Recent advances and trends for digital coherent 100Gb/s and beyond technologies in submarine optical cable

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Outline

- Introduction
- 100G submarine cable systems
- Innovative technologies for beyond 100G systems
- Summary
Recent growth of international traffic demand has driven a drastic capacity enhancement of trans-oceanic submarine cable systems supported mostly by the break-through of digital coherent technologies with large spectral efficiency.

The introduction of 100G/s technology has stimulated the investment for new build systems as well as capacity upgrade of legacy systems as it can deliver large capacity in a more cost-effective way.

Recent advances and trends in submarine industry are presented and discussed based on our records and activities.
Technology Trend for 100G and Beyond

- **400G DP-16QAM**
- **400G/1T DP-QPSK Superchannel**
- **100G DP-QPSK**
  - 50GHz spacing
- **100G DP-BPSK**
  - [legacy cable]
  - 100GHz spacing

**Technologies**
- SD LDPC FEC
- Higher order modulation
- Nyquist/ Super-channels
- NL compensation
- Advanced Fiber
Outline

Introduction

100G submarine cable systems

Innovative technologies for beyond 100G systems

Summary
Components for Submarine Cable System

Submarine cable
Branching unit
Power feeding equipment

Cable Station

Installation & Maintenance

Repeatered System

Repeaterless System

Line terminal equipment
## Advanced Components for 100G Submarine System

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<th>Applied Key Technologies</th>
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<td>SLTE</td>
<td>- Multi-level modulation (BPSK, QPSK, 16QAM)</td>
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<tr>
<td></td>
<td>- Polarization multiplexing and demultiplexing</td>
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<td>- Digital coherent detection</td>
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<td>- Digital compensation for linear effect (CD, PMD)</td>
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<td>- Error Correction (LDPC based soft decision FEC)</td>
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<tr>
<td>Cable</td>
<td>- Low loss and Large Effective Area fiber</td>
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<td>- Uncompensated dispersion map</td>
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<tr>
<td>Repeater</td>
<td>- Er-doped fiber amplifier (same as 10G/40G system)</td>
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<td></td>
<td>- Increased output power</td>
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<td>- Flat and wide gain characteristics</td>
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Digital-Coherent Technology

<table>
<thead>
<tr>
<th>Modulation Format</th>
<th>Channel Spacing</th>
<th>SE [b/s/Hz]</th>
<th>Carriers</th>
<th>Optical Spectrum</th>
<th>Constellation Map</th>
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</thead>
<tbody>
<tr>
<td>100G DP-QPSK</td>
<td>50GHz</td>
<td>2</td>
<td>1</td>
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Coherent Receiver
- Unmatched sensitivity
- Hybrid Mixer Chip by PLC
- Tunable lasers
- Narrow linewidth

LSI digital signal processing
- Digital Adaptive Impairment Compensation
  - Polarization-mode dispersion
- Ultra-large Chromatic dispersion compensation
- Digital polarization demultiplexing (increased SE)
  - Advanced SD-FEC

DSP stages (100GbE)
- CDC
- Pol-Demux
- Phase recovery
- SD-FEC

Modulation Format | Channel Spacing | SE [b/s/Hz] | Carriers | Optical Spectrum | Constellation Map
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LDPC based Soft Decision FEC

First generation:
Reed-Solomon (RS) FEC

Second generation:
Concatenated hard-decision FEC

Third generation:
Soft-decision FEC with iterative decoding (Large NCG > 10dB)

Log-likelihood ratio (LLR) calculation

Converged LLRs
DP-QPSK: High Capacity and Long Reach

- Short-medium reach upgrades and transoceanic new builds
- Dual polarization + Quadrature phase keying provides high spectral efficiency [2 bit/Hz/s - 2.67 b/s/Hz]
- Ultra-large dispersion compensation capabilities in the DSP processor (up to 12,000km)

![Graph showing Q value (dB) vs. Distance (km) for uncompensated link with large core fiber.](image)
DP-BPSK: Robustness against Fiber Nonlinearity

- Ultimate performance for transoceanic 100G upgrades
- Dual polarization + Binary phase keying provides strongest tolerance to nonlinear effects in D+/D- submarine links

BPSK provides maximum robustness against phase noise
Fiber Technology

- **SMF** (0.5 dB/km)
- **DSF** (0.3 dB/km)
- **DMF** (0.2 dB/km)
- **D+** (0.16 dB/km)

Digital Coherent

- **EDFA**
- **Single channel**
- **DSF**
- **NZ-DSF** (0.2 dB/km)

Capacity/Reach

- **100G DWDM**
- **40G DWDM**
- **10G DWDM**
- **2.5G DWDM**

80s 10s 90s 00s 10s
Repeater Technology

1480nm Pumps

Analog

- OOK
- 5G~2.5G WDM
- 7dBm [5-10nm]
- 5dBm [2-5nm]

Digital Coherent

- DPSK
- 10G DWDM
- 12dBm [>20nm]
- 15dBm [>30nm]
- 18dBm [>35nm]
- 40G DWDM
- 100G DWDM
- DP-QPSK
- Nyquist QAM
- >20dBm [>40nm]

980nm Pumps

- 980nm Pumps
- 100G DWDM
- 400G/1T

90s 00s 10s 20s
Outline

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Summary
Key Technologies for Increasing Fiber Capacity

- Multi-level Modulation
- Spectral Efficiency
- Impairments Compensated
  - CD-PMD
  - SPM
  - XPM
- Fiber Cores
- Fiber Core Area [µm²]
- Repeater Bandwidth [nm]
- 100G DP-QPSK, SSMF, C-EDFA
Spectral Efficiency 1: Higher Order QAM

- Number of bit per symbol can be increased
- Baud-rate per channel can be relaxed
- Spectral efficiency can be increased
- Digital processing is required in transmitter

40 x 117.6 Gb/s PDM-16QAM OFDM Transmission over 10,181 km with Soft-Decision LDPC Coding and Nonlinearity Compensation

Error free transmission for 40 Channels

Q versus distance

OFC 2012, PDP5.C.4
Spectral Efficiency 2: Super-channels

Optical super-channels enable:
- 400G and beyond signals with practical electronics
- Reduced channel spacing with digital pulse shaping and other technologies

Next generation equipment will be based on both QAM and super-channel technologies.
Next Generation FEC

- **High performance LDPC**
  - Low Q limit < 5dB
  - Still large complexity

- **Adaptive overhead for on-demand performance**
  - Spectral efficiency is optimized to line OSNR
  - Latency can be reduced

1) 40 × 117.6 Gb/s PDM-16QAM OFDM Transmission over 10,181 km with Soft-Decision LDPC Coding and Nonlinearity Compensation. OFC 2012, PDP5.C.4
2) High Capacity Field Trials of 40.5 Tb/s for LH Distance of 1,822 km and 54.2 Tb/s for Regional Distance of 634 km, OFC 2013, PDP5.A.4
Compensation of Fiber Nonlinearity

Optical fiber nonlinearity limits the maximum Q factor after transmission.

Back-propagation algorithm can compensate the fiber nonlinearity.

Approx. 1dB improvement was obtained in 100Gb/s-10,000km transmission.

![Graph showing Q vs Power (dBm)]

<table>
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<tr>
<th>Power/channel (dBm)</th>
<th>Q (dB)</th>
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<tbody>
<tr>
<td>0.5</td>
<td>9</td>
</tr>
<tr>
<td>1</td>
<td>9.5</td>
</tr>
<tr>
<td>1.5</td>
<td>10</td>
</tr>
<tr>
<td>1.75</td>
<td>10.5</td>
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Optical “Forward” Propagation

Data In → Optical Link → 90 degree hybrid → Digital “Back” Propagation

Optical domain (real fiber) → Analog to Digital → DSP domain (virtual fiber)

Data Out

Tx

PD

Virtual Link

CDC

NLC

1dB
Experimental Tests on Dispersion managed systems with back-propagation NLC algorithm

- SMF+DCF link
- DMF link
- NZ-DSF link

1) Nonlinearity compensation using very-low complexity backward propagation in dispersion managed links. OFC2012, OTh3C4
2) 100G upgrade over legacy submarine dispersion-managed fiber link using fiber nonlinearity compensation and maximum-likelihood…, OFC2012, OTu2A
3) Low Complexity Nonlinearity Compensation for 100G DP-QPSK Transmission over Legacy NZ-DSF Link with OOK channels, ECOC2012, Mo1C5
Multi core fiber

- Capacity increase in proportion to the number of core.
- Multi core EDFA is required for practical deployment.

6,100km transmission over 7-core fiber

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Thanks to the advancement in digital coherent 100Gb/s technologies and the transmission optical fiber, the deployment of 100Gb/s is underway in many projects for trans-oceanic submarine cable systems.

The adoption of 100Gb/s DWDM in submarine networks significantly increases fiber capacity in a cost-effective way.

100Gb/s technologies can be also applied to legacy systems for efficient capacity upgrades.

Advanced key technologies, including FEC, nonlinearity compensation, digital multi-level modulation or optical super-channel, will enable larger capacity of submarine cable systems beyond 100Gb/s.
Empowered by Innovation

NEC