40 Gb/s and 100 Gb/s Ultra Long Haul Submarine Systems

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Abstract: Optical modulation formats for 40Gb/s and 100Gb/s ultra-long haul transmission are described. The suitability of coherently detected dual-polarization phase shift keying (DP-PSK), with digital signal processing (DSP), for submarine applications at 2000km, 4000km and 8000km is examined.

1. INTRODUCTION

Most optical transmission is based on intensity modulation or differential phase modulation with incoherent detection. The electrical signal produced by incoherent detection is proportional to the square of the magnitude of the optical signal, losing the phase and polarization of the optical field. On the other hand, when O/E conversion is performed via coherent detection, amplitude, phase and polarization of the optical signal are transferred to the electronic domain in the receiver.

Many optical propagation impairments are linear functions on the phase of the optical electric field. The two dominant linear impairments are chromatic dispersion (CD) and polarization mode dispersion (PMD). When incoherent detection is used, compensation for linear impairments must be performed in the optical domain before O/E conversion. This involves tuning optical dispersion compensators or optical filter compensators, and adding extra amplifiers to accommodate associated loss. As optical transmission rates increase from 10Gb/s to 40Gb/s and beyond, this task becomes more arduous as performance sensitivity to linear impairments increases, shrinking the tolerance for error in optical compensation.

When coherent detection is used, the amplitude, phase and polarization of optical signals can be captured in the electronic domain. With this information, the linear channel transfer function of the transmission system can be extracted. By applying the inverse linear transfer function in the electronic domain via digital filtering, CD can be compensated without penalty. PMD and polarization dependant loss (PDL) can also be tracked and compensated in the same manner. All compensated linear impairments can be quantified and presented in the network management software allowing for in-service comprehensive optical performance monitoring for CD, PMD, and PDL [1]. Electronic compensation for linear fiber impairments is a key enabler for 40Gb/s propagation and beyond, as the tolerance to linear impairments is significantly reduced as line-rate increases.

The ability to access the phase of the optical signal also enables advanced modulation techniques, such as quaternary phase shift keying (QPSK), where symbols are encoded using both the amplitude and phase of the optical field to increase spectral efficiency. The ability to track polarization with coherent detection simplifies polarization de-multiplexing in the receiver, enabling dual-polarization (represented with prefix DP) modulation formats to further increase spectral efficiency.

Figure 1 compares the maximum achievable spectral efficiency and OSNR limited performance of several optical modulation formats at 40Gb/s and 100Gb/s. A significant increase in spectral efficiency can be achieved by using coherent detection with dual-polarization, multi-level modulation formats.

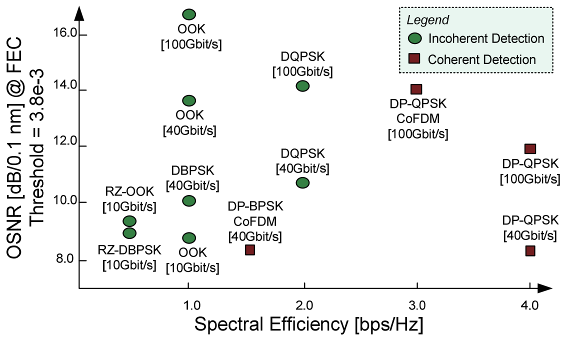

Figure 1. 40G/100G Modulation Comparison

In this work, we analyze three different coherent transceivers: the 40G DP-QPSK transceiver, the 40G DP-BPSK CoFDM transceiver, and the 100G DP-QPSK CoFDM transceiver.

In the 40G DP-QPSK transceiver, two polarizations are modulated with quaternary phase shift keying (QPSK) to achieve 2 bits per symbol per polarization. The net result is 46Gb/s of data with a 11.5 GHz baud rate.

The 40G DP-BPSK CoFDM transceiver substitutes QPSK for binary phase shift keying (BPSK) on each polarization. By reducing the number of bits per symbol, increased tolerance to phase noise is achieved, resulting in improved reach. This concept is illustrated in Figure 2. Since the baud rate is maintained at 11.5GHz, the data rate is reduced to 23Gb/s. To maintain an aggregate data rate of 46Gb/s, two DP-BPSK carriers are frequency division multiplexed (FDM) into one 50GHz optical channel. Frequency selectivity of the coherent receiver is used to de-multiplex the two DP-BPSK subcarriers and avoid ultra narrow optical filters. This process is referred to as coherent FDM (CoFDM). A comparison of a CoFDM channel with a 40G DP-QPSK single carrier channel is offered in Figure 3.

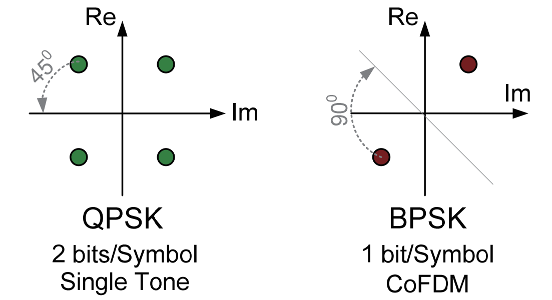

Figure 2. PSK Constellations

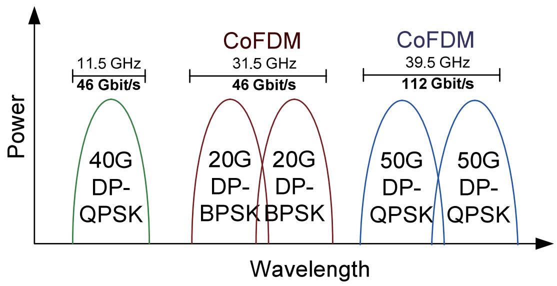

Figure 3. 40G/100G DP-PSK Spectral Occupancy

The 100G DP-QPSK CoFDM transceiver operates in a similar manner to the 40G DP-BPSK CoFDM transceiver. In this case, each CoFDM carrier is modulated with QPSK, and operates at a 14GHz baud rate to achieve 112Gb/s with two carriers in one 50GHz optical channel.

All three transceivers presented in this work use coherent detection and real-time digital signal processing (DSP). The limitations of the CD (±50,000 ps/nm), and PMD compensation (25ps mean DGD) are defined by the size of the digital filters in the DSP portion of the coherent receiver.

2. EXPERIMENTAL SETUP

Field trial analysis of both the 40G DP-QPSK transceiver and 40G DP-BPSK CoFDM transceiver has been demonstrated on the southern route of a Trans-Pacific submarine cable operated by Southern Cross Cables [2]. The southern link of the Southern Cross Cables Network (SCCN) traverses the Pacific in two sections: Segment D from Morro Bay, California to Kawaihae, Hawaii and Segment C from Kawaihae to Auckland, New Zealand [3]. Segment D propagation distance is 4135km with 60km repeater spacing and a 10nm amplifier bandwidth. Segment C propagation distance is 8002km with 45km repeater spacing and a 10nm amplifier bandwidth. Field trial analysis of the 100G DP-QPSK CoFDM transceiver has been performed on a 2000km Caribbean link with similar physical layer properties to the SCCN, a repeater spacing of approximately 55km, and a 17nm amplifier bandwidth.

The characteristics of the optical fiber used in both segments of the SCCN, and the Caribbean link are identical. The majority of fiber propagation occurs on a hybrid of large core fiber (LCF) and reduced slope fiber (RSF). Periodically there are compensating fiber (CMF) spans to create a dispersion managed cable. The dispersion managed cable is fully compensated near 1552 nm. The relevant properties of the optical fiber are presented in Table 1.

Fiber Property	Fiber Characteristics		
	LCF	RSF	CMF
Aeff [um^2]	72	52	80
Fiber Loss [dB/km]	0.21	0.2	0.19
Dispersion (1550nm) [ps/nm/km]	-3	-2.47	17.2
Dispersion Slope [ps/nm^2/km]	0.103	0.085	0.057

Table 1. SCCN Fiber Properties

For field trial analysis, the submarine line terminal equipment (SLTE) was added at each terminal of the subsea links. The SLTE included Nortel's Optical Multiservice Edge 6500 (OME 6500) and Common Photonic Layer (CPL) platforms. No changes were made to any subsea line. The OME 6500 shelf housed all 40G and 100G submarine transceivers as well as idler functionality. CPL provided optical amplification and wavelength multiplexing functionality. The OME 6500 and CPL were combined and coupled directly to the submarine cable plant. The SLTE configuration is given in Figure 4. No optical pre or post compensation was used for any operating wavelength.

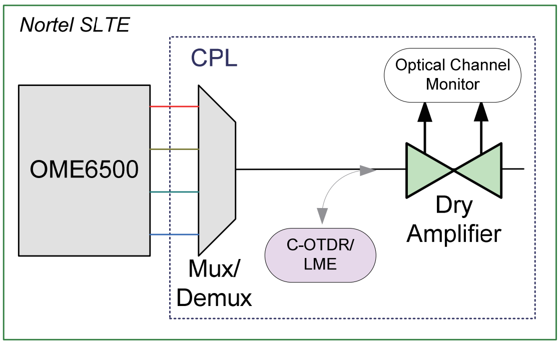

Figure 4. Nortel SLTE Configuration

3. PROPAGATION ANALYSIS

Measured performance, in terms of net system margin, is presented for the 100G DP-QPSK CoFDM transceiver at 2000km, the 40G DP-QPSK transceiver at 4000km, and the 40G DP-BPSK CoFDM transceiver at 8000km.

Before performance was characterized, in-service CD and PMD measurements were performed using the coherent receiver. The results of the CD measurements are given in Figure 5. The mean PMD was measured at 11ps for SCCN Segment C, 7ps for SCCN Segment D, and 3.5ps for the 2000km Caribbean link.

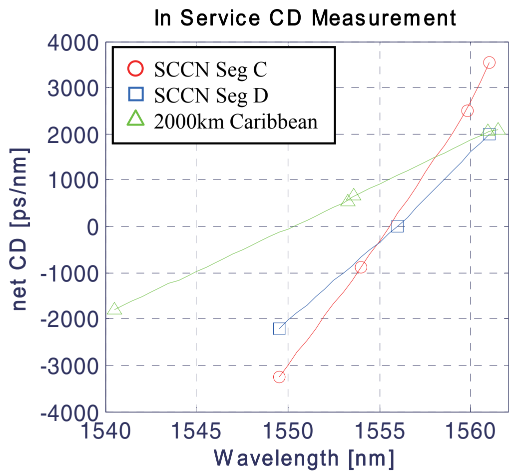

Figure 5. In-Service CD Measurements

To estimate operating margins with significant WDM impairments, a test channel was surrounded by as many as six

DP-PSK interfering channels on a 50GHz optical grid to provide WDM impairments. Receiver noise loading was used to measure net system margin in terms of OSNR. The grouping of channels was swept across the available bandwidth and the net system margin measurement was repeated in three test location: mid-band, red-band, and blue-band. Figure 6 shows an example of red-band testing on the 2000km Caribbean link. Figure 7 shows an example of blue-band testing on the 8000km SCCN Segment C. As seen in both figures, high power idle channels were required to consume unused power provided by the subsea amplifier, and control test channel launch powers.

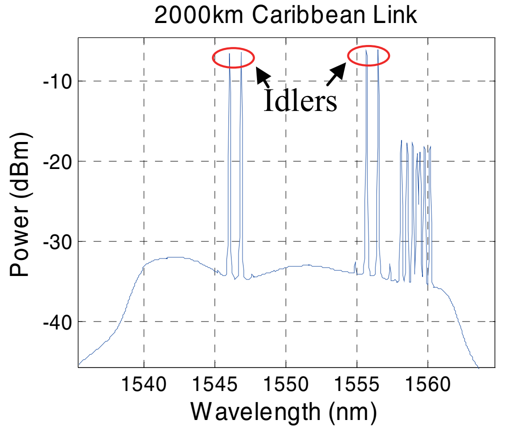

Figure 6. 2000km Caribbean Link Receive Spectrum – Red Band Testing

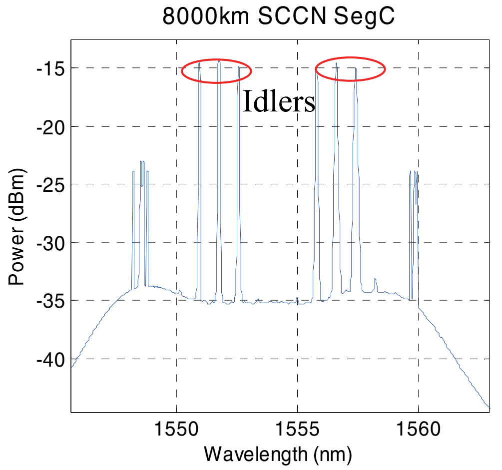

Figure 7. 8000km SCCN Segment C Receive Spectrum- Blue Band Testing

The results of the net system margin measurements are given in Figure 8. On all systems tested, the worst case performance was observed at the center of the operating bandwidth.

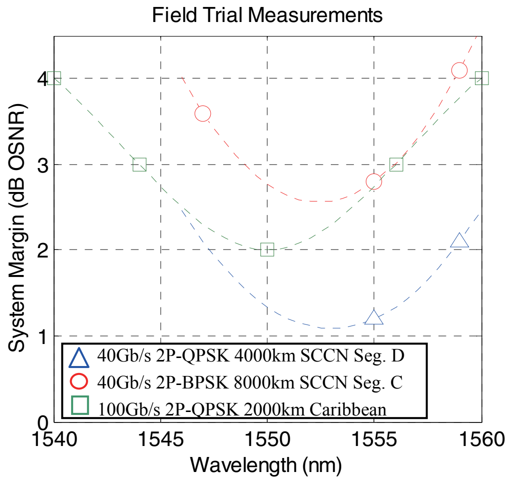

Figure 8. Measured Net System Margin for 40G/100G technology on Dark Fiber

By comparing the results in Figure 8 with single channel measurements, it was concluded that WDM fiber nonlinearities were the source of the performance variation across wavelength. Dispersion managed submarine systems have low chromatic dispersion near the center of the operating bandwidth, and accumulate large amounts of CD near the band extremities. At the point where the net system CD is 0ps/nm the system is said to be 100% compensated. This point occurs near 1555nm on the SCCN, and at 1552nm on the 2000km Caribbean link. When small amounts of CD are accumulated after long distances of fiber propagation, neighboring WDM signals interact strongly to create nonlinear phase noise via Cross Phase Modulation (XPM).

To provide further insight into this observation, a simulation exercise was performed on the SCCN Segment C. The goal of the simulation exercise was to quantify the performance penalty caused solely by XPM as a function of accumulated chromatic dispersion in the dispersion managed subsea cable. In the simulation, one 40G DP-BPSK CoFDM test channel was surrounded by 13 DP-BPSK CoFDM interfering channels at a launch power of -5 dBm per channel, per repeater. The optical channel separation was 50GHz. The simulation was repeated at many wavelengths across the available bandwidth. The simulations were compared with single channel simulations to separate single channel effects from WDM effects. All simulations were performed using our in-house split-step Fourier propagator. No external pre or post dispersion compensation was examined.

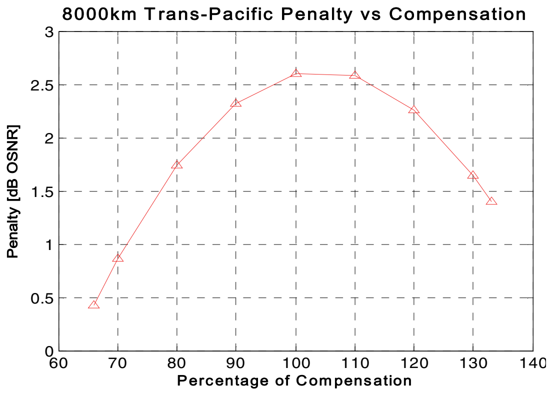

Figure 9. XPM Penalty Dependence on CD Compensation

Simulation results, shown in Figure 9, confirm that XPM is a significant impairment on the dispersion managed submarine system for coherent PSK with 50GHz optical channel spacing. In Figure 9, the net CD is represented as a percentage of chromatic dispersion compensation in the dispersion managed cable. More than 100% compensation produces net positive dispersion on a typical subsea cable (compensating fiber has positive dispersion). On a dispersion managed cable, the percentage compensation is determined by the operating wavelength due to slope mismatch between primary fiber and compensating fiber.

4. SUMMARY

Based on measurements presented in this work, the maximum 40G/100G capacity per fiber pair has been calculated for all links examined. This estimation is presented in Table 2. For comparison, an estimation of capacity for 10Gb/s technology on a 33GHz grid is also presented. To reach maximum capacity with acceptable margins on the SCCN segment D, 40G DP-BPSK CoFDM is required near the center of the band.

Link	Estimated Max. 10G Capacity [33GHz Grid]	Estimated Coherent 40G/100G Capacity [50GHz Grid]
4000km SCCN Seg D.	500 Gb/s	1520 Gb/s
8000km SCCN Seg C.	400 Gb/s	800 Gb/s
2000km Caribbean	800 Gb/s	4400 Gb/s

Table 2. Estimated Capacity per fiber pair

The dominant impairment on the submarine links examined was XPM. Dispersion managed cables maintain low chromatic dispersion for the entire propagation distance, which enhances the effects of XPM. New submarine cables could be optimized for multi-level PSK modulation formats by reducing the amount of optical compensation in the dispersion managed cable, or choosing optical fiber with high dispersion slopes.

5. REFERENCES

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[2] Nortel Networks and Southern Cross, “Southern Cross and Nortel Achieve 8,000km 40G Milestone on Submarine Cable”, http://www2.nortel.com/go/news, © August 12, 2009

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[4] S.J. Savory et al, “Transmission of 42.8 Gbit/s Polarization Multiplexed NRZ-QPSK over 6400km of Standard Fiber with no optical dispersion compensation”, In Proc OFC, Anaheim, Ca, March 2006, OTuA1