

## **FAULT TOLERANT OPTICAL DESIGN FOR UNDERSEA SENSORS AND SCIENTIFIC OBSERVATION SYSTEMS IN HARSH UNDERSEA ENVIRONMENTS**

Lee Richardson, Alexey Turukhin, Earl Parsons, Robert Thomas, Patrick Corbett, Greg Wolter, Fakher Ayadi, Dmitriy Kovsh, Ekaterina Golovchenko, Stuart Abbott (TE SubCom); Philip Tennant, John Reardon (L3 Maripro) and Mike Mulvihill (University of Washington)  
Email: lrichardson@subcom.com

TE Subsea Communications, 250 Industrial Way West, Eatontown, NJ 07724, USA.

**Abstract:** In this paper we describe a novel optical architecture providing enhanced fault tolerance for a scientific observation system. The design was validated through laboratory experiments that demonstrate error-free transmission performance for the surviving portion of the network in the presence of multiple simultaneous node failures. This design has application to scientific sensor networks as well as node networks used for oil and gas exploration and production and where fault tolerance is especially important.

### **1. INTRODUCTION**

Distributed undersea scientific networks are an essential tool for future ocean science studies. Scientific networks such as NEPTUNE [1] and the Regional Scale Nodes (RSN) network [2, 3] can provide real-time data from scientific instruments located on the ocean floor. The RSN is a component of the National Science Foundation's (NSF's) Ocean Observatories Initiative (OOI). The construction and early operation of this northeast Pacific Ocean cabled ocean observatory is being lead by the University of Washington (UW).

These instruments are connected by submarine fiber optic links in a network that provides communication between the undersea instruments and the shore terminals. In contrast with traditional telecom systems, where deployment in high-risk areas are avoided by design, scientific networks are often located in harsh undersea environments and may be subjected to catastrophic environmental changes such as tsunami, earthquakes and hot vents. This aggressive environment can damage the nodes or the fibre optics link of

undersea sensor and scientific observation systems. It is imperative that the design of submarine sensor and scientific observation networks ensures connectivity between the surviving scientific nodes and the land-based observation station in the event of multiple faults in the system.

In this paper we describe a novel optical architecture providing enhanced fault tolerance for the RSN scientific observation system. The design is validated through laboratory experiments that demonstrate error-free performance for the surviving portion of the network in the presence of multiple simultaneous node failures. This design has application to other scientific sensor networks as well as node networks used for oil and gas exploration and production.

### **2. DESCRIPTION OF SYSTEM AND TESTBED**

The fully expanded RSN undersea scientific network might contain 12 undersea science nodes, 16 repeaters, and approximately 1680 km of undersea cable. The undersea science nodes will contain various scientific instruments that will

require bidirectional communication with the shore station. Commercially available optical transceivers will be located in the shore station and in the individual nodes. The system divides into a Northern Cable Line and a Southern Cable Line. Fig. 1 provides a schematic of the network.

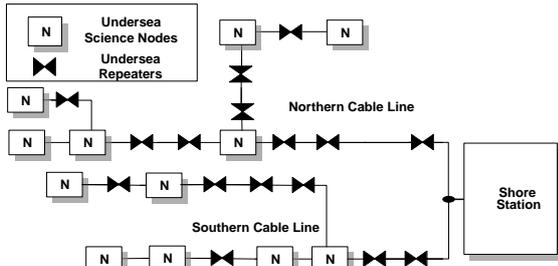


Fig. 1: Schematic of full RSN undersea scientific network.

Two test beds, each capable of supporting bi-directional transmission, were constructed to replicate the wet plant that is to be deployed in the network. Transmission experiments were performed using a combination of commercial transceiver modules for the representative measured channels and continuous wave (CW) tones to fully load the system. The fiber spans of both test beds were constructed from the fiber types specified in the system design. The lengths of the tested spans closely matched the lengths of the designed system spans, and the dispersion map of the test bed was designed to approximate the network dispersion map design.

Two test beds were constructed; one represented the Northern Cable Line and the other the Southern Cable Line. This work details the measurements performed on the Northern Cable Line though similar measurements with similar results were achieved with the Southern Cable Line.

The Northern Cable Line test bed consisted of 4 nodes and 7 repeaters connected to the Shore transmitter and receiver as shown in Fig. 2. Nodes N5a, N3a, N3b and N4a were emulated using passive optics, and nodes N3b and N4a, as well as the shore terminal, contained

commercial transceivers. The through-loss of the nodes was controlled by optical attenuators to replicate the expected loss of the deployed nodes. Nodes N3b and N4a were the only nodes monitored for performance. Additional loading was provided by CW tones that mimicked the traffic from nodes not present in the test bed.

To represent the full loading, beginning of life (BOL) conditions shown in Fig. 2, the shore terminal provided 24 wavelength channels ( $\lambda_s$ ), and nodes N3a, N3b, N4a, and N5a used 8  $\lambda_s$ , 4  $\lambda_s$ , 8  $\lambda_s$ , and 4  $\lambda_s$ , respectively. This configuration represents the fully deployed system at the beginning of its functional lifetime.

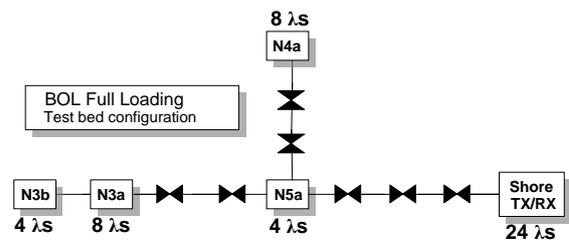


Fig. 2: Northern Cable Line test bed, beginning of life (BOL), full loading conditions.

Only a few nodes will be present in the system when initially deployed. With fewer nodes present there will be fewer optical channels, increasing the power per channel. Higher power per channel leads to stronger nonlinear effects on the data signal which could potentially degrade the performance. To verify the performance under these initial loading conditions, the test bed was modified by removing N4a, 4  $\lambda_s$  from N5a, and 4  $\lambda_s$  from N3a. Node 3a still had 4  $\lambda_s$  and N3b had 4  $\lambda_s$  as seen in Fig. 3.

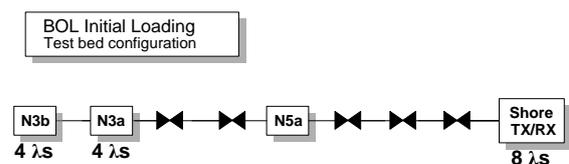


Fig. 3: Northern Cable Line test bed, beginning of life (BOL), initial loading conditions.

Over the life of the system, cable cut repairs as well as other impairments may degrade the system performance. To evaluate system performance under end of life (EOL) conditions, the fully loaded test bed was modified as shown in Fig. 4. Extra loss of 3 dB was inserted between N5a and N4a as well as between N5a and N3a as indicated in the figure. This extra loss represents the loss caused by a cable cut repair. In addition, the output power of the repeater closest to the shore station was decreased by 3 dB to represent further system impairment.

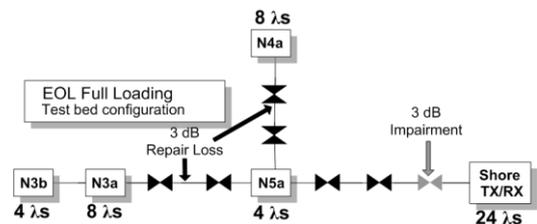


Fig. 4: Northern Cable Line test bed, end of life (EOL), full loading conditions.

### 3. TESTBED PERFORMANCE

The goal of the first set of transmission performance measurements was to verify the wet system design. The measurements were broken down into three parts: Beginning of Life (BOL) under initial loading conditions, BOL under full loading conditions and End of Life (EOL) under full loading conditions.

Performance is reported in terms of Q margin which is the difference between the measured Q-factor and the target Q-factor. For BOL conditions, the Pre-FEC Q target was 15.7 dB shore-to-node and 16.0 dB node-to-shore. For EOL conditions, the Q target was 12.3 dB in both directions. Table 1 details shore-to-node results while Table 2 includes the node-to-shore measurements. Measured values of pre-FEC Q-factors above 11.3 dB indicate post-FEC error-free transmission.

When the system is initially deployed, only a few scientific nodes will be populated. The first performance

measurements were carried out under these conditions as illustrated in Fig. 3. The transmit (Tx) and receive (Rx) spectra measured at the shore station are shown in Fig. 5. The performance results were recorded in Tables 1 and 2 under the BOL Initial Loading. Sufficient margin was observed for both measured channels in both directions.

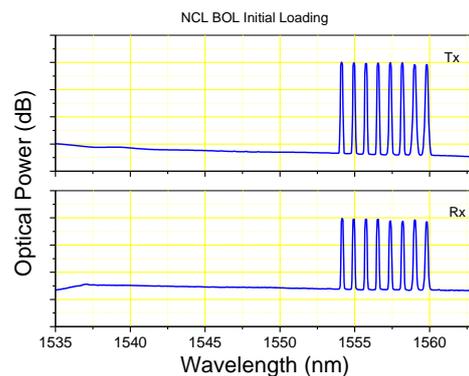


Fig. 5: Transmit (Tx) and receive (Rx) spectra for BOL initial loading, measured at shore station.

The performance of the fully loaded system under BOL conditions (Fig. 2) was then measured. The Tx and Rx spectra are shown in Fig. 6 with performance results in Tables 1 and 2. Ample margin was observed for all channels in both directions.

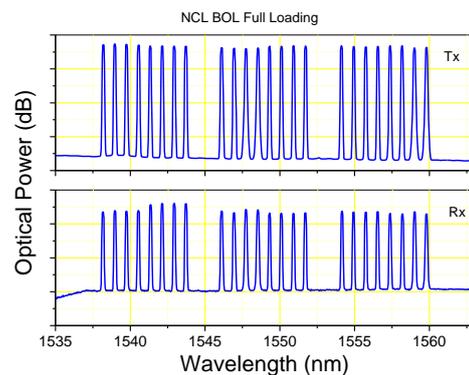


Fig. 6: Transmit (Tx) and receive (Rx) spectra for BOL full loading, measured at shore station.

The test bed was modified as in Fig. 4 to emulate EOL conditions and the performance measured. The Rx spectra measured at the shore station and nodes

N3b and N4a are shown in Fig. 7 with performance results in Tables 1 and 2 under EOL full loading.

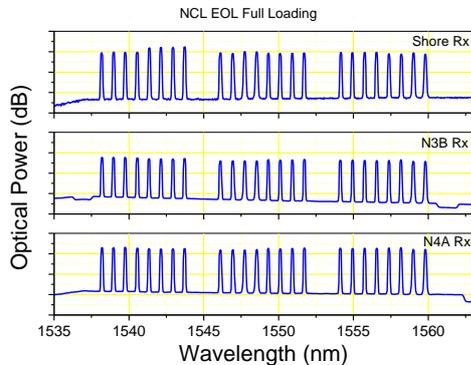


Fig. 7: Receive (Rx) spectra for EOL full loading, measured at shore station, N3b and N4a.

The EOL margin was greater than the BOL margin. This is due to the fact that the Q target for EOL was much lower than BOL.

Wavelength (nm)	Q Margin (dB), Shore-to-Node		
	BOL Initial Loading	BOL Full Loading	EOL Full Loading
1559.79	1.2	0.8	3.9
1558.98	1.1	1.1	4.6
1548.52	-	1.2	4.6
1547.72	-	1.2	4.5

Table 1: Q margin for measured channels shore-to-node under BOL initial loading, BOL full loading, and EOL full loading conditions. Q target was 15.7 dB for BOL and 12.3 dB for EOL.

Wavelength (nm)	Q Margin, Node-to-Shore		
	BOL Initial Loading	BOL Full Loading	EOL Full Loading
1559.79	0.2	0.1	3.8
1558.98	0.9	0.9	4.6
1548.52	-	0.3	4.0
1547.72	-	0.9	4.6

Table 2: Q margin for measured channels node-to-shore under BOL initial loading, BOL full loading, and EOL full loading conditions. Q target was 16.0 dB for BOL and 12.3 dB for EOL.

These measurements together verify the wet system design. Performance targets were met under BOL initial and full loading as well as EOL conditions.

#### 4. BRANCH AND NODE FAILURES

The next set of transmission measurements demonstrated the impact of failed nodes on the operation of remaining nodes in the network. These emulated conditions do not represent standard operating conditions for the RSN system. These experiments were designed to illustrate the performance of the surviving portion of the network in the presence of node failures.

If the harsh undersea environment causes node failures, data channels from the failed nodes will be removed from the system. This increases the power per channel for the remaining channels which creates the potential for performance penalties caused by nonlinear effects.

The first scenario considered determined the impact of N3a failing on N3b in the initial loading configuration. The setup is detailed in Fig. 8 and is labeled Fault 1. The shore terminal loading remained the same as for initial loading conditions while the  $\lambda$ s from N3a were removed. Results of Q measurements are shown in Table 3. The remaining channels continued to perform above the Q target. No change in channel performance from Shore to N3b was detected.

This scenario is equivalent to the full loading simultaneous failure of N3a, N5a, and N4a with a cable cut between N5a and the first repeater to N4a.

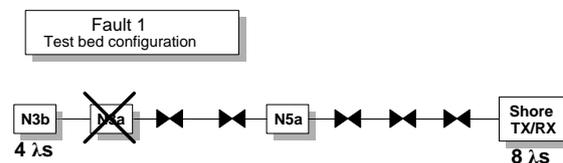


Fig. 8: Northern Cable Line test bed, BOL initial loading conditions, fault 1. The channels from N3a were removed.

For the next scenario, a break in the branch connecting N5a with N4a was emulated by removing the loading tones and data from N4a in the BOL full loading configuration. There was no input into the repeater closest to N4a in the inbound

direction and hence only noise was generated from this branch. The configuration is shown in Fig. 9. The loading from the shore end remained as for the fully loaded system. Results in Table 3 show that the surviving channels performed above the Q target. No changes in channel performance from Shore to N3b were detected.

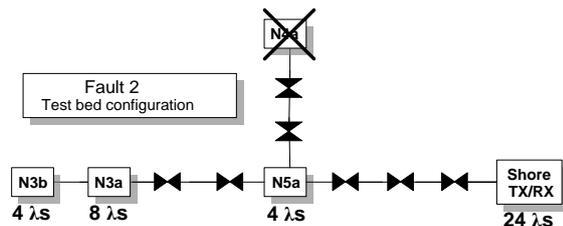


Fig. 9: Northern Cable Line test bed, BOL full loading conditions, fault 2. The channels from N4a were removed.

The next experiment emulated a break in the other branch of the Northern Cable line and demonstrated the impact on N4a. The shore loading was again for the full loading configuration. Only noise was generated on the inbound path between N3b and N5a and no signals were present at the input to repeater in the inbound direction. The configuration is shown in Figure 10. Results measurements are shown in Table 3 with the remaining channels above the Q target. No changes in channel performance from Shore to N4a were detected.

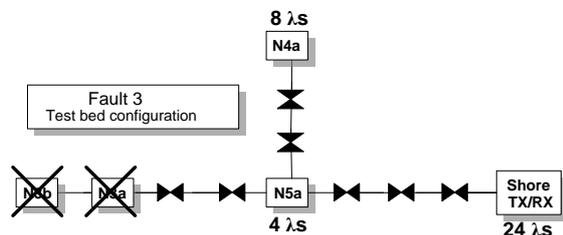


Fig. 10: Northern Cable Line test bed, BOL full loading conditions, fault 3. The channels from N3a and N3b were removed.

These experiments demonstrate that the system design allows for multiple failures while maintaining performance for the surviving portion of the network.

Wavelength (nm)	Q Margin, Node-to-Shore		
	Fault 1 Initial Loading	Fault 2 Full Loading	Fault 3 Full Loading
1559.79	1.3	4.9	-
1558.98	1.6	3.9	-
1548.52	-	-	4.9
1547.72	-	-	4.6

Table 3: Q margin for measured channels node-to-shore under Fault 1 initial loading, Fault 2 full loading, and Fault 3 full loading conditions. Q target was 16.0 dB.

## 5. SUMMARY

We have demonstrated that all performance targets for full loading BOL, full loading EOL, and initial loading conditions were met.

A robust system design is critical to sensor networks which are, by nature, located in higher risk areas. During the emulation of several fault scenarios, we have demonstrated the fault resilience of designed system: the transmission performance of all surviving channels was measured to be above the Q target. Hence, the surviving part of the system may be functional over the time period needed for a network repair.

## 6. REFERENCES

- [1] A.D. Chave, et. al., "The NEPTUNE Scientific Submarine Cable System," SubOptic 2001.
- [2] P. Barletto, et. al., "Expanding Cabled Ocean Observatories," SubOptic 2013, accepted for publication.
- [3] P. Tennant, et. al., "Commissioning of a System that Terminates on the Seafloor," SubOptic 2013, accepted for publication.