Network nodes for ocean data exchange through submarine fiber optic cable repeaters

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OCEANS 2022, Hampton Roads | 978-1-6654-6809-1/22/$31.00 ©2022 IEEE | DOI: 10.1109/OCEANS47191.2022.9977361

***Abstract*— As humanity progresses and globalization advances, humanized environment and associated systems increase in complexity and size. In earth systems, oceans represent an essential element of equalization and normal functioning. Ocean-atmospheric interactions are nowadays believed to be at the heart of all earth vital signs and climatic behaviours, and therefore are essential to accurate monitoring and understanding of earth systems. The work presented is a preliminary result of the K2D- Knowledge and Data from the Deep to Space, project which addresses the challenge of creating underwater network nodes to provide power and communication to land through the submarine fiber optic cable repeaters. The N^{2}ODE system will consist of a set of subsystems that will allow continuous monitoring and interaction with fixed and mobile underwater devices.**

***Keywords*— submarine fiber optic, optic cable repeaters, underwater communication, continuous monitoring and interaction.**

I. Introduction

Climate change and overexploitation of resources are impacting ocean ecosystems in an unprecedented way. Conversely, societies are becoming complex and very sensitive to environmental factors. The comprehensive description and monitoring of marine ecosystems are urgent and require new approaches, that enable both biodiversity preservation and social risk reduction. The deep-sea environment is the most challenging regarding in situ data acquisition and presents the largest information gap [1] [2].

The K2D (Knowledge and Data from the Deep to Space) project addresses this gap by proposing to take advantage of the already existing (and future) large and widespread infrastructure of telecommunications subsea cables (Fig 1) to produce a network of real-time continuous monitoring of oceanographic variables. The underlying concept takes advantage of the signal repeaters distributed along communication cables to establish data and power access points. Therefore, it aims to the development of a global-scale monitoring system for oceans, able to tackle the entire water column in all existing depths, from the deep sea to coastal areas. This proposal is based on the integrated operation of Autonomous Underwater Vehicles [3], allowing the cost-effective gathering of extensive and complete ocean data, including physical, chemical and biological variables [4].

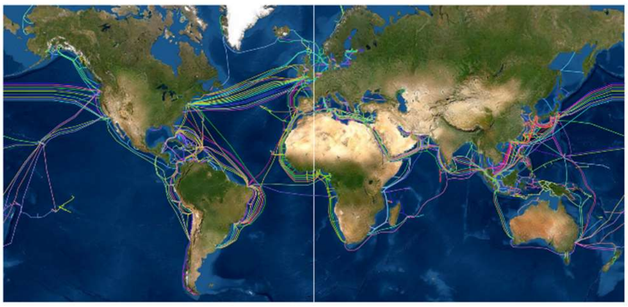

Fig 1. The current state of the existing submarine telecommunication cables network (obtained from TeleGeography's Telecom Resources).

For this purpose, newly deployed cables would be equipped with sensors connected to their signal repeaters, forming what is known as SMART (Science Monitoring And Reliable Telecommunications) cables [5]. Examples of key variables that can be measured extensively and in a cost-effective way by SMART cables are ocean bottom pressure, sea surface height, subsurface temperature, and salinity. The continuous observation of such variables would allow the study of phenomena such as the variability in the Atlantic Meridional Overturning Circulation (AMOC), sea level change, barotropic tides and wind energy flow [5]. Bottom sensors associated to the cables and AUVs in the water column, combined with satellite data, show great potential to provide data for novel ocean models and a more complete description of ocean-atmosphere interactions and the marine environment.

II. System Description

The key components of the K2D system are the N²ODEs, multipurpose devices designed to be installed in the vicinity of the repeaters, forming local observatories or monitoring stations, spread along small-to-moderate distances. These devices form a tree-like structure, rooted in the cable repeaters. The main intention is that this structure can be versatile, varying in shape, size, number, and type of systems that can accommodate. A representative sketch can be seen in fig. 2.

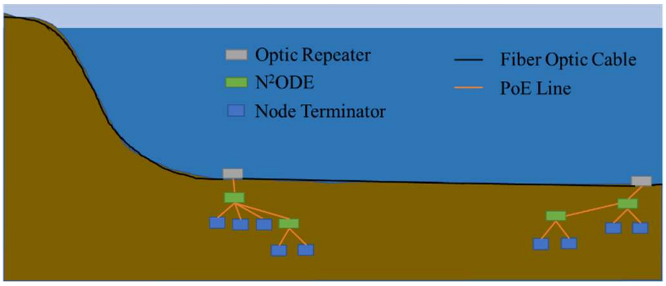

Fig. 2. Proposed submarine network, in this case showing two local observatories evolving from two different repeaters.

Repeater Interface

The repeater interface is the root of the tree-like structure, it provides the interconnection between an N²ODE system and the long communications cable. To minimize the impact on the sensitive communications equipment, the power drawn from the repeater must be kept at a minimum, also with minimum variations. From the N²ODE system perspective, the repeater interface converts the optical fiber and power lines into multiple ports with a common configuration, both physical, as well as functional, as shown in Fig. 3. In the N²ODE system, the choice standard was ethernet and power (24V PoE), using industry-standard 8-pin underwater connectors.

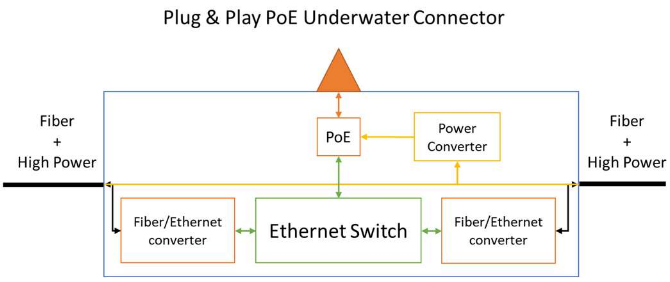

Fig. 3. Internal scheme of the repeater interface.

N²ODEs

The N²ODEs act as hubs to provide branches and extensions to the network, therefore enabling multiple topologies. All N²ODEs have the same underwater plug and an arbitrary number of matching sockets. Naturally, other N²ODEs can be attached in a cascaded configuration. In order to implement this, each N²ODE has to propagate the power connection and includes an Ethernet switch to allow the cascading of other Ethernet connections. It also includes power management electronics, so that the outputs are protected. Furthermore, it includes Ethernet-controlled relays, so that power to each output port can be individually switched on or off, as shown in Fig. 4.

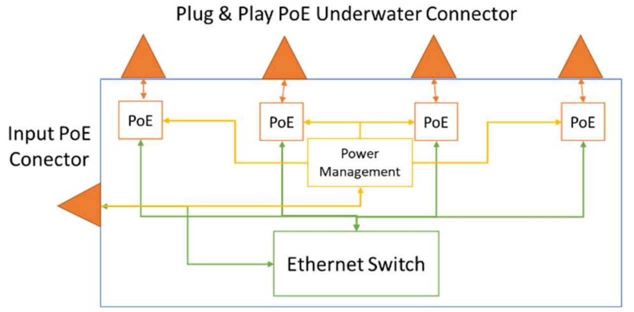

Fig. 4. Internal scheme of the N²ODE.

N²ODE Terminals

The N²ODE terminals are devices connected to any of the N²ODE sockets that do not propagate the network. Since they share the same physical connector, with the same PoE standard, they can be installed in any of the network N²ODEs, with no need for reconfiguration. These N²ODE terminals can be sensors, actuators and other system interfaces, including:

1) AUV Docking Stations

A docking station is a system interface capable of charging and relaying data to and from autonomous underwater vehicles. Mechanically, the docking station is a simple receptacle for AUVs combined with communications and localization reference peripherals. For the foreseen applications employing the K2D concept, high data rates, in the order of MB/s are required so that AUVs can upload large amounts of collected data and receive new missions remotely. However, a high data rate can only be achieved at (very) short distances, requiring AUVs to navigate at short ranges or to dock ultimately. This sets strong performance requirements for the AUVs that concern positioning. By taking advantage of the structure, landmarks and beacons are attached to the docking station to enable precise short-range localization, setting the foundations for precise short-range manoeuvring.

2) Active Beacons

Given the static nature of the N²ODE network, additional beacons can be attached to aid long-range navigation of AUVs (larger than a few tens of meters and up to the range of acoustic signals). By either employing query-response or synchronized schemes, the AUVs can use the active beacons to estimate their geolocation, assuming that the absolute position of the N²ODE terminals are known. Depending on the acoustic sensor carried on the AUV, trilateration, triangulation or a combination of both can be employed.

3) Wireless Communications

Several types of wireless communications can be implemented in order to create a line of communication between the N²ODE network and AUVs. This connection will provide strategic information about the geographic positions and share the data from the network sensors with the AUVs.

Depending on the water conditions and distance, different communication technologies can be used, for example, acoustic [6][7] or optical [8].

4) Sensors Stations

Sensor stations are terminals that aggregate sensor information and transmit it using the ethernet backbone. These sensor stations may encompass all types of sensors that can be used underwater, and these devices can still have enhanced capabilities in signal acquisition, data processing and processing, memory and communications [9].

Considering that repeaters are extremely sensitive hardware, access to the repeater is limited. Thus, for demonstrating the concept of K2D, the development of the interface with a Y connection that provides communications and electrical power is part of the core activities to undertake. For standardization of the repeater connections, a generic interface with the repeater was developed.

III. Implementation

Due to the difficulty to access a submarine optic repeater an alternative experimental setup was developed. When dealing with relatively long cables, the voltage is normally chosen to be as high as possible so that the losses originated by the current flowing over wires are minimized. In this case, to avoid any safety issues, a relatively low voltage level had to be used, therefore the operating voltage of the cable was set to 48VDC, which is considered safe for humans.

The experiment used a 60-meter-long cable, with copper wires and 2 optical fibers: one end of the connector was simulating the shore-end, while the other was prepared to be deployed underwater. The shore end was connected to a watertight enclosure, the "Shore Gateway", with a 230VAC input connection.

A. Shore Gateway

The purpose of the shore gateway is to supply power to the cable and to provide an access point to the cable and the connected devices underwater. It is a temporary device essentially used to allow the deployment of the surface end-point at any desired location. It is composed of AC/DC and DC/DC converters. The AC/DC converts the AC input voltage into a 48VDC that supplies power to the cable and to internal DC/DC, which converts to 24 and 5VDC, used to power up electronic devices, which include:

- A single board computer acting as a router, logger and basic processor of data coming in from the devices attached to the cable;
- A media converter from fiber to Ethernet;
- An Ethernet switch;
- A wireless access point to connect to an external network, connected to the Internet
- An LTE router as a backup if wireless networks connected to the Internet are unavailable.

B. Repeater Interface

The underwater end of the cable was connected to a repeater interface, a pressure housing where:

- A DC/DC converter generated the N²ODE-standard level of 24VDC from the 48VDC "high voltage".
- Another DC/DC converter generated 5VDC for internal electronics;
- A fiber-to-ethernet converter was used to convert the optic into electric signals.
- Both the ethernet and 24V lines were fused in a single RJ45 PoE connector.

C. N²ODE

The output of the repeater was then connected to the first N²ODE. This N²ODE has a 4-port Ethernet switch, with one of the outputs used to control an Ethernet-controlled relay board. The other ports are used to provide the 3 PoE outputs of the N²ODE, therefore becoming a "3-Port N²ODE". Physically, these ports are industry-standard 8-pin connectors.

D. N²ODE terminals

To demonstrate the system versatility, 4 different node terminals were prepared to be randomly connected to the 3 available ports one docking station, one IP camera, one hydrophone sampler and one sensor station with pressure and temperature (Fig. 5. and Fig. 6.).

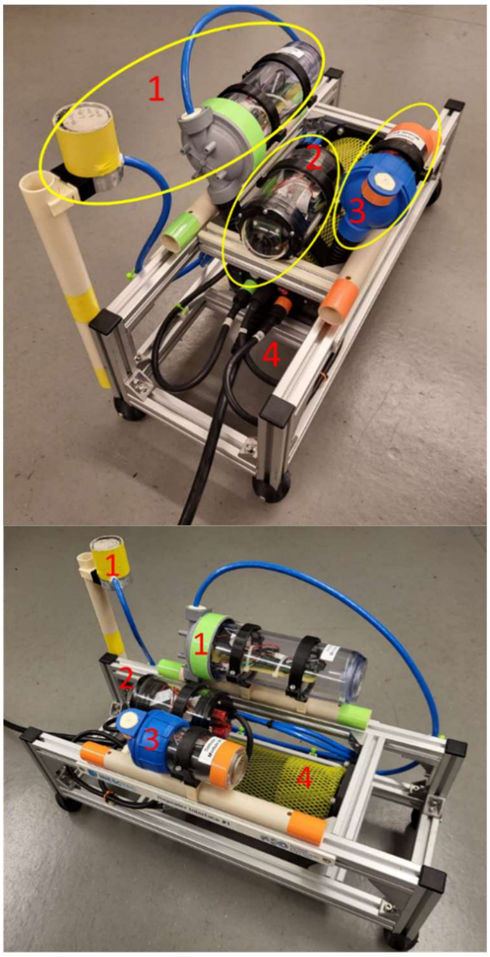

Fig. 5. Experimental setup developed to validate the network concept, 1- Hydrophone, 2- IP Camera, 3- Sensor Station and 4- N²ODE.

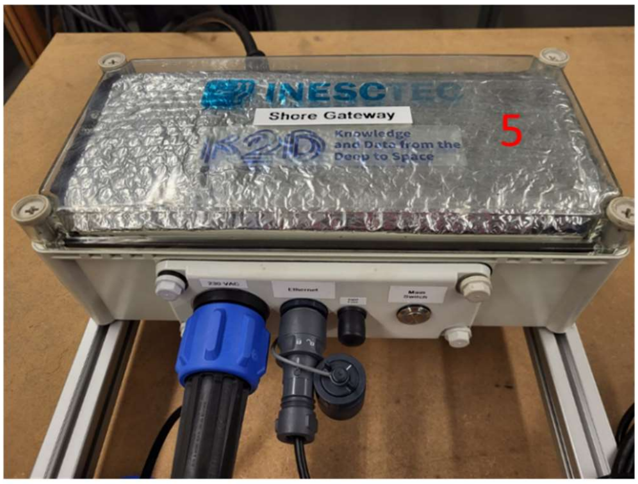

Fig. 6. Shore Gateway setup develop to validate the network concept.

i. Docking Station

A funnel-like docking station was used for the purpose of this project. It is composed of aluminium profiles supporting beacons, landmarks and watertight enclosures housing electronics, as shown in Fig. 7.

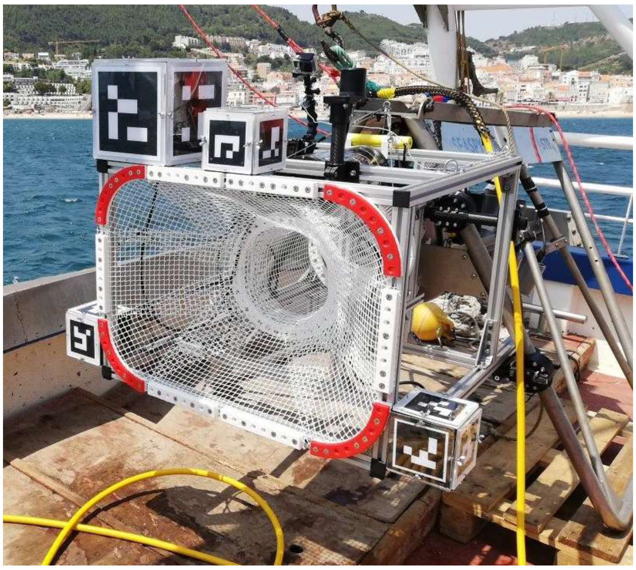

Fig. 7. Docking station setup used to validate the network concept.

The current version integrates active backlit ArUco markers and an acoustic beacon for short-range localization [10]. The watertight enclosure contains the electronics necessary to dim the lights of the markers and send periodic Phase-Shift Keying (PSK) acoustic signals. To reduce power consumption, their operation can be controlled so that peripherals are powered off whenever they are not needed [11].

ii. IP Camera

A 12 megapixels camera attached to a dedicated single-board computer was developed and connected to the repeater interface. Adding a dedicated computer enables local mildly intensive processing of the captured frames while it also enables versatility in configurations

iii. Hydrophone

The hydrophone used in the N^{2}ODE trial is a novel PVDF hydrophone for Underwater Communications and/or acoustic monitoring for frequencies between 20 and 120 kHz.

A multilayer structure was adopted for solving the low sensitivity of PVDF at frequencies below 1 MHz. The multilayer used in the piston-type hydrophone comprises 16 layers of 100 um PVDF sheets with 4 cm diameter connected in series, resulting in increased sensitivity while preserving the wide bandwidth necessary for effective underwater acoustic communications (UAWC) or other broadband applications.

The piston hydrophone is connected to a very low noise preamplifier which also acts as a high pass filter to ensure that this system effectively filtered sources of noise outside the target bandwidth. This is necessary given the numerous sources of low-frequency noise present in the marine environment, which can otherwise compromise a receiver's ability to correctly receive UAWC signals due to receiver saturation or masking.

Fig. 8. shows a comparative reception of tone signals transmitted every 5KHz between the developed PVDF prototypes (colour lines) and a calibrated TC4030 hydrophone (black line) connected to a 30 dB gain amplifier.

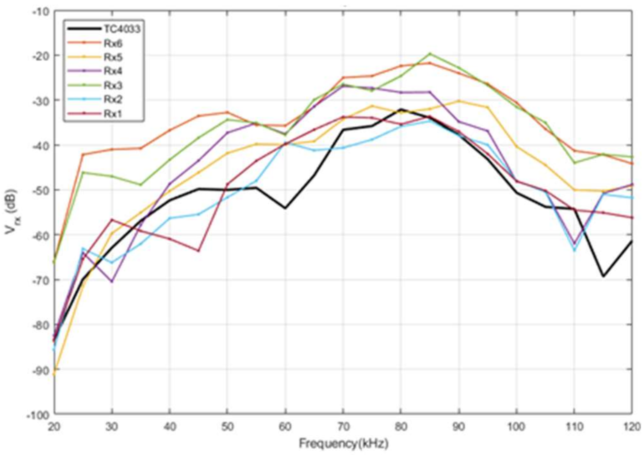

Fig. 8. Comparative reception, at 1m from the acoustic source, made with the tone signals between the PVDF prototypes and the calibrated PZT Hydrophone TC4033 connected to a CA1702 with 30dB gain.

Fig. 8. also shows that there is a gain variability between the prototypes which is probably due to the hand-made prototyping and that the signals received by the prototypes are equal to or higher than the signals received by the TC4030.

iv. Sensor station

The Sensor station has the main purpose to provide a central unit to use monitoring sensors and deliver data about water parameters.

To do so, a STM32L056C6T6 is used to control and process the measurements of the sensors. In this first implementation, it was used the sensor MS5837-30BA to measure temperature (-20ºC to 85º and 0.1ºC resolution) and pressure (0 to 30bar and 0.2 mbar resolution). Other sensors can be directly connected if using UART, I2C or SPI communication protocols.

To connect the Sensor station to the ethernet, a UART-ETH Converter was used. This converter is hosted by the STM processor which can change the ETH configurations if needed. The processor uses the UART channel to send the information measured by the sensors to the converter, which injects this information into the ethernet data bus.

Finally, the Sensor Station is powered by the step-down DC/DC converter XL4015 that transforms the 24VDC from the PoE to a 5V output.

IV. Experimental Trials

The experimental setup was deployed in the Sado estuary, in Portugal, for a period of 2 weeks in September 2022. The full system can be seen in Fig. 9.

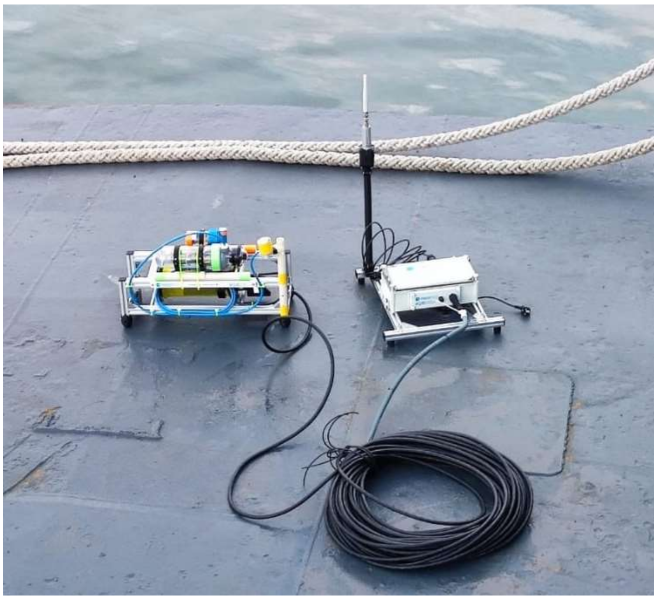

Fig. 9. The first experimental setup before deployment, with the 60-meter cable interconnecting the Shore Gateway (right) with the underwater structure (left).

The underwater component was installed with the help of Navy divers, who attached it to anchor points in the estuary bottom, to avoid current-induced motion. Depending on tide height, the depth varies roughly between 12 and 15 meters (Fig. 10.).

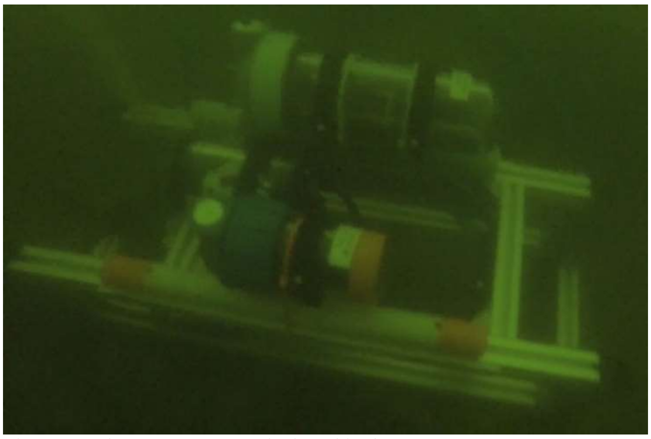

Fig. 10. Underwater structure deployed in the estuary

As far as testing was concerned, all subsystems were correctly reporting to a remote computer. As an example, Fig. 11. shows a spectrogram of an acoustic recording, retrieved from the hydrophone recording system, with a noticeable detection of a 65KHz tone from an acoustic pinger in the area.

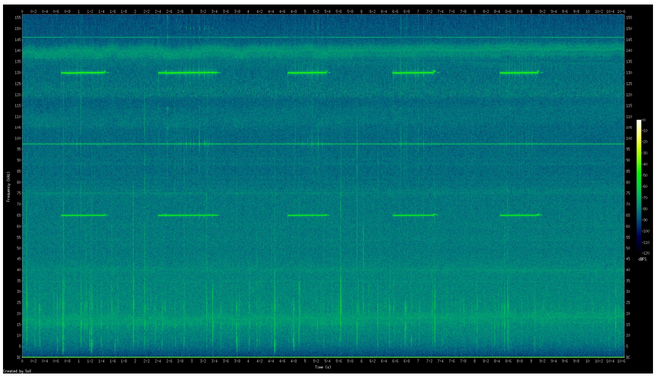

Fig. 11. Spectrogram was taken from an acoustic recording.

V. Conclusions

An underwater network to provide power and communication lines to land through the submarine fiber optic cable repeaters was presented. The optical repeater will connect to an N^2ODE through the repeater interface which converts any optical fiber and power into a known configuration. The network concept is formed by a set N^2ODEs act as hubs to extend the number and the diversity of node terminals. The system was implemented and tested in the Sado estuary, in Portugal, for a period of 2 weeks in September 2022, providing real-time access to sensor data, video and audio streaming. The node terminators were replaced in run time proving the network's versatility.

Acknowledgement

This work is co-funded by the project K2D: Knowledge and Data from the Deep to Space with reference POCI-01-0247-FEDER-045941, co-financed by the European Regional Development Fund (ERDF), through the Operational Program for Competitiveness and Internationalization (COMPETE2020), and by the Portuguese Foundation for Science and Technology (FCT) under the MIT Portugal Program. This work is also cofinanced by national funds through FCT–Fundação para a Ciência e Tecnologia, I.P., under project SONDA (PTDC/EME-SIS/1960/2020). T.M. thanks FCT for grant SFRH/BD/145070/2019.

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