Submerged Plant Equipment
Lecture I

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Submerged Plant Equipment Characteristics

High performance:
• Ultra-long transmission distance up to 14,000 km!!
• High data capacity: 250 Tb/s across the Atlantic!

Space & Power Limitations:
• All functionality must fit inside an undersea body.
• Equipment must be powered from shore through the cable conductor.

Reliability for a 25 year lifetime in the undersea environment:
• Water-proof and pressure-stabilized body
• High reliability optics/electronics.

Deployment:
• Equipment must support shipboard storage, deployment, and retrieval for repairs.

Unique technology for a unique environment
Elements of an Undersea System

- **Undersea cable** connecting all terminals, BUs and (R)OADM
- **Repeaters** with amplifiers for all fiber pairs
- **BU**: Branching Units to connect Trunk/Branches
- **WMU**: Wavelength Management Units – (R)OADM
Outline

- Cable
- Repeaters
  - Amplification and gain equalization
  - Self-healing of a chain of amplifiers; gain tilt
  - Pump manifold and reliability
  - Line Monitoring and High Loss Loopbacks (HLLBs)
  - L-band amplification
  - The pressure vessel
- Branching Units
  - Fiber routing and optical switches - Why only one branch leg (3 port BUs)?
  - Electrical reconfiguration – Recovering from shunt faults
- Wavelength Management Units: (Reconfigurable) Optical Add Drop Multiplexing
- System Reliability
Undersea Fiber-Optic Cable

Cable Characteristics:

- **Fibers**: Benign environment for optical fibers
- **Strength**: For deployment and retrieval
- **Electrical**: Power for repeaters and network elements
- **Armoring**: Protection against external aggression

More on cable next by Marsha!
Repeater
The Repeater

- The modern repeater is an amplifier for the optical data signals on the fiber.
- Amplification for fiber pairs
  - both directions of traffic: east and west bound
- High performance design for ultra-long distance transmission
  - Forward pumping for low noise figure
  - Single stage design
- 25 year design life
  - High reliability components
  - Higher order pump manifold
- COTDR path for fault localization
**Amplification**

**Erbium Doped Fiber (EDF):**
- Amplification around 1550 nm
- Bandwidth around 4.5 THz (1529 – 1565 nm)
- Optical pumping near 980 nm
- Significant gain variation across the amplification bandwidth (gain shape)

**Gain Flattening:**
- Gain flattening filter (GFF) to minimize gain variation across the amplification band
  - GFF is typically a Fiber Bragg Grating (FBG)
  - FBG reflection tuned to follow the EDF shape
  - Optical isolators suppress reflections and avoid lasing of the amplifier
- 0.1 dB gain variation leads to 10 dB across 100 repeaters (ignoring spectral-hole burning – more later)
Gain Equalization

- EDF Shape
- Fiber Loss Shape
- Raman Gain
- Spectral-Hole Burning
Stimulated Raman Scattering

- Nonlinear scattering of light with optical phonons (lattice vibrations)
- A higher energy photon is scattered creating a phonon and lower energy photon

Look close to the “pump” wavelength
What happens to a broadband spectrum of WDM channels?
Intra-Band Raman Effect

Raman Gain Spectra

$\lambda_1 \quad \lambda_2 \quad \ldots$

Raman Gain Tilt

Signal Wavelengths
Raman Gain Tilt

- Power transfer from short to long wavelengths
- Amount of power transfer depends on
  - Repeater power level (nonlinear)
  - Fiber (effective area)
  - Span length

![Raman Gain Tilt Graph]

- Wavelength (nm)
- Raman gain (dB)
- Power levels: 16.2 dBm, 17.7 dBm, 19.2 dBm
Gain Equalization

• EDF Shape
• Fiber Loss Shape
• Raman Gain
• Spectral-Hole Burning
Spectral-Hole Burning

EDFAs tend to equalize power spectral density across the band

- Amplification depends on spectral loading of the EDFA
- Lower amplification where the power is high and higher amplification where the power is low
- Nonlinear effect
- Must be included when designing the gain management
- Tends to mitigate any residual gain error
- Tends limit effectiveness of pre-emphasis
Spectral Hole-Burning in a 5,000km Amplifier Chain

Raw Data

Intensity (dB/resBW)

Wavelength (nm)

1550 1554 1558 1562

Intensity (dB/resBW)

Wavelength (nm)

1550 1554 1558 1562

Difference Spectra

Intensity (dB)

Wavelength (nm)

1550 1554 1558 1562

Difference (dB)

Wavelength (nm)

1550 1554 1558 1562

~6.5nm

A-B

3dB

~6.5nm

A-B

Spectral Hole-Burning in WDM Systems*

Measured and simulated gain vs. wavelength using an installed 6,650km undersea cable system

\* A. N. Pilipetskii et al., OFC’03
Gain Management in System Assembly
**Repeater Design**

Main Contributors to Gain Variation
- EDF shape
- Fiber loss shape (see Marsha)
  - Fiber loss minimum near 1565 nm
- Intra-band Raman effect
- Spectral-hole burning

Gain Equalization for amplifier/span combination!
- Precise characterization and custom gain flattening filter for each system design
- Results in nominal amplifier design
Gain and Loss

What happens with manufacturing variations?
- Span loss is higher/lower than nominal
- EDFA gain is higher/lower than nominal

Repeaters run is constant pump power mode
- Output power set by pump power
- Nominal gain set by EDF length
  - Average inversion determines optical bandwidth

Spectral Tilt
- Deviation from nominal gain and/or loss leads to a spectral tilt (first order, also some shape)
Gain Management

1. Gain equalization per amplifier/span combination
   • Gain flattening filter (GFF) – Typically a Fiber Bragg Grating

2. Gain tilt equalization
   • Adjustable (during system assembly) loss point (Loss Build Out – LBO) every several spans

3. Second order gain shape correction to address systematic GFF shape error
   • Shape Correction Unit (custom gain equalization filter)
Gain Management During System Life
Loss Fault

- Added loss causes negative signal tilt (vs. wavelength)
- Tilt propagates (SHB mitigates)
- Add gain (repair repeater) if needed
Pump Fault in a Chain of Repeaters

- A pump fault causes local signal tilt variation
- Tilt cancelled by next repeater(s) (to first order)
Repeater Pump Manifold
Pump Sharing: Higher Reliability

2 FPs = 2 Sets of “2 pumping 2 Fibers”:

Traditional:
“Fiber Pair Independence” (One pump-pair per FP)
(2.6 FIT per FPs)

New “Pump Sharing / Farming” (Power shared over 2 FPs)
(0.001 FIT per FP)

Higher Reliability
Pump Sharing: SDM / More Fiber Pairs

Pump Lasers are combined and shared in sets of four

“4 pumping 4 Fibers”

“4 pumping 8 Fibers”:

Support for twice as many FPs, with higher reliability
Line Monitoring System
Line Monitoring System

- Provides Undersea Monitoring and Fault Detection
- All optical principle, no active components in the repeaters
- Two operating modes: HLLB mode and COTDR mode
In-Service Line Monitoring

Line Monitoring System Signals

- LMS tones on the short and long wavelength side of the data transmission band

Automated Signal Interpretation

- Automatic Signature Analysis detects changes in loop gain and extracts span loss and repeater output powers.
- Reported parameters include span length, span loss, repeater input and output power levels, and tilt

Active Line Monitoring Systems are also in use

- Input and output power levels detected with photodiodes and reported to shore via command channel

Example RPT for One Traffic Direction

<table>
<thead>
<tr>
<th>LME Source</th>
<th>MAPS</th>
<th>AmptL Name</th>
<th>Span Loss (dB)</th>
<th>P_{in} (dBm)</th>
<th>P_{out} (dBm)</th>
<th>Gain (dB)</th>
<th>Tilt (dB)</th>
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<tbody>
<tr>
<td>LMS #1</td>
<td></td>
<td>R01</td>
<td>7.6</td>
<td>9.8</td>
<td>19.8</td>
<td>10.1</td>
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<tr>
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<td>R02</td>
<td>9.6</td>
<td>10.2</td>
<td>19.7</td>
<td>9.5</td>
<td>-0.9</td>
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<td>R03</td>
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<tr>
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<td>R05</td>
<td>9.8</td>
<td>9.8</td>
<td>19.7</td>
<td>9.9</td>
<td>-1.3</td>
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<td>R06</td>
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<tr>
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<td>R07</td>
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<td>19.4</td>
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<tr>
<td>LMS #2</td>
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<td>R08</td>
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<td>R09</td>
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<td>LMS #2</td>
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<td>R10</td>
<td>9.6</td>
<td>9.4</td>
<td>19.5</td>
<td>10.0</td>
<td>0.0</td>
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<tr>
<td>LMS #1</td>
<td></td>
<td>R11</td>
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<td>9.7</td>
<td>19.7</td>
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<td>R12</td>
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<td>10.1</td>
<td>-0.9</td>
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</tbody>
</table>
Out-of-Service COTDR Measurements

Rayleigh Scattering
• Fiber reflects optical power back towards the transmitter (< -30 dB)

Optical Time Domain Reflectometry (OTDR)
• Send pulse, look for reflected signal

Coherent (Correlation) OTDR (COTDR)
• Send pulse (pattern) on outbound path, look for reflection on inbound path through High-Loss Loopback
• Works over multiple spans for >10,000 km
• Locate faults with <1km accuracy
**Erbium Doped Fiber (EDF):**

- Amplification in the C-band (1529 – 1565 nm)
- Amplification in the L-band (1570 – 1608 nm) (if no light in C-band)
C+L Architecture

- Nearly double the capacity per fiber pair
- Enables compact cable designs with fewer fiber pairs for the same capacity
Repeater Mechanical
**Pressure Vessel**

- Cylindrical shape
- Material: BeCu
  (also Stainless Steel or Titanium)
- Good to 8000m

### Feature Nominal Value

<table>
<thead>
<tr>
<th>Feature</th>
<th>Nominal Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall Length</td>
<td>498 cm (196 in.) w bend limiting boots</td>
</tr>
<tr>
<td>Diameter (largest)</td>
<td>33 cm (13 in)</td>
</tr>
<tr>
<td>Design</td>
<td>8000 m (~12000psi)</td>
</tr>
<tr>
<td>Depth/Pressure</td>
<td></td>
</tr>
<tr>
<td>Approximate Weight Body with cones</td>
<td>225 kg (493 lb)</td>
</tr>
</tbody>
</table>
Cable to Repeater Coupling
Millennia Joint
Repeater Mechanical Design – 16 FP Repeater

- Upper Tray
- Erbium Doped Amplifier Trays
- Optical Pump Unit
- High Loss Loopback Trays
- Dual Amplifier Quad Supports 4 Fiber Pairs
- Up to Four Dual Amp Quads in a Network

16 FP Repeater Network in Type 300 Repeater Housing
Loading Repeaters onto the Ship
Repeaters on Board Ship Ready for Deployment
Elements of an Undersea System

- **Undersea cable** connecting all terminals, BUs and (R)OADMs
- **Repeaters** with amplifiers for all fiber pairs
- **BU**: Branching Units to connect Trunk/Branches
- **WMU**: Wavelength Management Units – (R)OADM
Branching Unit – Fiber Routing

The branching unit (BU) enables connections other than simple point to point

The Branching Unit

• A 3-port device: Trunk, A1 and A2
• Enables the creation of a branch of the main trunk
• Provides fiber routing and optical connectivity between 3 points
• Enables later network expansion
The branching unit can also contain remote controlled high voltage relays to enable switching of the power path

Cable Fault Recovery and Isolation:

- Recover from shunt faults (see also lectures by Katsuji Yamaguchi)
- Maintain traffic on unaffected segments during a ship repair
- Optical command control from shore
Power Switching States in the eBU

Power Switching States for Normal System Operation

- **a. T-A1 State**
  - Trunk
  - Sea
  - Ground
  - A1
  - A2

- **b. Grounded State**
  - Trunk
  - Sea
  - Ground
  - A1
  - A2

- **c. T-A2 State**
  - Trunk
  - Sea
  - Ground
  - A1
  - A2

- **d. A1-A2 State**
  - Trunk
  - Sea
  - Ground
  - A1
  - A2

- **Allowed Transitions**

- **- Powering Electronics**

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Powering submarine systems also requires creative architectures.

Before / After Dual Powering Fault
• BUs with stubs can be inserted into a cable to enable future connectivity without cutting into the trunk cable

• Any number of trunk FPs can be accessed for connection to a branch state

• Stubs can also support later addition of WSS ROADM or Dry ROADM.
Today’s branching units also contain remote controlled optical switches for even more functionality.

User configurable remote fiber switching allows:

- Autonomous or/and manual fault recovery
- Isolating the branch for a repair or later network expansion
- Adding and/or re-routing traffic in a branch
Cross-Cable Architectures

Fiber Switched BUs can provide intra-cable connectivity.
• Use for fault recovery, or for capacity routing flexibility.

Increases overall network availability.
• Protect on a FP basis, or use ROADMs to prioritize spectrum.

Increases path length:
• Could adjust channel data rates to match available OSNR.
Why Only 3-Port BUs?

BU placement is typically optimized for overall cable length

- Lower cost
- Lower latency

There are additional marine considerations to best protect the BU

- Seafloor conditions

(4-Port BUs exist for special applications)
Optical Add Drop Multiplexing
Enhanced Connectivity options
Multiple DLS on a single fiber pair

Wavelength Re-use
Bandwidth on a trunk fiber pair can be used for multiple DLS
Components in an OADM Node include:

- Branching Unit
- OADM Unit:
  - Passive fixed filtering
  - Switchable filtering
  - Wavelength Selective Switch based filtering

Modular OADM options:

- OADM unit can be deployed when the branch is landed
- Simplified sparing (universal spare for BU)
- Repair operation does not affect express fiber pairs
Switched Filtering

East In

West Out

Bypass Option 3
Bypass Option 2
Bypass Option 1

East Trunk
Through Filter Set

East Add
Filter Set

West Add
Filter Set

West In

East Out

Broadband Drop

Input Power

Input Power

Input Power

Input Power

West Drop

East Drop

Input Power

Bypass
Option 3
Bypass Option 2
Bypass Option 1

West Trunk
Through Filter Set

East Add
Filter Set

West Trunk
Through Filter Set

Broadband Drop
The Wavelength Selective Switch (WSS) is a pixelated device that supports reconfigurable filtering

- Key specifications:
  - Grid-flexible channel plan with a fine granularity e.g. 6.25 GHz
  - Very steep filter edges
    30 dB transition in approximately 20 GHz
Branching Node Example: PSBU + WSS ROADM

- Bi-directional Branch Access
- WSS Filtered Add/Drop
- Automatic bypass switching provided by eBU
Reconfigurable Optical Add Drop Multiplexing

Wavelength Selective Switch based OADM nodes support

- In service, gridless capacity reallocation
- Inline dynamic gain equalization
- (Optical spectrum acquisition)
System Reliability
System Reliability

System Design Life is typically 25 years

Transmission affecting failures require ship intervention

• Costly
• Takes time

Design for reliability

• High reliability components
• Redundancy

Expected number of ship repairs due to intrinsic failures is in the range of 0-3 depending on system size and complexity
Failures in Time

Failure Rate

- A common measure for failure rate is FIT, defined as the number of failures in $10^9$ device hours (114,046 years).
- Use average failure rate $\lambda$
- Probability of failure is $P_{\text{fail}} = 1 - e^{-\lambda t_{\text{system}}}$, where $t_{\text{system}} = 25$ years
- Effective failure rate for redundant components ($n=2$ for 1x1)
  $$\lambda_{\text{effective}} = \frac{-\ln(1 - P_{\text{fail}}^n)}{t_{\text{system}}}$$
- Total FIT is the sum of all single points of failure (including effective FIT rate from redundancy)
  - Reliability: $R=1-P_{\text{fail}}$

110 FIT means 2.4% will fail in 25 years

### Failure rates for components of undersea repeaters

<table>
<thead>
<tr>
<th>Component type</th>
<th>FIT target (95% confidence)$^1$</th>
<th>Field value (if available)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pump Lasers</td>
<td>0.1—0.2</td>
<td>110 (2.6)</td>
</tr>
<tr>
<td>Discrete Optical Components</td>
<td>0.2</td>
<td>0.01</td>
</tr>
<tr>
<td>Splices</td>
<td>0.01—0.2</td>
<td></td>
</tr>
<tr>
<td>Integrated Circuits</td>
<td>0.2</td>
<td>0.15</td>
</tr>
<tr>
<td>Passive Electronics</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power Electronics</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total per Amplifier Pair$^2$</td>
<td>4.6</td>
<td></td>
</tr>
<tr>
<td>Repeater Mechanical Integrity</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Total for a Repeater containing 4 Amplifier Pairs</td>
<td>21.4</td>
<td></td>
</tr>
</tbody>
</table>

$^1$Confidence bound applies where acceleration of the key failure modes is possible.
$^2$Taking laser redundancy into account.

Ship Repairs

- Failures are Poisson distributed.
- The expectation value of the distribution is the number of ship repairs.
- For Poisson the expectation value corresponds to the failure rate

Example
- 100 Repeaters
- 4 Fiber Pairs

- 800 Pumps (110 FIT)
- 19 Pump failures in 25 years
- 4x4 pump redundancy: no repeater failure due to pump failure

- Repeater: 11 FIT
- Expected number of ship repairs in 25 years: 0.24

Example for Repeaters Only
External Aggression

Majority of cable failures are due to external events:

- Ship anchors
- Earthquakes and mud slides
- Abrasion

Good reasons to armor or bury cable near shore.
Summary

- Cable
- Repeaters
  - Amplification and gain equalization
  - Self-healing of a chain of amplifiers; gain tilt
  - Pump manifold and reliability
  - Line Monitoring and High Loss Loopbacks (HLLBs)
  - L-band amplification
  - The pressure vessel
- Branching Units
  - Fiber routing and optical switches
  - Electrical reconfiguration – Recovering from shunt faults
- Wavelength Management Units: (Reconfigurable) Optical Add Drop Multiplexing
- System Reliability
Thank You