The NEPTUNE Scientific Submarine Cable System

A.D. Chave[1], H. Kirkham[2], A.R. Maffei[1], G. Massion[3], H. Frazier[4], A.M. Bradley[1], S.J. Gaudet[5], W. Wilcock[6], D.H. Rodgers[2], P.M. Beauchamp[2], J.C. Madden[7], and B.M. Howe[6]

Abstract

The NEPTUNE scientific submarine cable system will “wire” the Juan de Fuca tectonic plate and turn it into an interactive ocean sciences laboratory. NEPTUNE will provide 30 seafloor nodes distributed over a 500 by 1000 km area to which many scientific instruments may be attached. The nodes will supply power at the several kW level and data communications at a Gb/s rate. NEPTUNE will utilize an unconventional parallel power distribution system and industry-standard Ethernet data communications hardware.

Introduction

The study of the dynamic, interactive processes that comprise the earth-ocean system requires new approaches that complement the traditional ship-based expeditionary mode that has dominated oceanography for the past century. Long-term access to the ocean is needed to characterize the diverse range of spatial and temporal scales over which natural phenomena occur. This can be facilitated using ocean observatories to provide power and communications for distributed real-time sensor networks covering large areas. Real-time networks also enable an education and public outreach capability that can dramatically impact the public attitude toward the ocean sciences.

The NEPTUNE project (http://www.neptune.washington.edu) is a joint US-Canadian effort to "wire" the Juan de Fuca tectonic plate located off northwestern North America with 3300 km of dedicated scientific fiber optic cable hosting 30 science nodes spaced a nominal 100 km apart. Each seafloor science node will provide power at the multiple kW level and two-way communications at a Gb/s rate to many experimental packages. Two shore stations link these seafloor nodes to the Internet. Figure 1 shows the planned layout for NEPTUNE. Installation of NEPTUNE is expected to begin in the 2004-2005 time frame.

NEPTUNE differs from a conventional submarine telecommunications system in two key respects. First, NEPTUNE requires data input and output at many seafloor sites rather than a few land terminuses. Second, NEPTUNE has to distribute power at variable and fluctuating rates to many seafloor instruments in addition to energizing its own internal systems. For these and other reasons, the engineering solution for the NEPTUNE power and communications systems does not closely resemble those used in commercial telecommunications systems. However, NEPTUNE will take advantage of the submarine fiber optic cable technology used in telecommunications for its backbone, and will be installed using conventional cable laying assets.

Figure 1. Bathymetric map showing the layout for NEPTUNE. The yellow line and red dots denote the backbone cable and locations of the seafloor science nodes, respectively. The white line is the approximate boundary of the US and Canadian Exclusive Economic Zones.

1. Woods Hole Oceanographic Institution, Woods Hole, MA 02543, USA
2. Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA
3. Monterey Bay Aquarium Research Institute, Moss Landing, CA 95039, USA
4. Dominet Systems, San Jose, CA 95112, USA
5. National Research Council, Herzberg Institute of Astrophysics, Victoria, B.C. V9E 2E7, Canada
6. University of Washington, Seattle, WA 98195, USA
7. Institute for Pacific Ocean Science and Technology, Vancouver, B.C. V6K 4L9, Canada

The functional design of the NEPTUNE system must be driven by science requirements. For example, the locations of the 30 seafloor nodes in Figure 1 wil be determined by science needs. Through an assessment of present and projected future ocean instrumentation and experiments, system parameters such as the peak and average data rate, power level, and allowed data latency and jitter have been defined. Aggregate system capacity of 10 Gb/s and delivered power at the 2 kW level per site is sufficient to meet science goals. The system must also distribute accurate (1 µs) time information to seafloor instruments.

The infrastructure for NEPTUNE consists of five systems: communications, power distribution, system control, time distribution, and data management and archiving. Each of these components must be designed as end-to-end systems, and must be highly fault tolerant. Physical packaging of the seafloor nodes must be accomplished in a way which facilitates science as well as maintenance. The system engineering for NEPTUNE is presently underway, and the approach which is being taken in each area will be briefly described.

Power Distribution System

The NEPTUNE power system can be divided into three parts: the shore station, the delivery channel (i.e., the cable), and the node system.

The shore station converts utility power to DC for distribution to NEPTUNE. It is also responsible for load management and metering via the communications system. Considering the total load and losses in the cable, the peak power output of each shore station will be about 100 kW.

The insulation used in standard fiber optic cables limits the DC voltage to 10 kV, although a few long haul designs can handle as much as 15 kV. The electrical specifications rarely include the current carrying capacity. Based on the size of the conductor and heat dissipation considerations, standard cable should be capable of handling 100 A without difficulty, although this level is not approached in telecommunications applications. The resistance of telecommunications cable is high (typically 1 Ω/km), so that I^2R voltage drop will be the factor which limits the current in practice.

The node system powers the communications infrastructure which resides in the nodes as well as user instruments at standard voltage levels of 48 and 240 VDC. It also provides metering data to the shore station and implements most of a layered power control protocol.

The major difference between NEPTUNE and submarine telecommunications systems is the use of parallel rather than series connections of the loads. In this respect, NEPTUNE more closely resembles the terrestrial power grid. Parallel power offers significant advantages in efficiency, reliability, and flexibility over serial power in an environment where the loads vary with location and time. It is also readily compatible with the branching topology of the NEPTUNE system (see Figure 1).

Implementation of parallel power for NEPTUNE requires the development of a voltage-sourced DC-DC converter residing in the seafloor nodes and capable of operating over the 1-10 kV range at power levels of several kW. COTS converters of this type do not exist, and are being developed. The shore station counterpart to this converter is a source operating in the 1-10 kV range at the 100 kW level.

Fault tolerance considerations suggest that the DC-DC converters in the nodes should be redundant. A layered protection scheme is being designed to allow rapid and safe restoration of as much of the system as possible in the event of a cable fault or node failure.

Communications System

As for the power system, the NEPTUNE communications system consists of three parts: the shore station, the delivery channel (i.e., optical fibers), and the node system.

The shore station serves as the link between NEPTUNE, the data archive, and the Internet. It also monitors communication system performance and makes necessary adjustment to the seafloor communications components.

The node system must aggregate data from science instruments operating at highly variable rates, switching it onto the backbone cable and ultimately to the shore stations. It must also distribute command and control information to instruments.

The NEPTUNE communications system carries only data traffic; there is no need to carry mixed voice/data traffic as in a telecommunication system. For this and other reasons, all NEPTUNE communication systems will utilize the Internet protocols (IP) that dominate the data networking world.

There are several standard IP communications technologies which might serve NEPTUNE, and selecting from them has been guided by three principles:

1. NEPTUNE should utilize COTS components wherever possible to minimize development and acquisition costs.
2. NEPTUNE should choose a technology which meets the requirements without added complexity and cost from features which are not needed.
3. The communications technology must be available in a form factor and at a power consumption which is compatible with seafloor packaging.

Based on these and other considerations, Gigabit Ethernet (GbE) has been selected as the backbone communications technology for NEPTUNE. Ethernet is the most widely used data networking technology in the world, and has 10 and 100 Mbit/s standards in addition to a high data rate capability. GbE routing and switching hardware is readily available from many vendors. Standard converters are also available with the ability to drive 100 km or more of single mode optical fiber. This permits GbE hardware to serve the dual functions of a data concentrator/router and an optical fiber repeater, eliminating the need for optical amplifiers. This yields long haul 1 Gb/s full duplex communications using a pair of optical fibers. Higher data rates are feasible using multiple fiber pairs; the NEPTUNE goal of a 10 Gb/s backbone could be met by ten pairs of fibers. Each NEPTUNE node will contain a pair of GbE routers for redundancy.

A higher (10 Gb/s) rate version of GbE will be commercially produced in 2001, and will be evaluated when available. 10 GbE will have the same functionality as GbE, including range capability of 100 km on single mode fiber. The use of 10 GbE could substantially reduce the fiber count in the backbone cable, resulting in a significant cost reduction and enhanced data capacity..

The science instrument interface on NEPTUNE will be implemented using 10 and 100 Mbit/s Ethernet as the communications technology. A standard user interface is being developed which will operate in a "plug and play" mode, greatly simplifying the addition of new instrumentation to the network. This interface will include the incorporation of data about the data, or metadata, into the data stream.

System Monitoring and Control

Monitoring and control of the NEPTUNE data networks will be implemented using the simple network monitoring protocol (SNMP) served from network supervision work stations located on shore. SNMP clients will also be included in the power distribution system components to centralize and standardize all monitoring and control functions. SNMP clients can also be incorporated into the science instrument interface to simplify user level supervision. These high level system monitoring and control systems will function when the data communications backbone systems are operational.

In addition, NEPTUNE will include a low level or out of band control system. This will provide full control of all router functions through a standard serial interface, and can be used to configure the network and download software to the backbone routers. It also interfaces to the node power supplies. The low level control system is fully redundant, and operates on a pair of dedicated optical fibers. It consists of two separate half duplex systems operating in a master-slave mode. Each link on a given node will operate in a strict slave mode with communications initiated by a master on shore. Full duplex communication can be established by the master controller using both low level control systems for special purposes like software upgrades at specific routers.

The low level control system is being implemented using the serial ascii interchange loop (SAIL) protocol (ANSI/IEEE standard 997-1985) which is widely used in oceanographic instrument systems.

Time Distribution System

Accurate and precise time will be almost universally necessary for science experiments. This requires a reference standard and the distribution of a time signal across the seafloor network. In the US, the reference function is performed by the National Institute for Standards (NIST), who provide standard time which is distributed through the global positioning system (GPS) satellites. For NEPTUNE, high accuracy time from the GPS system will be distributed over the low level control fibers using a straightforward addition to the SAIL protocol. This allows high accuracy time to be transferred from the shore station to the nodes including correction for propagation delays on the backbone cable, and will provide synoptic time ticks everywhere on NEPTUNE. The accuracy goal of 1 μs is readily achievable.

For science users who do not require time at this accuracy, standard IP protocols are available for clock synchronization. The most widely used of these is network time protocol (NTP). Operating as a client in seafloor nodes and instruments, NTP is capable of clock synchronization with a few milliseconds accuracy across the NEPTUNE network, including correction for propagation delays.

Data Management and Archiving

Data acquisition issues include management at the source, management at the shore terminals, and quality control and assurance throughout. These must be considered as a whole rather than separately. NEPTUNE is developing a data resource that is user friendly and flexible enough to accommodate a broad range of queries. The purpose is to store data and metadata acquired on NEPTUNE in a way that ensures future availability and usability.

Physical Packaging

The seafloor nodes for NEPTUNE must be designed to facilitate the installation or removal of a large, diverse set of instrumentation. This requires the use of wet-mateable connector technology which is compatible with remotely operated vehicle (ROV) manipulators. Underwater-mateable electrical connectors for this purpose are readily available and have a good long-term reliability track record. By contrast, underwater-mateable optical connectors are an emerging technology, and are less attractive from both a cost and a reliability perspective.

While NEPTUNE will be installed using conventional cable laying technology, a major design goal has been minimization of the cost of maintenance of the seafloor plant. This precludes a design which requires a telecommunications-standard cable repair in the event of an electronic failure in one of the seafloor nodes. Since extensive use of standard oceanographic ship and ROV assets in NEPTUNE is anticipated for science purposes, it makes sense to design the infrastructure so that it can be maintained using the same tools.

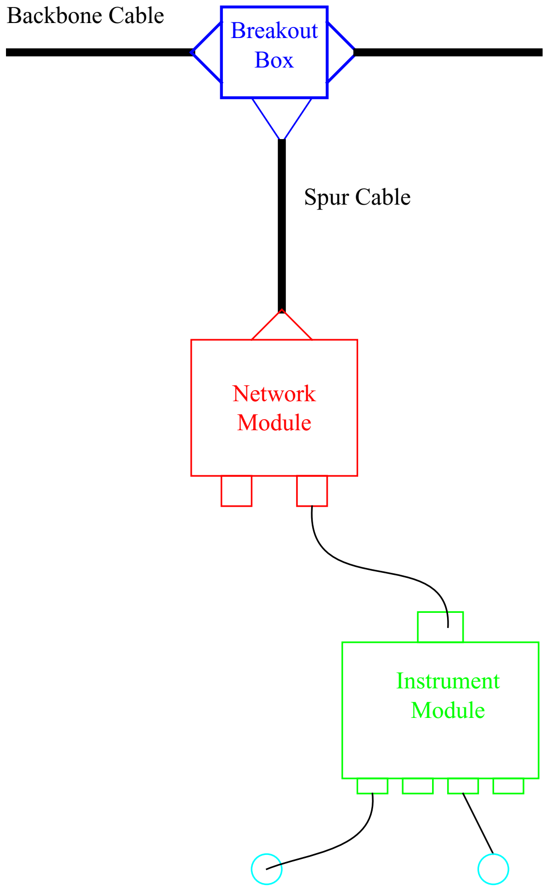

Figure 2. Sketch depicting the layout of a seafloor node. See text for discussion.

Figure 2 shows the layout of a science node. The backbone fiber optic cable contains an in-line breakout box which is functionally identical to a conventional branching unit. The third connection to the breakout box is a spur cable which is 1.5 water depths long. The spur cable contains two conductors and twice as many optical fibers as the backbone cable, and serves to bring all of these connections into the network module. The breakout box contains no active components, and should not ever require service that would necessitate use of a cable ship.

The network module contains the high (10 kV) voltage power supply and backbone router equipment, along with the low level control system. It is intended to be recoverable for maintenance or upgrading using conventional oceanographic research ship assets. This can be accomplished by attaching a lifting cable to the unit with an ROV and hoisting it with attached spur cable to the fantail of the research ship under dynamic positioning.

The instrument module contains the low (48 and 240 V) voltage power supplies, low (10/100 Mbit/s) speed data switches, and instrument control systems.It serves as the connection point for scientific instruments. The instrument module can either be located quite close to the network module or up to 100 km away, and more than one instrument module may be attached to a network module.

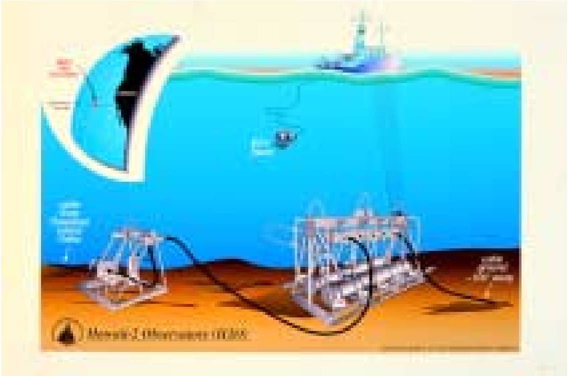

Figure 3. Cartoon showing the physical design of the Hawaii-2 Observatory. See text for discussion.

Both the network and instrument modules will be constructed like the junction box used for the Hawaii-2 Observatory (H2O) installation on the abandoned HAW-2 analog submarine telephone cable (see http://www.whoi.edu/science/GG/DSO/H2O/). Figure 3 is a cartoon depicting this ocean observatory. The junction box is about 2x1x1 m in size and is constructed entirely of titanium and plastic for corrosion protection. It contains two pressure cases to house the system electronics. An oil-filled manifold is placed about 1 m off the seafloor and houses a set of wet-mateable electrical connectors to which instruments may be attached. The H2O junction box is designed to be recoverable for servicing, and plugs into the telephone cable at a termination frame. For NEPTUNE, the instrument modules will be very similar to the H2O design. The network mode will be permanently attached to the spur cable, and hence will have an attached gimbal and cable termination box to house the necessary connections.

Conclusions

The instrumentation required for the long term study of the ocean must be supported by cable systems that provide both power and two-way communications infrastructure. NEPTUNE is the largest scale effort of this kind undertaken to date, and will facilitate a permanent scientific presence on the seafloor.