Basic Requirements and Options for Communication Systems in Scientific Underwater Cable Networks

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Abstract **- New innovative scientific underwater cable networks have been proposed and initiated in many locations around the world. These network have become feasible due to recent evolution of underwater telecommunication cable technology. However, their communication systems are quite different from standard telecommunication cable systems.**

Differences between the characteristics of existing submarine telecommunication systems and the basic technical requirements of scientific underwater cable networks will first be described. Options for the use of existing technologies include optical Gigabit Ethernet (GbE) over a separate DWDM optical transport, integrated CWDM GbE transceivers and DWDM with Raman modulators These will be presented along with their advantages and disadvantages. The present status of NEPTUNE communication system and considerations on it's reliability will also be presented.

I. INTRODUCTION

The use of modern optical submarine telecommunication cables and recent progress in related technologies make it possible to develop versatile, next generation scientific cables. These networks will provide electrical power and a wide range of data transmission capabilities to a variety of instrumentation deployed on the seafloor. Researchers will be able to access this equipment in real-time from laboratories and provide long-term, - data from the seafloor. These networks are expected to enable breakthroughs in multidisciplinary science fields.

Many new scientific underwater cable network projects are being proposed around the world. In the USA and Canada the NEPTUNE, MARS and VENUS projects have been initiated. NEPTUNE, a joint project between the USA and Canada, will realize a vast cable network of 3,000km in total length in the Northeast Pacific. MARS, located in Monterey Bay off the coast of California and VENUS in Canada precede NEPTUNE as test. In Japan the IEEE OES Japan chapter has proposed the ARENA project. The ESONET project in EUROPE will cover from the Mediterranean to the North Atlantic Ocean.

Communication systems proposed for these scientific cable networks are significantly different from existing optical underwater telecommunication cable systems. Most communication terminals (and associated optical transmitters and receivers) for these scientific observatories are placed in underwater housings that are not easily accessible for regular maintenance or repair. Conventional underwater telecommunication cable systems place all this equipment on shore and connect only between terrestrial stations (communications terminals).

It is extremely expensive to fund new research, development, and product qualification for telecom submarine-grade optical network equipment. Therefore, it makes sense for the oceanographic research community to determine if existing or soon-to-be-existing commercial-off-the -shelf (COTS) optical network products can be adapted to work adequately in the submarine environment.

From a conceptual design standpoint, the architecture of terrestrial and undersea optical networks are almost identical. However, from a practical standpoint, submarine optical networks require equipment with low electrical power demands, small physical size, adequate heat dissipation and heat tolerance, ultra high reliability, and minimal need for physical access by a technician. Thankfully, the demands of the terrestrial optical networking marketplace are driving commercial products in these directions. Ocean observatory design efforts continue to benefit by piggybacking on these ongoing R&D efforts.

One disadvantage to the rapid advances in optical network technology is the rate at which new products enter the marketplace. Ongoing design efforts can be interrupted because the potential cost and design benefits of the new products are too attractive to ignore. Thus, it is important to know the projected deployment date for an observatory so that one can work back to a design freeze date for the optical network. Given the typically fixed-cost nature of the observatory development efforts described here, the cost ramifications of freezing the design too soon can have significant effects on the geographic scope and features of the resulting observatory.

A related issue is sparing—if the technology moves on and you did not acquire enough equipment, redesign and upgrades may be required. However, this condition can be ameliorated if the observatory network architecture uses common, standard protocols, and a node-to-node communications design, which can propagate data without modification by intervening nodes when the end node designs are changed. In this way, nodes can be upgraded and replaced piecewise.

The remainder of this paper presents a snapshot of the optical network alternatives currently being considered by the NEPTUNE and ARENA ocean observatory data communications design teams. Section II examines the requirements for each of the design efforts. Section III sketches the technical aspects of the alternatives available for optical network transport equipment. Section IV reviews how node and network reliability can be accomplished using commercial-off-the-shelf equipment. In section V we review the status of the NEPTUNE and ARENA efforts and examine design decisions pertaining to each.

II. BASIC CONSIDERATIONS AND REQUIREMENTS

It is important that the choices made for the optical network design be based on the individual requirements for each of the observatories. Major considerations and requirements are listed below.

A. Network Configuration

All transoceanic commercial telecommunications systems are point-to-point links connecting shore to shore sites, with only occasional branches and no data input or output on the seafloor. On the other hand, scientific cable networks require most sensors, instruments and optical transmitters/receivers to be placed on the seabed. The science cable networks require a branching capability so scientists can economically deploy sensors three-dimensionally in scientifically interesting areas. Communications are also required between underwater observatories. These requirements are substantially different from those for transoceanic telecom systems, resulting in unique characteristics for scientific cable networks.

Interestingly, the submarine telecom community is moving toward meshed networks such as TPC-5 and SMW-3 for reliability and restoration [10]. Although these meshes are still sparse and built with terrestrially located hardware, the industry is becoming more familiar with the advantages of branching and mesh topologies which must be taken advantage of in subsea scientific cable design.

An additional difference is that telecom systems are land point to land point, with no inter-node comms on the seafloor. Observatories will involve as much node-to-node (i.e., seafloor-to-seafloor) as node to shore communications. As a result, the technical approaches have to be different.

B. Flexibility and Expandability

A subsea scientific network will need to grow with incremental funding, unpredictable scientific needs and future changes in requirements as more sophisticated sensors are developed. Thus it is crucial that the data transmission system should be flexible and expandable to accommodate this growth and change.

A related issue is the ease of expandability: a point to point OEO (optical-electrical-optical) based backbone requires changes to node electronics. An optical-only backbone network may require level balancing of inline components when a node is added, removed, or modified depending on the optical architecture (e.g., discrete lambda dropping at each node must be considered). This adds to complexity.

C. Signal Hierarchy and IP Network.

Conventional underwater and terrestrial telecommunication systems operate with forward-error – correction enhanced SONET transport systems. Although SONET provides for a reliable wide area data network, it lacks flexibility and expandability. Moreover, SONET systems that are designed for submarine telecommunication systems require very high availability (99.999%). They require more power and physical space than networks based on Ethernet technologies, for example. They also tend to be very expensive.

One promising alternative is an IP-over-Ethernet based network. The IP network allows for topologically independent extension and enlargement without affecting other nodes. The present scientific community is very familiar with Ethernet and TCP/IP based networks. They are manageable with commercially available data processing techniques prevalent in the Internet sphere.

D. Reliability and Cost

The reliability requirement for scientific cable networks is shared with commercial telecommunications. Most of the transmission terminals will be placed on the seafloor. The inaccessibility of this equipment makes it costly and time-consuming to repair or maintain these devices. Submarine telecommunications grade reliability is attained through high cost R&D and qualification work, which is recouped through a business model that research does not comply with. Furthermore, there is a likelihood of occasional system modifications expected for research, which would include repairs. Therefore the reliability/availability of an underwater research network must conform to a different cost/reliability model when compared with commercial telecommunications.

The underwater repeaters used in telecommunication systems are submarine-qualified devices whose simplicity provides high reliability. On the other hand, the underwater systems in scientific cable network designs must contain devices such as Ethernet switches, sensor interfaces and optical transmitter/receivers. It is not realistic to build these science networks with only submarine-qualified devices. Instead, commercial-grade COTS devices can be employed to satisfy less stringent scientific requirements. However, further measures need to be taken to increase reliability.

One viable solution would be to employ mesh or ring topologies. In mesh or ring networks, the network continues to work by bypassing failed segments when a portion of the network breaks. This can also increase the reliability for power feed systems. By employing commercial grade network equipment and increasing both equipment and path redundancy, we can obtain availability of the system without the use of extremely costly high reliability devices.

Redundancy should be considered as an alternative to submarine-qualification for critical or vulnerable devices.

E. Transmission Capacity

Transmission capacity requirements can be classified into three categories.

1) HDTV signals

Bandwidth requirements for HDTV depend on the signal compression mode. Japan's broadcasting system reduces the 1.5Gbps to 24Mbps using MPEG2. This enables home recording on D-VHS recorders. The images are degraded as compression increases at the 0.016 rate used in the satellite broadcast system. The degradation of images is small at this high compression. We suggest that the acceptable level of degradation for scientific use should be re-considered by taking terrestrial transmission and video recording into consideration. Reduced scan rates for seafloor scenes, which change slowly, and, the nearly monochromatic nature of the optical channel on the seafloor due to the strong wavelength dependence of the attenuation of light should be taken advantage of.

In addition, if the HDTV signal is transmitted over Ethernet, dropouts of packets can seriously affect the decompression process and may deteriorate the image quality. Quality of service (QOS) requirements must be considered. If full-bandwidth HDTV is required for subsea science, a dedicated path (packet or wave) may be required.

2) Time Synchronous Signal

For acoustic geodesy, time synchronous signals with accuracy from 5-10 microseconds is needed. A more stringent requirement exists for acoustic tomography. Even a 1 microsecond requirement does not allow for much future capability growth Among internet protocols the NTP protocol typically provides time synchronization with an accuracy typically in the order of milliseconds or higher. Another transmission path is likely needed for a time synchronous signal. IEEE 1588 with boundary clocks is another option. 1588 enabled switches are expected on the market soon.

3) Other Data and Control Signals

There are many kinds of sensors and instruments connected to scientific cable networks. Although the amount and the format of these data and control signals differ, the total amount of data is far less than that expected for the HDTV signal. IP networks can provide flexible infrastructures, which accommodate these diverse kinds of data.

F. Node-to-Node Communication

With the advent of sensor network technologies [9], a more recent requirement that is emerging is low-latency node-to-node interactions. If this proves to be a significant need it limits the topologies available for the optical network design.

III. TECHNICAL OPTIONS

Optical communication technology is evolving very rapidly, and the most promising options for undersea science network communications will change with time. However, it is worthwhile to examine the characteristics of currently available options and describe the advantages, disadvantages, and suitable applications. This will help to clarify and present the status and orientations of both the NEPTUNE and ARENA development efforts (which will be further discussed in section III).

A. *Optical GbE over DWDM with Intra-node Redundancy*

The optical solution for NEPTUNE at this time is a Gigabit Ethernet over DWDM solution. Current designs are shown in Fig. 1 and Fig. 2. Using commercially available optical transponders, EDFAs and multiplexing equipment, distances in excess of 200km are achievable. The equipment works within thermal, electrical and physical size parameters acceptable for oceanographic deployment. The availability of affordable terrestrial EDFAs allows pre-amplification on the order of 23 dB per channel.

The recently projected NEPTUNE design uses 8 wavelengths carrying 1 GbE (Gigabit Ethernet) each. Commercial equipment requirements become greatly simplified with this deign since the demultiplexor gratings need not be temperature stabilized. DFB lasers in the transponders are stabilized via Peltier coolers.

The NEPTUNE project has presently laboratory tested commercial off-the-shelf (COTS) optical Ethernet equipment manufactured by Network Electronics, (www.network-electronics.com), which prove the viability of an optical Ethernet solution for underwater research networks. Distances of 50km un-amplified and over 200km amplified have proven to operate with BER rates below 10^{-12}. This equipment operates in an appropriate thermal output range and electrical power range compliant with the NEPTUNE power system design.

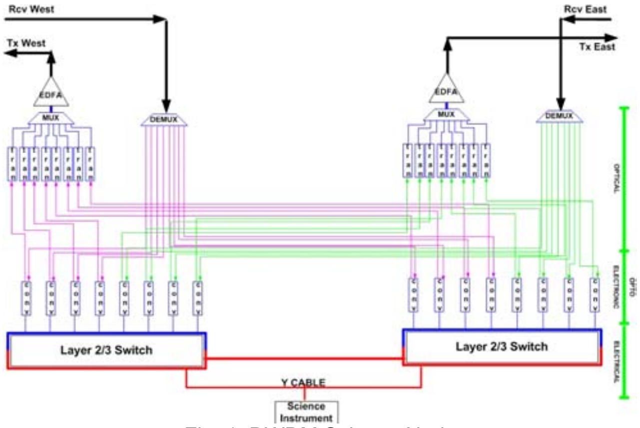

Fig. 1: DWDM Science Node

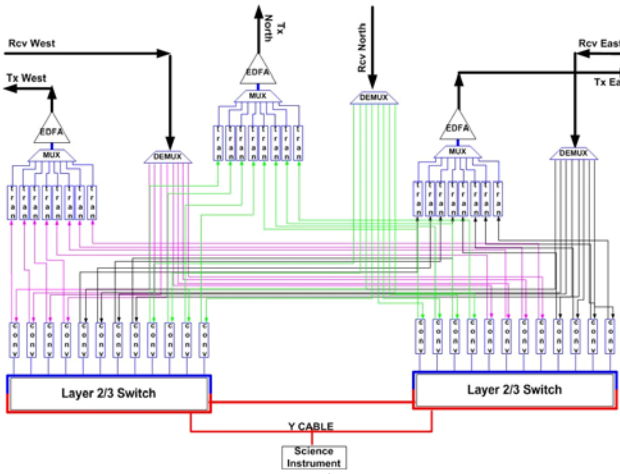

Fig. 2: DWDM Branching Node for Deployment at Mesh Points

The various characteristics of the system tested in the laboratory are shown in the table below.

TABLE I
DWDM CHARACTERISTICS

Typical Transceiver Specs (Network Electronics Transponders)	
Wavelength:	1528 nm – 1562 nm
Wavelength Output Power:	+0 dBm out
Receiver Sensitivity:	-19 dBm in
Dispersion Penalty:	2dB @ 17km (Nortel Lasers)
Typical WDM Parameters (Network Electronics Mux/Demux)	
Mux Attenuation:	4dB
DeMux Attenuation	5dB
Common Telecomm Fiber Specs (Corning SMF28E)	
Attenuation:	0.19 dB @ 1550 nm
Dispersion:	18 ps/(nm.km)
EDFA Preamplifier Specifications (Nortel/Bookham 1AOC28)	
Gain:	23 dB
Maximum Input:	-10 dBm
Optical Budget Estimate – 178 kilometer maximum	
Input	0 dBm
Attenuation	3(mux) + 3(demux) + 2(dispersion) + .19dB/km x 178km – 23(gain) = 19dB
Output	Input – Attenuation = -19dBm

B. GbE over CWDM Alternative

One promising approach to optical networking, is Coarse Wave Division Multiplexing (CWDM) technology. Its assets are similar to DWDM with lower cost but a greater limitation on distance. The Mux/Demux equipment investigated for this technology is generally of a higher attenuation compared to DWDM. Equipment from Cisco Systems. has a per wavelength attenuation of 9dB for the Mux/DeMux pair. In addition the fiber attenuation is slightly higher for the broader frequency range of CWDM, which covers 1470nm-1610nm, being about 0.24 dB/km over SMF28E at 1470nm.

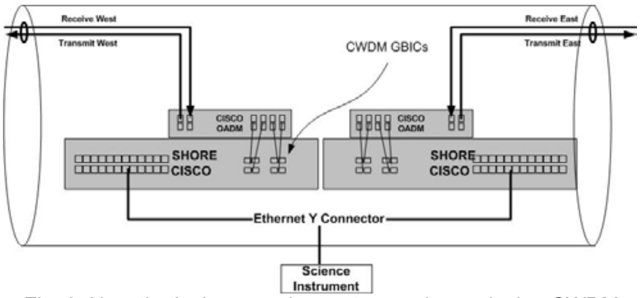

Fig. 3: Hypothetical ocean observatory node employing CWDM capable of distances less than 80km

The attenuation problems mentioned are not surmountable using commercially available amplification as of this writing since EDFAs do not cover the entire CWDM spectrum. The SOA (semiconductor optical amplifier) devices presently available are relatively new and have not developed a reliability profile comparable to EDFAs. Further SOA still has some issues with crosstalk and similar effects at 1Gb/s signal rates. Thus the likely sphere of application for CWDM is for unamplified networks with node separation less than 80km or as extension networks to a network deployed over a large geographic area. There are some reliability, cost and size advantages when the amplifiers are omitted. Reliability and power consumption is also improved because CWDM does not need temperature control of laser diodes. Cisco Systems, presently offers a complete solution which is rather compact.

The NEPTUNE project has evaluated CWDM equipment at a "spec sheet" level (Fig. 3) but have not elected to test it in the laboratory due to its 70km attenuation-limited distance constraint. However, CWDM appears to be very attractive for a small system connecting 1GbE networks at shorter distances such as in coastal applications. The facile nature of IP/GbE mentioned for the extension of NEPTUNE also provides the ability to interconnect with other GbE optical implementations.

A set of characteristics we envision for a possible simple CWDM extension node design for NEPTUNE are shown in Table II.

TABLE II
CWDM CHARACTERISTICS

Typical Transceiver Specs (Cisco CWDM GBICS)	
Wavelength:	1470nm - 1610nm
Wavelength Output Power:	+3 dBm out
Receiver Sensitivity:	-29 dBm in
Dispersion Penalty:	3dB
Typical WDM Parameters (Cisco)	
Mux Attenuation:	4dB
DeMux Attenuation	5dB
Common Telecomm Fiber Specs (Corning SMF28E)	
Attenuation:	0.24 dB @1470nm
Dispersion	18 ps/(nm.km)
Optical Budget Estimate – 80 km. maximum	
Input	0.24 dB @1470nm
Attenuation	4(mux) + 5(demux) + 3(dispersion) + .24dB/km x 80km = 31dB
Output	Input – Attenuation = -29dBm

C. 10 GbE Solution

An obvious simplification of an 8-channel GbE DWDM solution is to condense the wavelengths into one 10GbE stream. Cisco Systems currently manufactures a switch which meets NEPTUNE specification in its DWDM line, which utilizes two 10G GBICs.

One challenge with 10G signaling over long distances is the adverse effects of dispersion on signal shape, as shown in Fig. **4**. It works very well for short distances or where dispersion-compensation of some sort can be employed.

The tractable data rate as a function of dispersion [1], D, and distance, s can be given by:

Bitrate(Gb/s) x Length(km) = 1000 / 4Ds

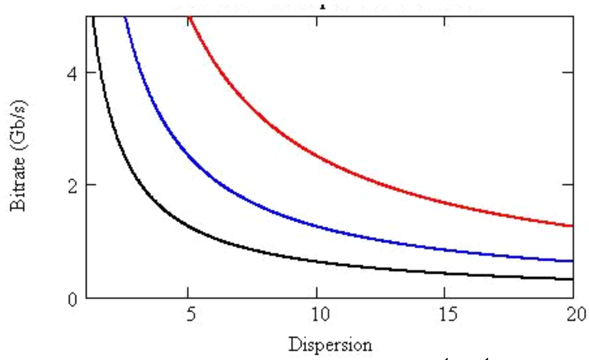

Fig. 4: Bit Rate vs Dispersion (Gb/s vs ps $nm^{-1}km^{-1}$) at 100km

The spectral line width of the DFB laser limits the modulation rate of the signal over long runs of dispersive media. More importantly, signal chirp due to the very high-speed electrical modulation of the laser results in edge phenomena, which result in signal distortion at long distances. This latter quantity is difficult to quantify, and is very dependent upon the driver circuits.

One solution is to omit electrical modulation of the laser, and to use optical modulation, which omits chirp altogether. The latter method is somewhat complex and expensive, employing Lithium Niobate crystals and a Mach-Zehnder interferometer. However, recent developments by Intel have led to a silicon wafer based model, which promises compaction and cost effectiveness. [8]

D. DWDM System with Optical Modulators

Optical fiber telecommunication technology is evolving very rapidly. Recently, a new optical modulator has been proposed by Tokura et al[3] which uses a Raman amplifier for DWDM systems and could be used in submarine applications.

In the Raman modulator, the modulated driving current modulates the gain of the Raman amplifier, which modulates the carrier lightwave amplitude.

Fig. 5 and Table III show the system configuration and the principal characteristics respectively for this approach. In this system, all light sources, with highly stabilized wavelengths, are placed in terrestrial stations. In each underwater observation node, a corresponding wavelength is dropped from an optical fiber and returned back to the terrestrial station through another (the second) optical fiber after being modulated by the Raman modulator. The same wavelength in the second optical fiber is also dropped at the same node, and is returned back to the other terrestrial terminal through the first optical fiber after being modulated. Thus, even if the underwater cable is broken, all underwater observation nodes can continue data transmission via one of the terrestrial terminals.

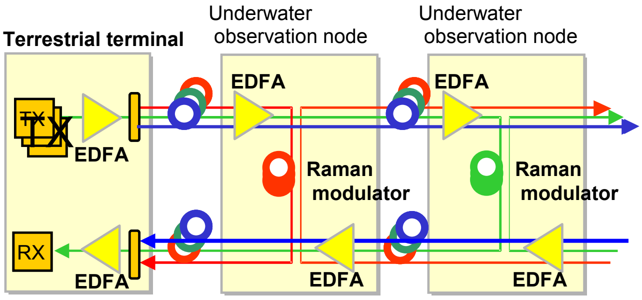

Fig. 5: Configuration of DWDM with Raman modulators

TABLE III Principal Characteristics of the system

.Item	Value
Telemetry capacity at each node	100 Mb/s
Number of WDM signal channels	20
Total cable length	Several thousand km
Wavelengths of signal lights	1,550 nm band

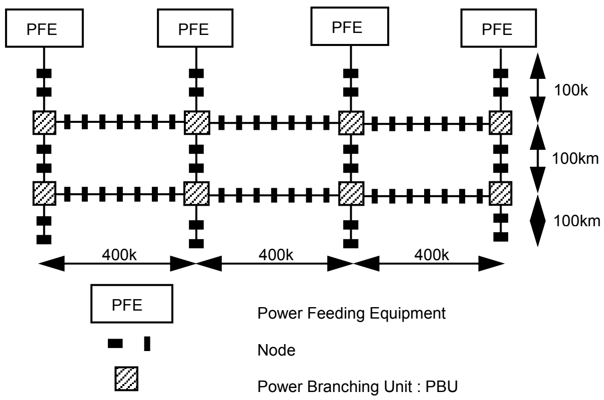

Fig. 6: Engineering model of underwater cable network for ARENA

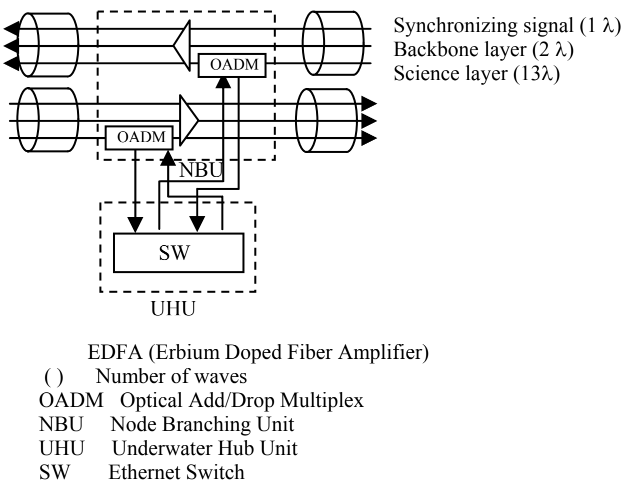

Fig. 7: Proposed wavelength assignment for ARENA system

The features of this system are:

(a) Simple configuration

(b) The system consists of only field proven devices.

(c) The wavelength stabilization systems, including temperature controlled systems, are located in terrestrial stations.

(d) Robustness against cable faults.

(e) About a hundred wavelengths are available for use .

Signal balancing required for the addition of new wavelengths and transponders failing over the term of use of the cabled observatory can be partially compensated with the use of dummy lightsources beforehand. More detailed study of this will be done in the next stage of research and development.

Although not a COTS system, the system consists of COTS devices. These features imply high reliability and cost-effectiveness of the system.

One of the promising applications of the Raman modulator design is ARENA. Fig. 6 shows an engineering model for ARENA[4] in which two horizontal trunk cables are placed at adjacent sides of a plate boundary, and these trunk cables are connected to multiple terrestrial stations. The use of multiple terrestrial stations enables step-by-step construction of the network, corresponding to available funding.

In the proposed data transmission system for ARENA, one or a few wavelengths are assigned to each node as shown in Fig. 7. Each wavelength carries an IP or HDTV signal. Backbone layer connections between the terrestrial terminals increase the flexibility of the network. Since laser diodes are placed in terrestrial terminals, it is straightforward to increase the number of wavelengths without affecting previously installed nodes. The system is protected against cable faults since the signal is transmitted in both directions.

In the Raman modulator system all laser diodes requiring accurate temperature control are placed in terrestrial terminals. This increases the reliability of the underwater devices and lowers their power consumption. This would be a possible option for a future network. The detail of this system is described in the accompanying paper of OTO'04 [3].

IV. NODE AND NETWORK RELIABILITY

The presently accepted link topology for NEPTUNE is a meshed network architecture. Each node contains a grouping of DWDM optical and GbE electrical devices that carry the primary network traffic. The impact of meshing, and hardware redundancy of critical devices within the node, was determined by performing a study to statistically determine the expected node availability to science, repair rate of nodes, and optimum node channel configuration. This study was divided into two phases as follows:

Node Reliability – Determine the number of OEO repeated wavelengths versus dropping wavelengths within the packet switched fabric

Network Reliability – Examine the adequacy of a meshed topology, predict maintenance requirements and provide science users with availability estimates for connectivity to their instrument.

A. Node Reliability

The Node Reliability phase is relevant to designing the internal node architecture. DWDM channels in the NEPTUNE design pass through the node and can either be routed into the nodes electronic switching fabric, or simply passed through the node using OEO repeating in the opto-electronic layer. In such a design the number of wavelengths to repeat through a node vs. the number to be added/dropped within the node and must be determined. The cost, power consumption and reliability of the system are all functions of this number.

Certain assumptions were made in this study:

- Reliability calculations are only for the NEPTUNE datacomm subsystem (although comparable numbers are likely for power subsystem).
- The data to be transported from an instrument to the shore can be aggregated over more than one wavelength via Cisco Systems. Etherchannel algorithms or similar methods used by other vendors. This means that multiple redundant paths exist between adjacent nodes as the data is delivered to the shore. Parallel probability calculations prevail.
- Efficiency of transport is not taken into account. Therefore, reduced throughput caused by malfunctioning parts is not considered a failure in the reliability calculation.
- The intent of the reliability calculation is to find the probability that:
  - A particular instrument attached to a particular node will reach any exit path from the node.
  - Incoming traffic to the node will find at least one exit path from the node
- The failure rate of node components are not given as a function of time. Failure of a device is defined as follows: Given a large number of duplicate devices d, the failure rate Fd is the number of failed devices divided by the total number after Y years of operation.

FIT (Failure In Time) rates, f, used in this for the study are shown below. The success rate is e^{-tfH} where t is in years and H = 24x365.

TABLE IV
Subsea Component FIT rates used in the Node Reliability phase of the reliability study

Component	FIT Rate
Optical Transmitter	460×10^{-9}
EDFA	100×10^{-9}
Packet Switch	1000×10^{-9}
Optical Receiver	230×10^{-9}

Two distinct NEPTUNE Node Types are identified in this reliability study:

2-way node type - This is a node, which has 2 external ports for data transfer to a logical “East” and “West” leg. Eight instrument ports are provided on this type of node .

3-way node type - Also called a branching node, this is a node, which has 3 external ports for data transfer to East, West and North. Eight instrument ports are available on this node as well.

For each of these nodes, three different modes of operation are defined:

Instrument mode – the node transfers data from an instrument port to an East, West (or North in the case of a 3-way node) external port.

Transfer mode - The node receives the instrument data from one external port and passes it to the switch layer, and then transfers it to the next node via another external port.

Repeat mode - The node receives the instrument data from an external port and than transfers it to the next node via another external port, without first sending it through the switch layer. All processing is done by the optical layer, including the transponders. Thus, the data is OEO repeated.

The present NEPTUNE node design consists of a Network Electronics Fastlink optical transport system, Bookham EDFA, and a Cisco Systems, Inc. electrical GbE packet switch. These components are duplicated in the node for increased reliability through redundancy. Using the above design considerations a mathematical model was written for the node internals. It calculates the failure rate for the highly parallelized architecture. The model calculated the number of node-drops vs. pass-through as a function of reliability. The result is shown graphically in Fig. 8.

Based on this figure, the decision was made to drop all 8 DWDM channels in each node. The inherent benefits of this are that it provides:

- The most flexible routing capability during an outage providing the maximum number of alternate routes
- The most flexibility when tuning by providing the maximum number of possible paths for balancing traffic
- The least inter-node latency via direct node to node communications (but higher long distance latency)
- Full bandwidth access to the 8Gbps backbone

B. Network Reliability

The network reliability phase is relevant to designing the mesh and routing algorithms of the overall network architecture. In this design all of the DWDM channels pass through the network from node to node. At strategic points in the NEPTUNE design, 3-way backbone branching nodes are inserted, providing alternate data paths between nodes and shore, thus giving the architecture its reliability.

The objectives of the network reliability study was examined from the standpoint of three types of users :

The **scientist’s** reliability concerns are addressed by examining the number of data paths available from the equipment to shore as a function of time. As long as science has at least one path capable of carrying the instrument data, the science requirement is satisfied,

The **systems engineering and management** staff is concerned with the number of ship visits per year required to keep all devices in nodes running. This information is manifest in the block reliability for the whole observatory system.

The **design engineer** is concerned with the reliability of individual parts over time and their impact upon the number of wavelengths dropped or passed in the node

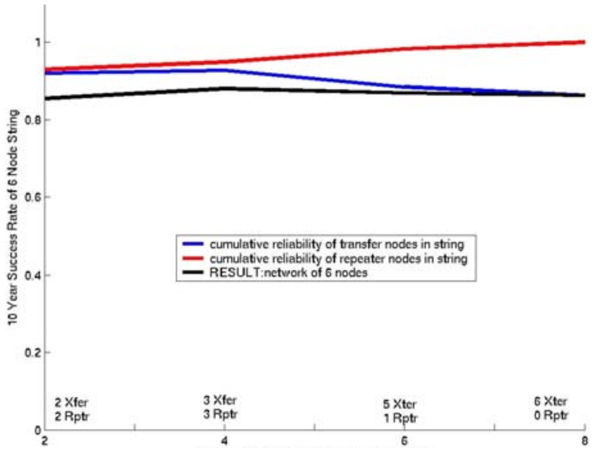

Fig. 8: Number of Wavelengths Dropped per Node

The Network Reliability study is performed by first assigning each major device in the node a reliability value. Each device within the node is given a state of failed or not-failed using a Monte Carlo algorithm. The node, as a complete entity, is either capable or not-capable of transferring instrument traffic based upon the failure state of the devices.

This Monte Carlo program was run using the FIT rates for the devices in the nodes. The outcomes are shown in the two plots below.

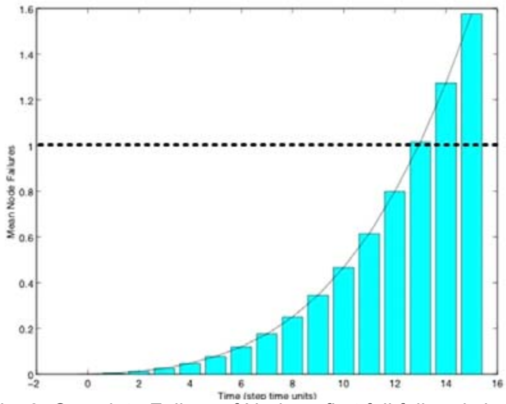

Fig. 9: Complete Failure of Nodes - first full failure is in year 13 Node Failure means that science instrument has NO path out of node at any date rate – No repairs over time.

The first plot above demonstrates that if the nodes are not periodically repaired as their internal devices fail, eventually the node will completely fail to transfer traffic after 13 years on the average. Due to the realistic likelihood of ship visits to deploy equipment, coupled with an expected cyclic maintenance program at each node, this is an acceptable risk.

Fig. 10 demonstrates that regardless of complete failures of an individual node the remaining nodes will continue to have a portal to transmit their traffic to the shore after 15 years. After 15 years, all 26 nodes on the x-axis have at least 5 remaining paths to the shore. Since annual repairs of all failures are anticipated, the result is far better with most paths to nodes surviving by year end.

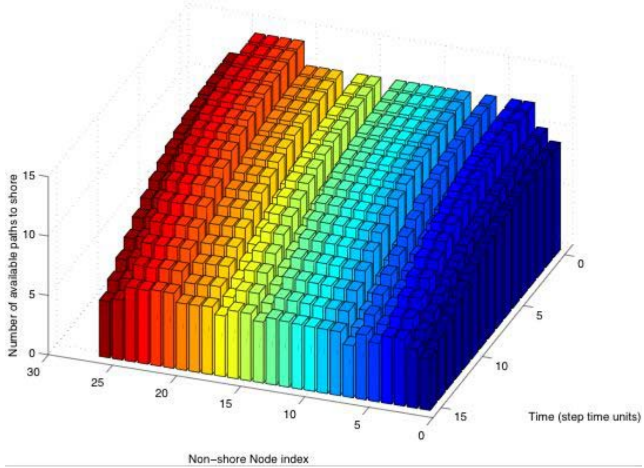

Fig. 10: Number of available paths between shore and each of 26 nodes over time. After 15 years, all 26 nodes on the x-axis have at least 5 remaining paths to the shore

The conclusion of this study is that the deployment of commercially terrestrial devices in a redundant and meshed architecture provides the oceanographic community with a flexible, extensible, and cost effective technique for use in regional cabled observatories.

V. ARENA AND NEPTUNE DESIGN STATUS

As the result of the initial feasibility study of ARENA performed about two years ago, IP over WDM was recommended as the most promising basic technology. However, the quantitative evaluation of reliability was left for future study. It was clear that we had to take a quite different approach from the underwater telecommunication industry to realize the required reliability.

After the feasibility study, a new idea using Raman modulators was proposed within the ARENA committee. As the system has many advantages, Tokura et al. [3] made a prototype and evaluated it. The early results show promising characteristics. It is still under fundamental study, and some effort is being made to increase the bit rate from about 50Mb/s to more than 100Mb/s.

As ARENA is still in the feasibility study stage, and the technology is evolving rapidly, the design of the communication system has not yet been fixed. However, IP over WDM is becoming the mainstream for optical communication systems and the present design would prevail for around five to ten years. The system using Raman modulators is one of the promising choices.

The present design status for the US NEPTUNE effort is strongly tied to the MARS testbed project. The MARS testbed is a single, 3-channel NEPTUNE-style node that is expected to be deployed off the California coast in the summer of 2005. Non-MARS work, specific to NEPTUNE's mesh and reliability architecture, has been completed as well. This includes the network reliability previously mentioned and a conceptual design for mesh branching units, and a power system design which insures the safety of adjacent nodes when a single node encounters a power failure or ground fault.

The key design elements researched in the laboratory for the MARS testbed node include thermal properties and optical transport properties of the suite of devices representative of those to be used in NEPTUNE. This includes Nortel EDFAs, Network Electronics optical transport system, and Cisco Systems electrical routers.

Thermal analysis has included measurement of the power consumption for all MARS data communications equipment under real data loads. These power values were used to drive heating elements that injected heat into a comparable node enclosure. This was done to determine a resulting temperature rise. These measurements have been completed in air and will be completed in a water bath in the near future.

The use of Fluorinert (an electrically inert cooling fluid) has been investigated. For MARS, It has been determined that the Cisco switch-routers will be immersed in Fluorinert, while the NE optical switches and EDFAs (which run cooler) and can be placed in a dry air section of the node enclosure. One reason for this is that Fluorinert filled an air gap found in commercial GBIC and SPF optics packages, disrupting the optical path.

The project team suspects that heat sinks providing thermal conductivity between electrical components and pressure housing walls may eventually be required for the full 8 channel capacity. The first experimental estimate of thermal conditions are shown in Fig. 11. The results shown in red are from tests that indicate that the addition of 4 cooling fans can affect the internal temperature of the node. It is apparent that temperatures of less than 35 degrees are achievable with a power injection of 90 watts, which is typical for this section of the node. Submersion of the node in water should bring the temperatures well below 30 degrees. The use of fans is well worth investigating should thermal issues become a problem (or for diagnostic/maintenance purposes). Small cooling fans that use sintered bearings are available with an MTBF on the order of 300,000 hours.

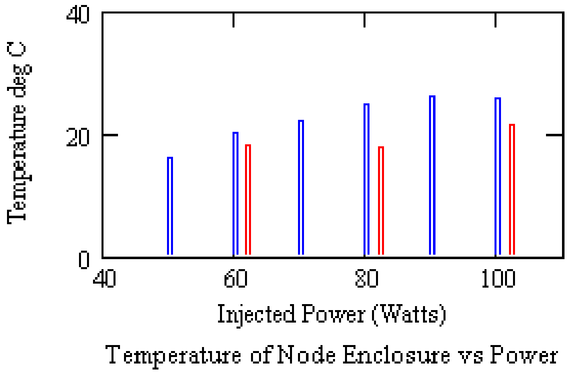

Fig. 11: Temperature of Node Enclosure vs Power

At this time, the ability of the chosen equipment to operate at the accepted GbE error rate of 10^{-12} has been proven over 100 km runs of Corning SMF28E fiber. Runs were done for 24 hours using both a booster EDFA and a pre-amp EDFA. More work is in progress to test past distances of 150km, which will cover all NEPTUNE distances excepting one shore connection. For these tests we will have the option of using both a booster amplifier and a pre-amplifier in concert. Additionally fiber of lower dispersion than SMF28E can be used for longer runs. We have proven the ability to transmit data at distances up to 220km using 2 EDFAs with NZDSF.

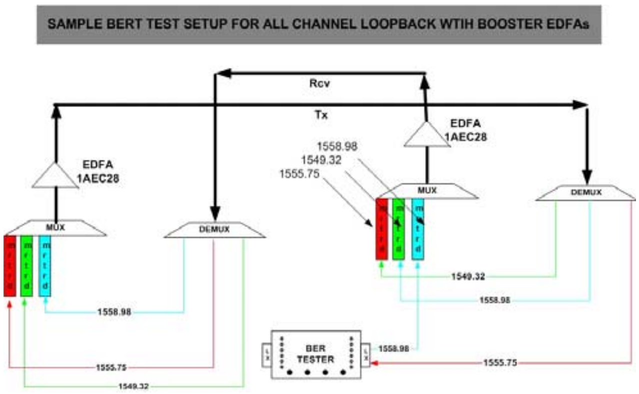

Fig. 12: Sample BERT test setup for all channel loopback with booster EDFAs

The above work completes the proof of concept for the primary data communications of the NEPTUNE system. Remaining major issues are improving a "Y" cable science connector to allow redundancy to the routers, and determining the reliability of wet optical connectors for node deployment.

This paper describes the technical options of communication systems for scientific underwater cable network and the present status of NEPTUNE and ARENA's communication systems. It also shows that both systems are based on almost the same basic requirements. Although the most desirable option depends on the network configuration, its scale, its scientific objectives, its capability of construction and maintenance vessels and the state of the art when the development is inaugurated, Both projects adopted an IP over DWDM architecture. This attests that the IP over DWDM approach will become mainstream in scientific underwater cable networks. Although there are differences between NEPTUNE and ARENA systems, this is partially due to the different development stages for each project.

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