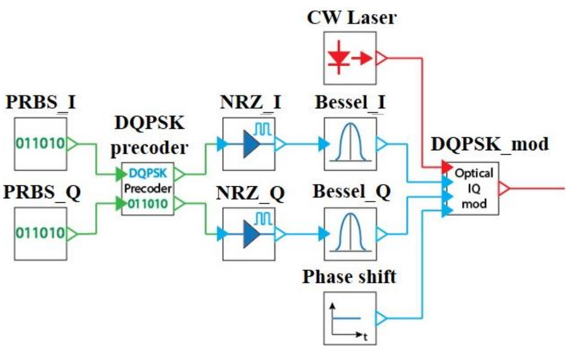
C. Re[illegible]eivers description

The received signal is separated into I and Q sequences. Then, they are fed through an optical one-bit delay line with a balanced photodiode – a 2DPSK demodulator/detector. Bessel filters are selected to filter the converted signal. Figure 4(b) shows the structure of a receiver with an IQ demodulator.

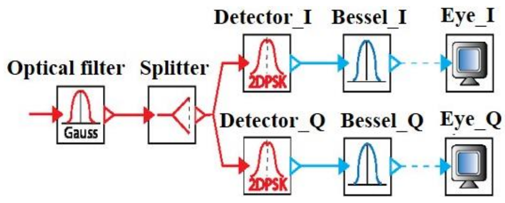
5.2 CTP software design the DWDM network

Using the CTP, the network topology, traffic client interfaces, working and protection paths, fiber types, fiber losses, and EOL margin are mapped according to the PEA's network requirements. All required parameters are encoded into the design tool. The topology type of the network is meshed because we require some specific working and protection paths. The types of equipment used at each node are specified in [7]. It is matched with PEA's network requirement at each node. The type of fiber connecting the nodes, the losses for each span (e.g., fiber type, total and span loss, among others), and the distances separating the nodes are specified in Table 3.

The required End of Life (EOL) margin per customer is a 3dB EOL aging loss. All ducts as service demands including the service type, the protection type and the number of channels between nodes (i.e., 40-Channel P2P 10GE or 100GE). In the initial design, all ROADM node builds support a full 40-channel 10GE and 100GE point-to-point demand. However, for this design, a transponder card is proposed based on a Traffic Matrix Demand and Lambda Connectivity. The network topology includes 54 ROADM and 173 ILA nodes are shown in Figure 1(a).

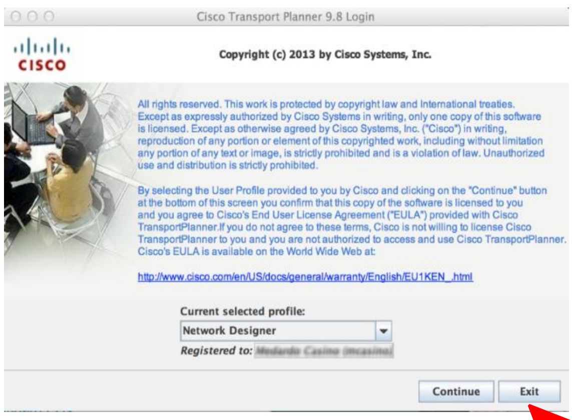


(a) Transmitter

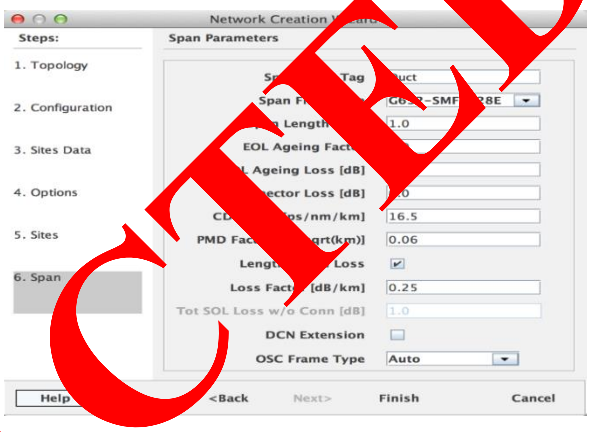


(b) Receiver

Figure 4 NRZ-DQPSK



(a) Starting the program



(b) Create a network with a wizard

Figure 5 CTP program for network design

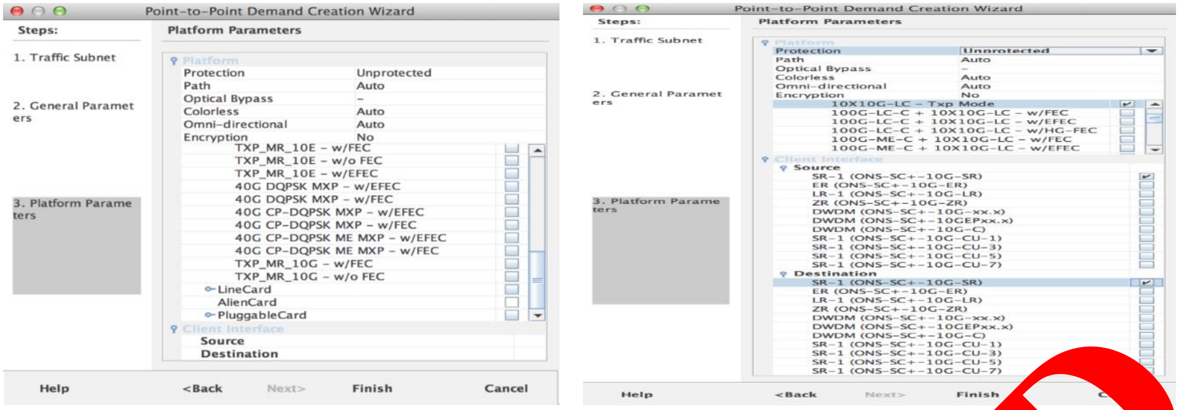
Table 3 PEA optical fiber infrastructure parameters

Parameters	Values
Splice Loss	0.15 dB/Point
Connector Loss	0.40 dB/Point
G.652 Attenuation	0.25 dB/km at 1550 nm
G.655 Attenuation	0.25 dB/km at 1550 nm
G.652 Chromatic Dispersion(CD) Coefficient	20 $ps\ (nm \times km)$
G.655 Chromatic Dispersion(CD) Coefficient	6 $ps\ (nm \times km)$
G.652 Polarized Mode Dispersion (PMD) Coefficient	0.2 $ps\ /(km)^{1/2}$
G.655 Polarized Mode Dispersion (PMD) Coefficient	0.5 $ps\ /(km)^{1/2}$
Operation Margin for each span	≥ 3 dB

We need to run the CTP software platform using a wizard to create network topology. Figure 5(a) shows the startup of CTP including the CTP version, copyright information and the network designer profile. In the next step, we create the topology (e.g., mesh, ring, linear), configure the node details (e.g., node type ROADM, ILA). Then, we set the span parameters (optical fiber cable parameters) as shown in Figure 5(b).

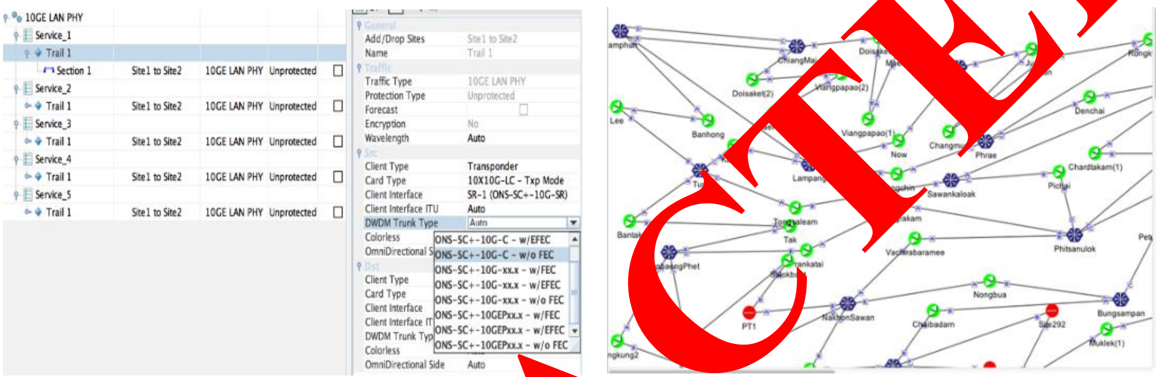
In Figure 5(b), the list of the fiber types allows selection of the fiber to be used in the design. Mixed fiber types cannot be defined using the wizard, but will have to be selected at the span level. A span with mixed fiber types has to be defined by inserting a Pass-Through Site as a demarcation point. PEA optical fiber infrastructure is mixed with ITU-T G.652D and ITU-T G.655. Some fiber types (e.g., dispersion shifted in C-band) will not be allowed to run in the analysis, so the file will have to be sent to the "mstp_network_design" alias. Measurement units for span length are based on the selections made at the project level. We define a multiplier factor to calculate the End-of-Life (EoL) fiber losses based on Start-of-Life (SoL) losses (e.g., 1.1 defines a 10% increment of loss between EoL and SoL). We also define an additive value to calculate the End-of-Life (EoL) fiber loss based on the Start-of-Life (SoL) loss (e.g., 1.0 defines a 1 dB increment of loss between EoL and SoL). The concentrated losses at the two edges of the span are taken into account in fiber distribution panels. The value set here is added at both edges of the span. Different values for the two edges can be defined at the span level later. If it is flagged, SoL losses for the span are calculated by multiplying the length and the loss factor. If it is not flagged, the SoL loss field becomes available to specify the SoL fiber loss. If it is flagged, DCN extension is assumed for management of the two nodes facing the span and OSC is not used.

In Figure 6(a), we can configure the traffic point-to-point demand by choosing the type of transponder cards (type of



(a) Configure transponder card (b) Create protection

Figure 6 Point-to-point demand creation



(a) Trail creation (b) Completed model

Figure 7 Service trail creation and analysis

card also defines the data rate, modula[illegible]on tech[illegible]ue, and error correction type, among other pa[illegible]s). I[illegible] 6(b) we configure the protection of tr[illegible]ffic. [illegible] DWDM Operations Guide se[illegible]tion on “C[illegible]Types” to identify the part numbers of [illegible]se transponde[illegible]s. The “_Y” suffix refers to [illegible]e [illegible]n supportin[illegible] Y-cable protection. Line Card re[illegible]ers to [illegible]M interfaces on the routers. A pluggabl[illegible]ard is when D[illegible] pluggable optics are used by the c[illegible]ent (no transponder[illegible] Alien Card allows you to model a [illegible]WD[illegible] device from a 3rd party.

We spec[illegible] of [illegible]ery traffic demand on this demand editor. T[illegible]where w[illegible]anually force the types of transp[illegible] pluggab[illegible]d o[illegible]er relevant parameters to the tra[illegible]fic de[illegible]ds as sho[illegible]n Figure 7 (a). The completed [illegible]el, rea[illegible] to be analyze by CTP, is shown in Figure 7(b). T[illegible] nodes (IAL, ROAMD) and fiber links.

5.3 Si[illegible]ion of coherent DQPSK and non-coherent DQPSK

The benefits of coherent CP-DQPSK in the simulation phase are verified using MATLAB, as shown in Figure 8. This illustrates that coherent DQPSK provides approximately 4 dB improvement over the OSNR sensitivity compared to non-coherent DQPSK.

6. Experimental results

In Section 5, we set up an experimental network with three (3) scenarios to analyze the performance of DQPSK modulation techniques in a DWDM system. They are (1) using an IQ modulator in a 4-channel DWDM system, (2) using CTP software to design the DWDM network with 100GE transponders, 10GE using CP-DQPSK implemented with FEC/EFEC and HG-FEC, and (3) comparing the OSNR values of coherent and non-coherent DQPSK.

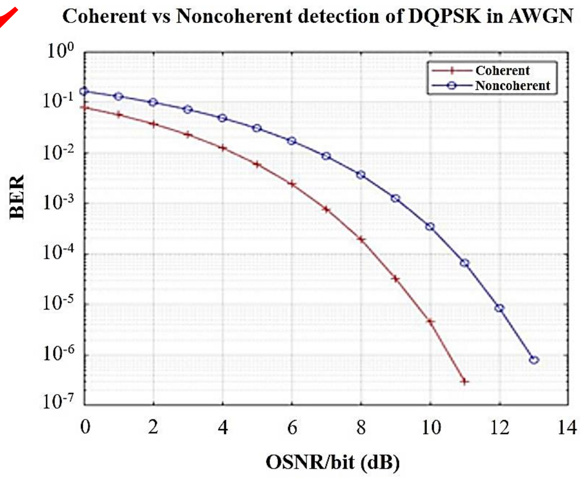
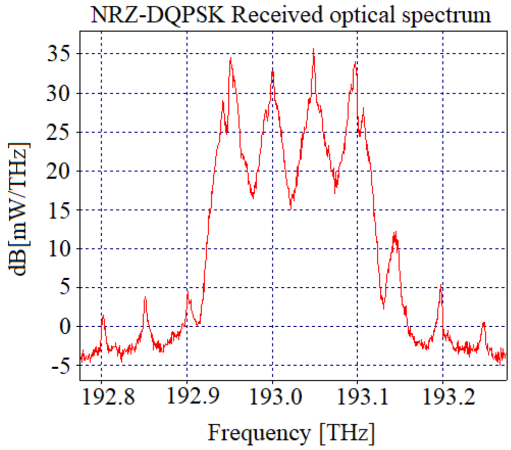
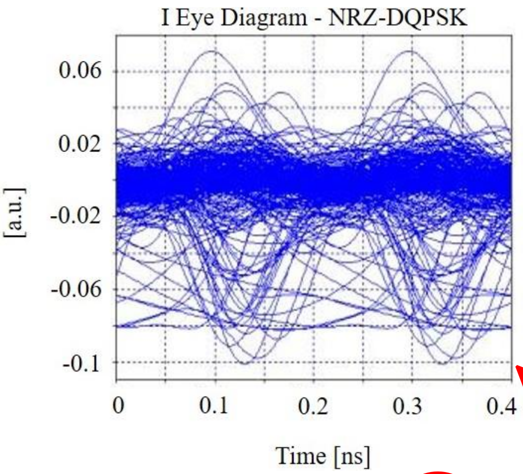


Figure 8 Comparison of coherent and non-coherent of DQPSK 100GE transponder in AWGN.

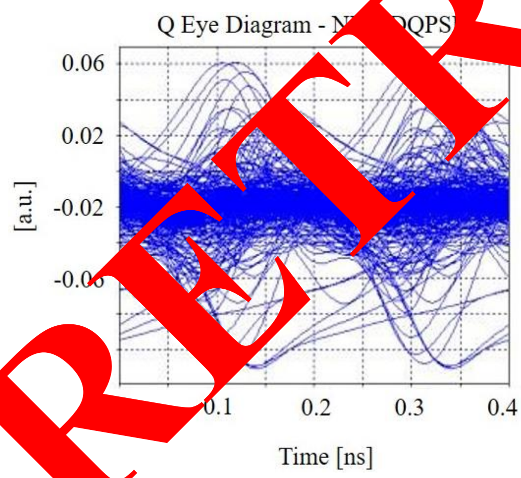
In the first scenario, the performance of the proposed DWDM system with DQPSK modulations is analyzed using eye diagrams. The performance of the 4-channel DWDM system with NRZ-DQPSK was analyzed to confirm that its



(a) Received optical spectrum



(b) I eye diagram of channel 1



(c) Q eye diagram of channel 1

Figure 9 Performance of a 4-channel DWDM system with NRZ-DQPSK

fiber non-linearity coefficient is 10 $W^{-1}km^{-1}$. The optical spectrum of received signals is shown in Figure 9(a). The new spectral components of NRZ-DQPSK are near 192.8 THz, 192.85 THz, 193.15 THz and 193.2 THz, peaking at approximately 5-8 dB. Eye diagrams are shown in Figure 9(b), (c) and BER values are extracted from the eye diagram displays for NRZ-DQPSK and are shown in Table 4.

The highest BER values of the NRZ-DQPSK signal range from $6.55e^{-14}$ to $2.67e^{-12}$, which is still acceptable for practical communication systems. These results confirm that the system with implementation of DQPSK modulation has increased performance of overall system.

Table 4 BER of DWDM NRZ-DQPSK (4-channel)

Channel	BER of NRZ-DQPSK	
	I	Q
1	$4.21e^{-14}$	$2.67e^{-12}$
2	$8.75e^{-12}$	$5.97e^{-12}$
4	$6.55e^{-14}$	[illegible]
4	$2.43e^{-13}$	5.20[illegible]

In the second scenario, we use the [illegible] to design [illegible] network topology, traffic client [illegible]terfaces, [illegible]king and protection paths, fiber types, fiber losses and [illegible] margin. They are mapped accor[illegible] to the PEA's [illegible] Network requirements as described in [illegible].

The optical summ[illegible] is sh[illegible] in Table[illegible] 5 and 6. The link availability is also shown in [illegible] Table 7. The optical summary shows [illegible] parameter details [illegible] performance of the wavelength service. [illegible] Tables 5 and 6, the point-to-point service between UBN_[illegible]C and NMA_ADDC is shown with the wavelength chan[illegible] carrying 10GE LAN PHY service (Table 5). The second wavelength channel carries 10[illegible]E LAN PHY service between NMA_ADDC and SMC (Ta[illegible] 6). The point-to-point service between UBN_ADDC and [illegible] ADDC is assigned to wavelength channel No. 37 (λ_{37}) 1[illegible] or the 192.30 THz C-band DWDM 50 GHz ITU-T grid. The transponder card used is the OTU2-XP with [illegible] function to enhance the BER and to improve perfo[illegible]ance over long distances, approximately 431.60 km, without regeneration. The second service is point-to-point between NMA_ADDC and SMC is assigned to wavelength channel No. 1 (λ_1) 1530.33 nm or 195.90 THz. The transponder card used is a 100G trunk type with the HG-FEC function to enhance the BER and to improve the long distance over approximately 350.99 km, without regeneration. The BER performance evaluation target is 10^{-15} for the first service with a BER of 0.01 for the second service. The OSNR values of the first service at the source node are 15.77 dB and 15.40 dB. For the second service at the source node, they are 15.90 dB and 16.35 dB. At the destination node, they are 13.34 dB and 13.14 dB for the first service and they are 14.44 dB and 14.80 dB for the second service. The performance of all OSNR values exceed the margin and the ITU-T G.692 recommendations. Therefore, the wavelength channel can carry the traffic and decode. For the protection type, the designed network uses fiber-switching with a link availability of 0.999987 or 99.9987 %, as shown in Table 7.

BER target capabilities of the channel's optical interface are 10^{-15} for an interface using forward error correction (FEC) and 10-12 for interfaces without FEC. SOL OSNR (dB) and EOL OSNR (dB) display the start of life and end of life average OSNR values at the receiver. The SOL OSNR margin (dB) and EOL OSNR margin (dB) display the SOL OSNR and EOL OSNR margin calculation. They differ from the OSNR value at a certain power of the working point of the receiver client and the working area boundary. The SOL RX (dBm) and EOL RX (dBm) display the SOL and EOL average received power at the destination node in dBm. SOL and EOL Power margins (dB) display the SOL and EOL

Table 5 Optical summary design results for UBN_ADDC to NMA_ADDC

Parameter	**Value/Results**
Protect Type	Fiber-Switched
SOL	OK
EOL	OK
SE	OK
Wavelength (No.)	1558.98 (O-37)
Src Tx Type	OTU2-XP – w/EFEC
Dst Tx Type	OTU2-XP – w/EFEC
Span [Km]	431.6
BER target	1.0E-15
	1.0E-15
SOL OSNR [dB]	15.77
	15.50
EOL OSNR [dB]	13.34
	13.14
SOL OSNR margin [dB]	6.30031
	5.91255
EOL OSNR margin [dB]	3.87031
	3.52445
SOL RX [dBm]	-13.70
	-13.46
Residual CD [ps/nm]	471.40
	1,021.40
CD Robustness [ps/nm]	[-350.0, 1300.0]
	[-350.0, 1300.0]

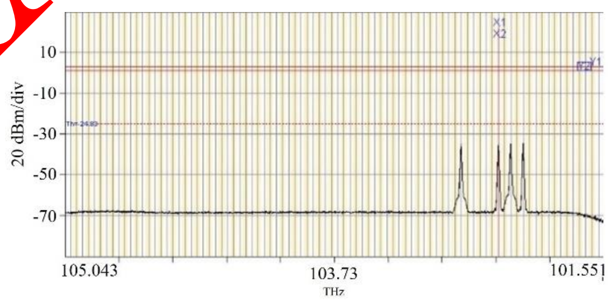
Table 6 Optical summary design results for NMA_ADDC to SMC

Parameter	**Value/Results**
Protect Type	Y-Cable
SOL	OK
EOL	OK
SE	OK
Wavelength (No.)	1530.33 (O-01)
Src Tx Type	100G, w/HG-FEC
Dst Tx Type	100G, w/HG-FEC
Span [Km]	350.99
BER target	0.01
	0.01
SOL OSNR [dB]	15.9[illegible]
	16.3[illegible]
EOL OSNR [dB]	14.44
	14.8
SOL OSNR margin [dB]	4.08572
	[illegible].62162
EOL OSNR margin [dB]	2.58879
	[illegible].95719
SOL RX [dBm]	[illegible]2
	-[illegible]1.82
Residual CD [ps/nm]	473.20
	523.21
CD Robustness [ps/nm]	[-37000.0, 37000.0]
	[-37000.0, 37000.0]

Table 7 Link availability results

Source Destination	**Serv. Circuit**	**DWDM Card**	**Protection**	**Link Availability**
NMA - HQ	Service_1	[illegible]LC	Y-Cable	0.999999
NMA - SMC	Service_2	100G	Y-Cable	0.999999
UDN - UBN	Service_3	OTU2-XP	Fiber-Switched	0.999987
UBN - NMA	Service_3	OTU2-XP	Fiber-Switched	0.999987

(a) Direction A



(b) Direction B

(c) Optical Spectrum Analyzer

Figure 10 Optical spectrum of 100 GE transponder experimental measurement power budget margin at the receiver in decibels. It is defined as the offset between the receiver working point and the BER curve. A positive value indicates no power problems. Residual CD (ps/nm) displays the total dispersion value of the circuit. This total is the difference between the sum of CD robustness of the source, destination transponders and the sum of fiber dispersion and dispersion compensation due to Dispersion compensation units (DCU) in the circuit. CD robustness (ps/nm) displays the chromatic dispersion robustness of the receiver.

The third scenario is a simulation comparing the OSNR values. The value of the result illustrates that coherent DQPSK provides an approximately 4 dB improvement in the OSNR sensitivity over that of the non-coherent DQPSK described in Section 5.

Finally, we can measure the spectrum of the 100 GE transponder by the use of OSA to verify the optical signal and noise. We measured it at the point on the demultiplexer card where the ROAMD site is located as shown in Figure 10. The measurement results show the spectrum of the three 100 GE transponders and one supervisory channel, each wavelength channel and OSNR value meets the required value according to ITU-T G.698.

7. Conclusions

At the beginning of this paper we demonstrate designing and performance evaluation of a PEA DWDM network. First, we investigated a 4-channel DWDM system including an optical IQ modulator using NRZ-DQPSK. The performance of conventional NRZ-DQPSK modulation has been improved by utilizing CP-DQPSK. This improvement provides a significant benefit for long haul transmission systems. The simulation results indicate the DQPSK robustness is sufficient to deal with fiber nonlinear effects on long haul DWDM optical systems.

Secondly, the designed network of the PEA DWDM network includes the environmental parameters, optical fiber and the network equipment of a DWDM system following the requirements of bandwidth. Physical constraints, including the DWDM equipment and optical fiber cable, have to be taken into account in the design phase. We observed the design based on the CTP program and found that there are three possible schemes: (1) using different modulation formats of the transponder card to affect the performance of the transporting the wavelength channel on the signal rate with 10GE and 100GE. The experimental results show that using a coherent CP-DQPSK modulation format is for high CD robustness, PMD robustness and the low OSNR. The results confirm that the system can correct the DCUs. This can work without highly precise fiber characterization and signals can be transmitted over long distance without Electrical-Optical-Electrical regeneration. (2) FEC, EFEC, and HG-FEC aim to improve the distance signals can be transmitted. A signal can travel through a wavelength channel, traversing the network without regeneration, especially a 100GE signal. (3) Protection type of Y-cable gives a higher availability more than from fiber switching.

Finally, the benefit of coherent CP-DQPSK in the simulation illustrates that coherent DQPSK provides approximately 4 dB OSNR over non-coherent DQPSK. Furthermore, the experimental results using OSA to verify OSNR value meet the required values according to ITU-T G.698.

8. Acknowledgements

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