A Need for Underwater Ethernet Standards and Practices

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Abstract – The success of the worldwide Internet lies partially in the ease of installation, low-cost, reliability, and flexibility of Ethernet-based technologies, products, and standards. The same benefits might be realized for ocean observatory infrastructure if Ethernet technologies are employed. However, existing Ethernet standards were designed for terrestrial applications and must often be violated when the technology is employed in oceanographic applications that require non-Ethernet compliant connectors and penetrators.

This paper recounts recent experiences building Ethernet cabling systems for use in ocean observatory applications. Experiences with the MARS, VENUS, MVCO, PRIMO, and NEPTUNE ocean observatories are described. The possibility of research into extensions of the Ethernet standards and/or the establishment of standardized testing procedures and perhaps testing laboratories for ocean observatory Ethernet applications is discussed.

I. INTRODUCTION

The ocean sciences community is currently embarking on several efforts to design and install underwater systems (observatories, buoy systems, sensor networks, etc.) in which Ethernet is the primary communication technology being used [1][2]. Ethernet cabling standards enable the development, widespread-use, and inter-operability of Ethernet systems worldwide. However, these standards were designed for terrestrial building infrastructure and related systems. Oceanographic applications often have physical constraints that require customized wiring and non-Ethernet compliant underwater connectors and penetrators. Together, these impact the physical characteristics of the Ethernet channel. Additionally, scientists sometimes want to push the limits beyond standard specifications to extend the range to their instrumentation, even at the cost of performance.

Although many of the observatory systems that have been designed employ fiber-optic Ethernet connections to the shore as the backbone interface, they use copper Ethernet connections to scientific instrumentation. The latter can be referred to as access layer connections (as opposed to backbone layer). Although underwater fiber-optic based Ethernet systems eliminate many of these problems, they are a costly solution and not practical for all underwater connections and applications.

Based on our experiences with Ethernet cabling systems currently in use for ocean observatory applications, some of these performance impacts can be mitigated by using different types of connectors, pin assignments, and manufacturing techniques. We have built and tested systems operating at 10, 100, and 1000 mbps. For measuring the physical cable characteristics, we use a commercial Fluke 4300 cable analyzer. For Gigabit Ethernet bit error rate (BER) testing, we use a commercial Ancott bit error rate tester. Some of the cables were also tested under pressure and temperature. Work still needs to be done to characterize the performance of these systems in terms of bit error rate, range, and throughput, especially when operating outside the normal Ethernet cabling specification limits.

It is important to understand the different aspects of physical characterization of the Ethernet channel and BER testing. By looking at the physical characteristics of the Ethernet channel, we can quantitatively assess it and determine if it is within the accepted industry performance limits. On the other hand, BER testing tells us if the channel is performing satisfactory with respect to layer 1 data transport at full load (i.e., under stressful conditions). It will not identify if you are on the edge of a working system with respect to the aforementioned physical parameters. If you are near the limits, changing out a component or replacing a cable could turn a working system into one that doesn't perform well or has intermittent problems. Further, as a system ages, a working system could begin to develop problems.

As underwater communication bandwidth demands increases to 100BaseT and 1000BaseT, it becomes important to understand the characteristics of the physical Ethernet channel in terms of crosstalk, return-loss, and attenuation and the effects these have on bit error rate (BER), performance, and interoperability. Additionally, since many of these systems are custom built, optimizing the pin assignments and construction techniques can greatly aid in the physical Ethernet characteristic performance.

II. ETHERNET PHYSICAL CHARACTERISTICS AND TEST STANDARDS

Applicable Ethernet physical characteristics, terminology, and test standards are described below [3][4]. A good description on copper test parameters can be found on the web at kb.flukenetworks.com.

A. Physical characteristics

Wire-map: The wiring for the Ethernet channel should conform to either EIA/TIA 568B or EIA/TIA 568A standards. Most of the systems deployed use 568B.

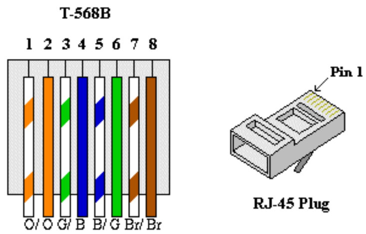

Fig 1: Ethernet EIA/TIA 568B wiring standards.

10Base-T and 100Base-TX use 2 pairs (4 wires): pins 1,2,3,6 are transmit+, transmit-, receive+, and receive- respectively. 1000Base-T uses all 4 pairs (8 wires) for bi-directional communications.

Length: Length in meters. The length should not exceed 100 meters (328 feet) for 10Base-T, 100Base-TX and 1000Base-T standards. Cat5e or Cat6 cabling is recommended.

Attenuation: Also called insertion loss. Electrical signals transmitted by a link lose some of their energy as they travel along the link. Attenuation measures the amount of energy that is lost as the signal arrives at the receiving end of the link. It is a linear function of cable length.

Return Loss: Return Loss (RL) is a measure of the reflections that are caused by the impedance mismatches at all locations along the link and is expressed in decibel (dB). Nominal characteristic impedance of each link segment is 100 ohm.

Crosstalk: Crosstalk occurs when the signals in one wire are electromagnetically coupled into another wire. As frequency increases, this effect becomes stronger. Twisting the two wires of a wire pair together minimizes the effect of signal coupling between pairs of wire in the cable. The tighter the twist, the more effective the cancellation and the higher the data rate supported by the cable. Crosstalk can be minimized by maintaining the twist rates for the entire length of the segment. Near End Crosstalk (NEXT) is the portion of the transmitted signal that is coupled back into the received signal. Far End Crosstalk (FEXT) travels in the same direction as the transmitted signal to the far end of the link.

Propagation Delay: Propagation delay is a measure of the time required for a signal to propagate from one end of the circuit to the other. Delay is measured in nanoseconds (ns). Maximum link delay allowed is 570 ns and 5.7ns/m.

Delay Skew: Delay skew is the difference between the propagation delay on the fastest and slowest pairs in a UTP cable. Skew should not exceed 50ns and skew between all pair combinations should not vary by more than +/- 10ns.

B. Testing Standards

For underwater Ethernet applications, we are primarily concerned with 10Base-T, 100Base-TX, and 1000Base-T standards (e.g., IEEE 802.3i-1990, 802.3u-1995, 802.3ab-1999). These standards are periodically revised and superceeded with newer standards. For example, IEEE 802.3-2002 has recently been superceeded with IEEE 802.3-2005.

III. EXPERIENCES WITH UNDERWATER OBSERVATORIES AND ETHERNET CABLING

A. Marth's Vineyard Coastal Observatory (MVCO)

The Martha's Vineyard Coastal Observatory (MVCO) is a cabled facility operating along the coast of the northeastern USA since 2001. The observatory provides real-time and archived coastal oceanographic and meteorological data for researchers, students, and the general public. Recently, a scientist was experiencing an intermittent Ethernet communication problem to his instrument, which in the previous year had worked fine.

One problem we encounter with Ethernet systems is that they are ubiquitous; i.e., you plug them in and they "just work". Unfortunately for underwater applications, many people don't realize that they can be on-the-edge of a working system, and without characterizing it, you wouldn't know. Upon investigation, the underwater cable that was used had several splices containing non-compliant ethernet cable. The Ethernet channel, i.e., the cable with its underwater connectors, did not pass a 100Base-T test using a Fluke 4000 cable tester. Although re-splicing was an option, reducing the length of the cable was not due to the experiment design. Due to time-constraints, and the fact that high-bandwidth 100mbps was not needed, the system was set to operate at 10mbps. Reducing the bandwidth of the system to 10mbps makes it more robust due to the difference of the transmission frequency and encoding used. The system worked satisfactory and met the needs of the scientist. It is interesting to note that protocols running on top of Ethernet, such as TCP/IP, will usually mask bit-errors via retransmissions and may result in lower performance.

B. Monterey Accelerated Research System (MARS)

The Monterey Accelerated Research System (MARS) is a single node system scheduled to be deployed in 2006. It is designed to be 50km off the coast of California in approximatly 900 meters of water. As part of the design and development of the data communication system, the Woods Hole Oceanographic Institution (WHOI) along with Ocean Design Incorporated (ODI) investigated, characterized, and tested running Ethernet (10Base-T, 100Base-TX and 1000Base-T) over the underwater science instrument Ethernet channel built for the MARS observatory. The Ethernet channel test setup is shown in Fig. 2.

We discovered that connector pin assignments can have a significant impact on the physical characteristics of the Ethernet channel. The pin assignments used for the MARS penetrators and connectors were selected based on passing the 10Base-T and 100Base-TX tests with the highest headroom for crosstalk (>20dB margin was achieved). In general, keeping twisted wires next to each other and maximizing the separation between the transmit and receive pairs yields the best results.

Construction techniques can also have a significant impact on the physical characteristics of the Ethernet

Fig 2: Test setup at WHOI. Ethernet channel consisting of a penetrator, 10meter Cat5e cable, ODI underwater ROV wet-mateable connector, 90 meters Cat5e cable, and a second penetrator. Physical Ethernet characteristic tests are conducted with Fluke DSP4000 series cable analyzer.

channel. Ethernet pairs of wires are twisted together, typically at different rates to minimize crosstalk. To maintain reliability on Ethernet, the twist rates of the pairs should be maintained and should not be untwisted any more than necessary as this can have a sizeable negative impact. The outer jacket should also be kept close to the connections. For underwater connectors and penetrators, this can be difficult due to the requirement for solder-pot boot seals. Working with ODI during the assembly process, we were able to get the twist-rate as close to the solder-cups as possible and succesfully configure the termination to achieve minimal crosstalk. The photos in Fig. 3 show a close-up of a 12-pin ODI wet-mateable connector during the assembly process.

Fig 3: Close-up of connector during the assembly process

The physical layer tests were performed with a Fluke cable analyzer, and the Ethernet channel (as shown in Fig. 2) passed the 10Base-T/100Base-TX tests and failed the 1000Base-T test. The channel is adequate for MARS since it is only designed for 10/100 mbps communications to the instruments. Should the bandwidth requirements increase to 1000 mbps, then work needs to be done on the channel to bring it into compliance with the 1000Base-T standards.

This same test setup was also used for BER testing using a Cisco 3750 Ethernet switch (running proprietary Cisco test software) and a commercial Gigabit Ethernet test device by Ancott. Results of the BER test matched the results of the physical layer tests performed with the Fluke cable analyzer – the 10Base-T/100Base-TX tests showed no errors and the 1000Base-T testing showed some errors.

Note that the backbone communications of MARS uses fiber-optic Gigabit Ethernet external to the node, and a mixture of fiber-optic and copper (1000Base-T) inside the node. We successully built and tested the copper Gigabit Ethernet channels that pass through internal bulkhead penetrators. These bulkhead penetrators are important to MARS. The communications node is split into two halves, a liquid cooled half for copper routers and a dry half for the optical devices. The half which is flooded with Fluroinert cooling liquid is separated by an internal bulkhead. Several 14-pin penetrators are embedded in this bulkhead to carry a mixture of telemetry, power, and four 1-Gigabit Ethernet links from the optical equipment to the routers. These Gigabit Ethernet links are critical. At WHOI, we were able to sucessfully transport Ethernet packets through the internal bulkhead penetrator at 1000mbps. This was accomplished only after careful experimentation with pinout allocations and maintaining the wire twists. Upon actual assembling of the production bulkhead for MARS, the intial twist rate of the Ethernet wires was maintined to only 1-2 inches of the solder cups. During consequent quality testing, the Fluke 1000Base-T tests failed. Subsequent reassembly after re-twisting the pairs corrected the problem.

The deep-water MARS observatory science cable connections also present an interesting problem for the Ethernet system. The MARS system requires full redundancy in its communication's components including the Cisco routers. In order to provide this redundancy it was necessary to cable the science instruments to both routers using a "Y" arrangement. (Due to the expense of additional pins in ocean wet connectors, it is not feasible to have double Cat5e cables all the way to the science instruments, thus we only have one Cat5e which is split inside the communications node). Note that only one side of the Y connection is attached to an active Ethernet port at a time. Nonetheless, the Y cable impacts the ability of the resulting cable to pass the physical Ethernet specification without an anomaly impedance warning since the conjunction of the science end of the cable with 2 legs each terminate in an Ethernet port, which effects the impedance of the system. This in turn could reduce the power/distance characteristic of the system.

Subsequent testing of the Y cable method at the 100mbps rate, which is all that is required for MARS, showed that the system performed within spec. However, testing at 1000mbps failed to meet the specification. In the future 1000mbps can be further tested, and perhaps an acceptable, restricted range of operation could be specified for use at these data rates.

C. VENUS Observatory

The VENUS observatory system supports two seafloor cable arrays. The first array, a 4 km deployment at 100 meters depth in Patricia Bay, Saanich Inlet, Vancouver Island, supports studies of ocean processes and animal behaviour in a confined inlet and will be deployed in early 2006. The second array, a 40 km deployment at 300 meters depth in the Strait of Georgia, supports studies of ocean dynamics, animal movements and sediments in the Fraser River Delta and will be deployed in late 2006. Each VENUS array is designed to support multiple underwater nodes linked by a common fiber-optic backbone. Each node supports a variety of instrument packages which communicate through up to eight copper 10/100BaseT channels using Ocean Design Incorporated (ODI) ROV wet mateable connectors.

In the original VENUS proposal, the scientists envisioned using Ethernet channels to communicate with instrument platforms located kilometres from the node. This requirement conflicted with the existing Ethernet standards and a compromise of trying to maximize the Ethernet channel length between the node and instruments was selected as a design goal. For compatibility with MARS and to support NEPTUNE Canada, VENUS also elected to use the same 12 pin ODI connectors and was able to benefit from the extensive testing done on the MARS connectors.

The flying leads to the science experiments were originally designed for a length of 88m. However, testing revealed that differences in dielectric properties of the fluid in the pressure balanced jumpers combined with the impedance mismatch between the wires and the wet-mate connectors resulted in failing the attenuation criteria. A maximum total length of 77m was established; equating to 70m on the science jumper, 4m on the node jumper and a total outboard pigtail length of 3m. It should also be noted that newer meters use CAT5e standards for 100Base-TX testing that essentially requires the 1000Base-T requirement for all four pairs even though only 2 pairs are required for 100Base-TX. This can result in erroneous cross-talk failures being observed. This was resolved by analyzing the detailed output for the functioning transmit and receive channels [5].

D. Polar Remote Interactive Marine Observatory (PRIMO)

PRIMO is a cabled observatory scheduled to be deployed in 2006 approximately 3 miles south of Palmer Station, Anarctica in 130m of water. The observatory will consist of a vertical profiler with CTD, current meter, sensors for chlorophyll and CDOM fluorescence, oxygen, nitrate, a bio-optical package, and an under ice video observation system The profiler will rise to the surface multiple times per day from a seafloor-mounted platform consisting of a winch, ADCP, and a remote video camera. This system requires high-bandwidth 1000mbps connectivity directly to some of the instruments. Although fiber-optic Ethernet connections are used as the backbone interface to shore, due to cost and complexity, we prefer to use a 1000mbps copper interface for the instrument connection. The total length of the Ethernet channel is short, i.e., 1-2 meters, so crosstalk is our primary concern.

To minimize cross talk, and based on our experience with the MARS system, we selected oversize Subconn 12-pin penetrators/connectors. These penetrators/connectors would provide us with maximized pin separation between all the transmit and receive pairs of the Gigabit Ethernet interface (see Fig. 4).

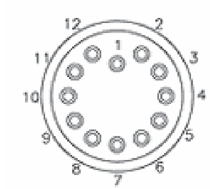

Fig 4: Subconn 12-pin connector spacing. GigE pairs connected to pins 2&3, 5&6, 8&9, 11&12.

The Gigabit Ethernet pairs were connected to adjacent pins, and separated from the next pair by an unused pin. The Ethernet channel consists of 2 female bulkhead penetrators, an in-line connector, and Cat6 cabling. Total length is approximately 2 meters. Physical testing with the Fluke 4300 cable analyzer demonstrated that the Ethernet channel passed 1000Base-T tests with more than 4dB headroom (see Fig. 5)

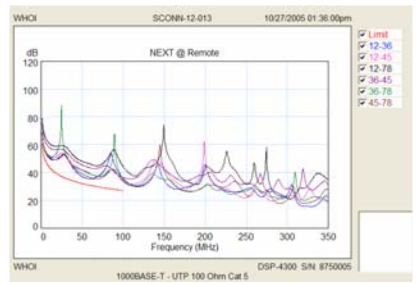

Fig 5: 1000Base-T crosstalk measured over Ethernet channel with 2 bulkhead penetrators and 1 in-line connector.

E. NEPTUNE Observatory

Neptune USA is pending until at least 2007, and NEPTUNE Canada has begun this year. The 100Base-TX Ethernet constructs of the initial Neptune design were templated to MARS since the latter is a prototype. However, as we approach the NEPTUNE implementation date it is likely that science would deisre 1000Base-T copper connections to their instruments. At this time we will embark on characterizing and developing science cables for this data rate.

IV. LESSONS LEARNED

We have shown that 10Base-T, 100Base-TX, and 1000Base-T systems can operate properly through underwater cables, connectors, and penetrators. However, it is critical that the wiring is correct (e.g., EIA/TIA-568B), and that attention be addressed to pin assignments, type of cable used (Cat5e/Cat6), wire twist rates, and manufacturing techniques. Additionally, there is a need to physically characterize the Ethernet channel to avoid operating near the limits of the system, especially for long-term deployments or where interoperability may be an issue. There is also a need to provide BER testing and/or packet-level testing for when the node is deployed, and for performance monitoring and diagnostics. Using high-quality cabling such at Cat5e or Cat6 is recommended to increase any margin. For underwater applications where mechanical stress and vibration is a concern, stranded Ethernet cable is recommended.

Standards change over time, and there will be a need to document which standards are applicable for underwater Ethernet applications. Additionally, identifying and recommending standard commercial test equipment and procedures could prove useful, as well as developing inexpensive BER/IP packet testers for observatory interoperability testing.

V. FUTURE WORK

A. As more ocean observatories are installed, we need to collect more information and experiences in underwater Ethernet applications.

B. Develop tables of BER vs throughput vs distance and include entries that are outside of the normal specifications (e.g., scientists who want to push 200meters and are willing to sacrifice speed).

C. Connector testing – recommendations for connectors and pin assignments for 100Base-TX and 1000Base-T applications.

D. Consider an IEEE effort to develop Ethernet cabling standards for underwater application.

E. Investigate building inexpensive BER/IP packet testers for observatory infrastructure interoperability testing.

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