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Review

Technology Review of Cabled Ocean Observatories

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Abstract: Cabled ocean observatories (COOs) have enabled real-time in situ ocean observations for decades, thereby facilitating oceanic understanding and exploration. This review discusses typical COOs worldwide in terms of system configurations and state-of-the-art technology, including network structures, power supply modes, and communication capabilities, and provides a comprehensive analysis of their technical routes. The main characteristics of line, ring, star, and grid networks and their applicability in COOs are elucidated, and the advantages and disadvantages of various power supply modes, as well as the opportunities brought by the development of communication technologies, are described. The insights gained from these discussions can inform the implementation of grid structures, optimization of cable routings, expansion of COO scales, application of dual-conductor submarine cables, and upgrading of communication capacity. On this basis, the challenges and future research directions related to COOs are presented.

Keywords: ocean observatory; submarine cable; network structure; submarine communication; power supply

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1. Introduction

The rapid development of electrical power, communication, and electromechanical technologies has enabled the construction of in situ sensing systems for ocean observations. Since the 1990s, multidisciplinary cabled ocean observatories (COOs) have been installed on the seafloor, even at thousands of meters under the surface [1,2]. Submarine cables are used to feed power and transmit information, and as a result, real-time data can be obtained any time. This approach has revolutionized oceanography research [3] by enabling continuous observations of seafloor environments and water columns [4,5].

The critical infrastructure of COOs includes science nodes, submarine optical cables, and shore stations. Submarine optical cables connect numerous types of equipment to shore stations [6]. COOs provide more possibilities for connecting researchers, educators, and the public [7]. The technological breakthroughs promoted by COO solutions will expand the applicability of products originally designed for submarine communication networks. These non-telecommunication applications are expected to contribute significantly to the development of the industry over the coming years [8].

After decades of development, COOs have evolved from isolated observatory stations to observatory networks that cover entire regions of sea. The scale is constantly expanding, and the functions are becoming increasingly complex. Notably, the submarine networking, high-voltage DC power supply, and long-distance data transmission technologies determine the basic form and normal operation of COOs.

2. State-of-the-Art Research and Development

To date, many countries have constructed COOs, mainly for scientific observations. The system scales, network structures, layout depths, sea environments, and investment details of these networks vary widely, and these projects adopt distinct technical routes with unique network characteristics.

2.1. Network Structure

There are currently significant differences among COOs around the world. Some systems have thousands of kilometers of backbone cables, whereas some only have a few kilometers. However, most of them use common network structures, such as lines, rings, and stars. The network structure selections are generally based on reliability evaluations, life cycle costs, and the technical feasibility of construction, maintenance, and operation.

2.1.1. Line Networks

In a line network, each node is connected in series, and therefore, this type of network requires the shortest cable length. Additionally, they are relatively straightforward and inexpensive to construct. However, once the cable fails, the entire network will fail. Thus, the reliability of this type of structure is low.

In general, line networks are used in systems with relatively simple or singular tasks, such as the Victoria Experimental Network Under the Sea (VENUS) [9] in Canada, the Monterey Accelerated Research System (MARS) [10], and the Martha's Vineyard Coastal Observatory (MVCO) in the United States. The task nodes in a line network are usually simple, although this does not necessarily mean that the network scale is small. A typical example is the Seafloor Observation Network for Earthquakes and Tsunamis (S-NET) [11] in Japan, which includes six segments. Each segment is a line network, and the six parts together comprise a ring network [12]. Because the equipment installed in this system is relatively simple, all nodes were connected in series on the backbone cable.

2.1.2. Ring Networks

Similar to line networks, each node in a ring network is connected in series. Owing to the ring structure, information and energy can be transmitted in two directions, which increases the reliability of ring networks relative to line networks. Additionally, the transmission and control mechanisms are relatively simple because each node only has one physical link with adjacent nodes. However, it is not easy to expand ring networks because of their closed loop structure. Moreover, in a ring network, a slight modification in one node may affect the entire system.

Compared with a line network, the biggest advantage of a ring network is that when a backbone failure occurs, the system can usually continue operation if it has fault tolerance or fast isolation capabilities. Most of the ring network structures worldwide are large-scale systems. For example, the North-East Pacific Time series Undersea Networked Experiments (NEPTUNE) [13] in Canada was the first large-scale deep-sea COOs in the world [14]. It has 800 km of backbone cables, 120 km of spur cables, and 60 km of extension cables [15,16]. Other larger ring networks include the Dense Ocean Floor Network system for Earthquakes and Tsunamis (DONET) [17] and the DONET2 [18] in Japan. DONET is a long-term seafloor earthquake and tsunami monitoring network led by the Japan Agency for Marine-Earth Science and Technology (JAMSTEC), with a total length of approximately 320 km. Construction of DONET2 (with a backbone cable length of 450 km) began in 2010 to expand the monitoring area to the west of DONET.

2.1.3. Star Networks

A star network has a central node, such that all other nodes are connected directly to the central node. This structure facilitates centralized control because all communication between nodes must proceed via the central station. Moreover, a single node (besides the central node) failure will usually not affect the operation of other nodes. Star networks are easily expandable in terms of adding new nodes. Only one submarine cable needs to be linked to the central node, and other nodes operate independently. This feature also makes it easy to diagnose and isolate faults relative to the central node. In addition, because data communication for all nodes must be transmitted through the central node, which facilitates management and maintenance. Therefore, many "node-type" COOs use star networks to connect various instruments through extension cables, e.g., NEPTUNE, DONET, and DONET2.

However, the long cables needed for a star network increase the overall cost of the submarine system in terms of installation and subsequent maintenance. Additionally, a star network is highly dependent on the central node, i.e., the entire network will fail if the central node fails. Therefore, the reliability of the central node must be extremely high, which introduces some difficulties for subsea systems. As a result, star networks are rarely used as the backbone for COOs.

2.1.4. Grid Networks

In a grid network, each node is connected to at least two other nodes. This structure has high reliability; however, the structure is complex, and the construction costs are high.

Grid networks were implemented for COOs as early as 20 years ago. The NEPTUNE project in North America, which has a grid network architecture, was proposed around the year 2000. Japan designed a new type of submarine cable network for scientific research, the Advanced Real-Time Earth Monitoring Network in the Area (ARENA), in January 2003. Additionally, construction of a subsea network with grid topology was planned around the Japanese archipelago [19–22]. The ARENA project was stopped at the demonstration stage because of financial and technological reasons, and construction was not reinitiated.

One of the advantages of a grid network is that each observation node can be accessed from multiple landing stations. Thus, even if one segment of submarine cable loses power and data transmission capabilities, all observation nodes in the network can continue to function and transmit data to the shore [23].

With the rapid development of related technologies, especially circuit fault isolation and protection, remote intelligent monitoring, and operation health management [24–31], it has become increasingly feasible to design and construct grid networks. However, the growing network scale potential increases the possibility of system failure. Therefore, more efforts should be invested in designing the routing systems to reduce the probability of damage due to human activities.

2.2. Power Supply Modes

In most cases, COOs use a direct current (DC) power supply, which can be either constant current (CC) or constant voltage (CV) [32]. In the CC mode, all nodes are connected in series, whereas in in the CV mode, all nodes are connected in parallel using seawater as a current returning pathway.

2.2.1. DC Constant Current

The CC feeding system is commonly adopted by submarine communication systems owing to the following advantages.

(a) It is robust against submarine cable shunt faults. Because power is usually supplied from both ends of the submarine cable, even if the cable is disconnected at one point, power continues to be supplied. Thus, only the potential distribution of the submarine cable changes.

(b) When a submarine cable shunt fault occurs, it is easy to locate the fault point by measuring the DC resistance between the feed line and the ocean ground when the system structure is simple [23].

Systems using the CC mode (e.g., DONET, DONET2, S-NET) have fewer types of instruments and fewer functions, e.g., earthquake and tsunami early warnings [33]. Cable systems using retired communication submarine cables, such as A Long-Term Oligotrophic Habitat Assessment (ALOHA), the Hawaii-2 Observatory (H2O), and the Hawaii Undersea Geo-Observatory (HUGO), also adopt the CC mode because it is compatible with the existing communication submarine cables.

In addition, a CC system cannot be easily branched to form a grid network, and its energy utilization rate is relatively low [33]. Therefore, this mode is typically not adopted in systems with complex tasks or diverse instruments. The S-NET system is currently the largest submarine earthquake and tsunami observation network in the world, and the scale of its cable system is several times that of NEPTUNE Canada or the Ocean Observatories Initiative (OOI) Regional Cabled Arrays (RCA) [34]. However, S-NET has no extension interface, and the total undersea load is at least an order of magnitude smaller than that of NEPTUNE Canada or OOI RCA.

2.2.2. DC Constant Voltage

The CV mode represents new technology in the submarine communication field. In long-distance submarine cable communication systems, the traditional CC mode can effectively prevent shunt faults, which are the most common type of failures in submarine cables. However, the CC mode cannot support the power level required by each node (e.g., NEPTUNE requires up to 10 kW), nor can it carry sufficient power several hundred kilometers away from the backbone [8].

In a system adopting the CV mode, the power feeding equipment outputs a constant voltage, and all nodes are connected in parallel, with seawater serving as the current loop. If branches are required in the network, the nodes can be installed anywhere, and it is easy to configure the system with a ring or star topology. The parallel operation scheme of a CV power supply means that the current of each section of the backbone can be different, and thus, the CV mode can provide significant power while easily adapting to variable loads. For these reasons, the CV mode is more suitable for purpose-built or science-driven COOs [35]. In fact, most recent COOs apply the CV mode, including VENUS, NEPTUNE Canada, MARS, and OOI RCA.

The main conclusion drawn from numerous preliminary studies is that large multi-functional networks should use the CV mode. Moreover, a key factor for a large network is its ability to provide power at locations far away from the backbone because scientific instruments may be located in geologically active areas of the seafloor where communication cables are not typically laid [8].

In a sense, NEPTUNE Canada and OOI RCA adopt hybrid modes, and they require sufficient currents to maintain the operation of the repeaters and to provide power to the observation nodes. Dummy loads are therefore commonly required to minimize backbone currents [33]. In NEPTUNE Canada, the optical repeaters on the backbone are adjusted to higher currents and a wider current range. Although this approach is more flexible, it also involves more complex and expensive repeaters [35].

2.2.3. AC Power Supply

There are a few systems that employ an AC power supply, although this is only suitable for short cable distances because much more energy is consumed on the line than in the DC feeding method. For example, in the year 2000, the Woods Hole Oceanographic Institution (WHOI) built a coastal observation system (i.e., MVCO) near South Beach in Edgartown, Massachusetts. The system was close to the shore, and a single-phase 60 Hz AC power supply was used to avoid significant modifications to the power supply system of the shore laboratory. The cable has six conductors instead of three, as in a common three-phase circuit. The six conductors provide power to three separate power circuits at sea, and the six AWG13 power conductors in the submarine cable are insulated to 2.5 kV, which allows for the use of step-up transformers and single-phase 60 Hz AC [36].

Although both CC and CV modes have limitations, the development of related technologies is gradually compensating for these deficiencies. For example, high-power PFE (Power Feeding Equipment) equipment [37] can provide more power for CC systems, and various cable switching and fault isolation technologies can effectively reduce the risk of cable grounding in CV systems.

2.3. Communication Capacity

The acquisition of high-quality data is the foundation of ocean observation efforts, although the acquisition of massive amounts of data and deep mining are also important for increasing our understanding of the ocean. The multidimensional and real-time observation data acquisition capabilities of COOs continue to grow at an accelerated pace. COOs can support instruments that previously could not be used long-term on the seabed, such as camera lights, winches, tethered vehicles, and electromagnetic pulse generators. These complex and diverse instruments can operate continuously for long periods of time while avoiding the limitations and high costs of satellite data transmission; moreover, they can generate terabytes of data per year, which is orders of magnitude more than that collected from the oceans with previous instrumentation [38]. For example, a single node of NEPTUNE Canada running for two years will store over 1500 GB of data [39]. In 2000, the initial data flow for the basic scientific requirements of NEPTUNE Canada was predicted to be more than 60 TB/year [40].

The main requirements for COOs are communication stability and capacity. The stability aspect is straightforward for COOs, i.e., as long as the submarine cable does not fail, there is no need to worry about the impacts of meteorological conditions, the electromagnetic environment, or other factors. In contrast, increasing the capacity is rather difficult. Many COOs have been limited by the state-of-the-art of communication technology at the time of construction. For example, the capacity of one wavelength in submarine fiber-optic communication systems has increased from <2.5 G (before 2000), to 10 G (2005), to 40 G (2010), to 100 G (2012), and reached 200 G around 2018. The capacity is also limited by junction boxes, repeaters, and branch units (BUs).

Meanwhile, the transmission capacity of fiber communications has increased from the Kb level to currently over 400 Gb thanks to the development of optical fiber manufacturing technology, optical chips, optical amplification, polarization multiplexing, coherent detection, and digital signal processing, as well as improvements to the symbol rate and modulation mode. These factors also make it possible to significantly enhance the communication capacity of COOs by upgrading shore station equipment. The use of a single fiber can be improved by implementing an optical add-drop multiplexer (OADM) or reconfigurable optical add-drop multiplexer (ROADM) technology.

Table 1 presents the main technical parameters of selected COOs.

Herein, we discuss several typical COOs in terms of network structure, communication capacity, power supply mode, and construction pattern to highlight key insights and propose novel ideas.

Table 1 indicates that, in terms of network structure, COOs constructed before 2008 are generally of smaller scale and have relatively fewer nodes, and all of then adopt line network structures. However, the scale of these networks has gradually expanded with the development of relevant technologies. Ring networks have been adopted in the backbone, and star networks have been used in some branches. In terms of the power supply mode, CV has always been the mainstream because this mode can provide more power and adapt more easily to variable loads. For these reasons, the CV mode is more suitable for COOs with multiple functions.

The CC mode also has been used in certain scenarios. Several large-scale COOs in Japan have adopted the CC mode, which is mainly used to monitor tsunamis and seismic activity. In addition, the CC mode has been widely used in transoceanic communication systems. Therefore, COOs using retired cables will typically adopt the CC mode.

In terms of communication technology, unrepeated systems are usually less than 300 km, whereas repeated systems may extend beyond this distance.

Table 1. Main technical parameters of the representative submarine observation cable networks.

No.	Name	Country/ Region	Year	Length of Backbone Cable	Network Speed	Power Mode	Max Power	Max Voltage	Max Current	Max Depth	Number of Nodes	Number of Repeaters	Number of Branches
1	A Long-Term Oligotrophic Habitat Assessment (ALOHA) [5,41,42]	US	2007	20 km	100 Mb/s	CC	1.2 kW	1 kV	1.6 A	4728 m	1	0	0
2	Dense Ocean Floor Network system for Earthquakes and Tsunamis (DONET) [43]	Japan	2011	320 km		CC	3.3 kW	3 kV	1.1 A	4400 m	5	5	5
3	DONET2 [44,45]	Japan	2016	450 km		CC	5.5 kW	5 kV	1.1 A		7	8	7
4	Long-term Ecosystem Observatory (LEO-15) [46–48]	US	1996	9.6 km		CV	8 kW			15 m	2	0	0
5	Marine Cable Hosted Observatory (MACHO) [49]	Chinese Taiwan	2011	45 km	622 Mb/s	CV		0.44 kV		300 m	1	0	1
6	Monterey Accelerated Research System (MARS) [50]	US	2007	52 km	1 Gb/s	CV	10 kW	10 kV	1 A	891 m	1	0	0
7	Martha's Vineyard Coastal Observatory (MVCO) [36,51,52]	US	2000	4.5 km	1 Gb/s	AC	4 kW	1.5 kV		15 m	2	0	0
8	North-East Pacific Time series Undersea Networked Experiments (NEPTUNE) [15,16,53]	Canada	2009	800 km	10 Gb/s	CV	60 kW	10 kV	8 A	2660 m	5	7	6
9	Ocean Observatories Initiative (OOI) [54–56]	US	2016	900 km	10 Gb/s	CV	8 × 7 kW	10 kV		2900 m	7	8	0
10	Seafloor Observation Network for Earthquakes and Tsunamis (S-NET) [57–60]	Japan	2016	5500 km		CC	6 kW		1.1 A	7800 m	150		0
11	The Hawaii-2 Observatory (H2O) [2,61,62]	US	1998		256 Kb/s	CC	0.4 kW	3.3 kV	0.37 A	4979 m	1	0	0
12	Victoria Experimental Network Under the Sea (VENUS) [63–67]	Canada	2006	4 + 40 km	1 Gb/s	CV	3 kW	0.4 kV/1.2 kV		100 m/300 m	1 + 2	0	0

3. Insights and Proposals

3.1. Backbone Network

3.1.1. Using a Grid Network

Data from COO operations in various countries indicate that cable failures are the most common issue. In contrast to line, ring, and star networks, the grid network has multiple fault protection features. However, this type of network faces implementation challenges. First, in terms of power feeding, such networks require intelligent interactions among four directions of electrical power routes in the vertical and horizontal planes. A grid network can be powered using the CC or CV modes. Taking CC as an example, the power supply system typically comprises a circular power supply link and a horizontal protection link, as shown in Figure 1.

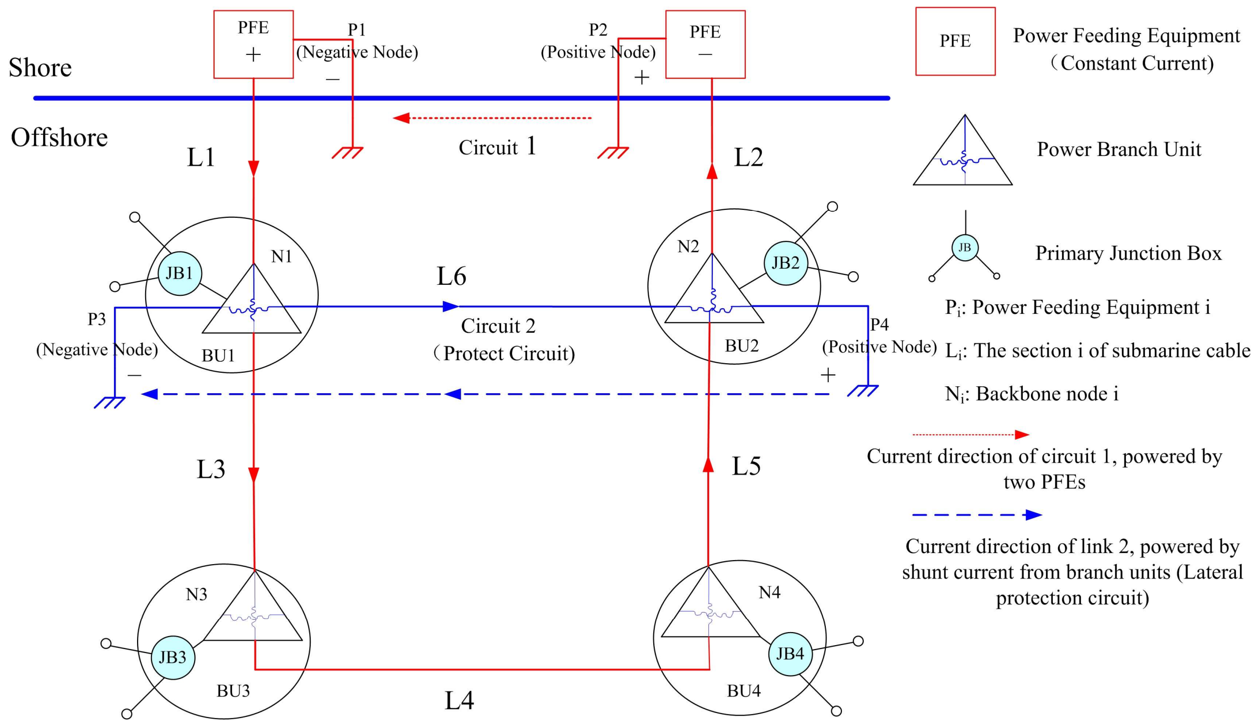


Figure 1. Schematic diagram of constant current power supply in a grid network.

The backbone network is divided into level 1 and level 2 power supply links. The level 1 link is in CC mode and is composed of a ring link; the level 2 link is also in CC mode (known as the lateral protection link), and the current is obtained from the level 1 link through the branching unit N1 or N2. When the level 1 link fails, the level 2 link is activated to provide a lateral protection power supply pathway.

To meet the requirements of a grid network in terms of information transmission, primary junction boxes (Figure 2) should be able to provide backbone transmission interfaces in four directions: north (N), south (S), east (E), and west (W). The power module distributes power to all other modules within the optical transport network (OTN) devices, thereby ensuring sufficient voltage supply. The central control module consists of a central process unit (CPU) and a communication module, among other components. It is mainly used for configuration, fault, performance, and security management of the equipment, and it also stores equipment management information. It can simultaneously interact with equipment in shore stations to send equipment information.

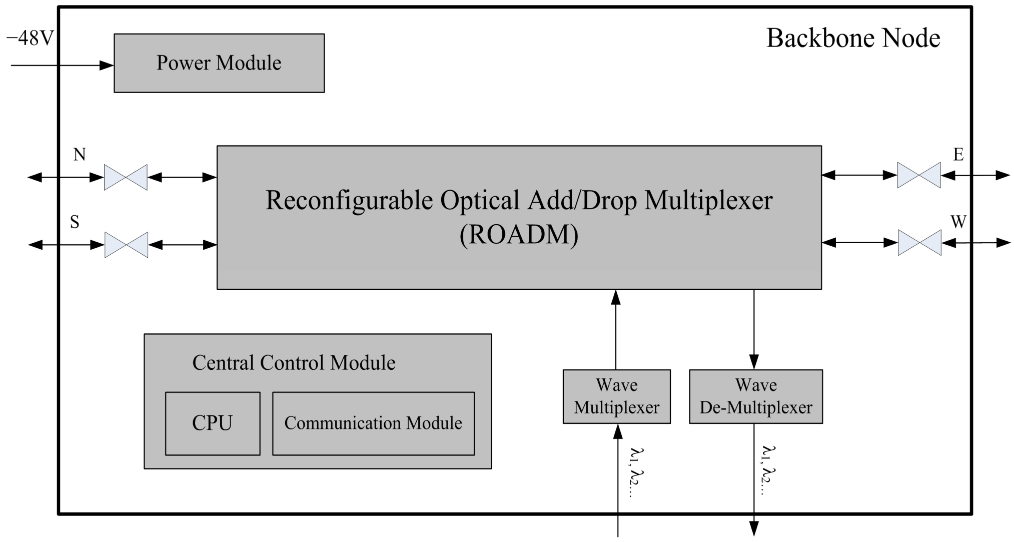


Figure 2. Block diagram of the optical transmission principle of a primary junction box.

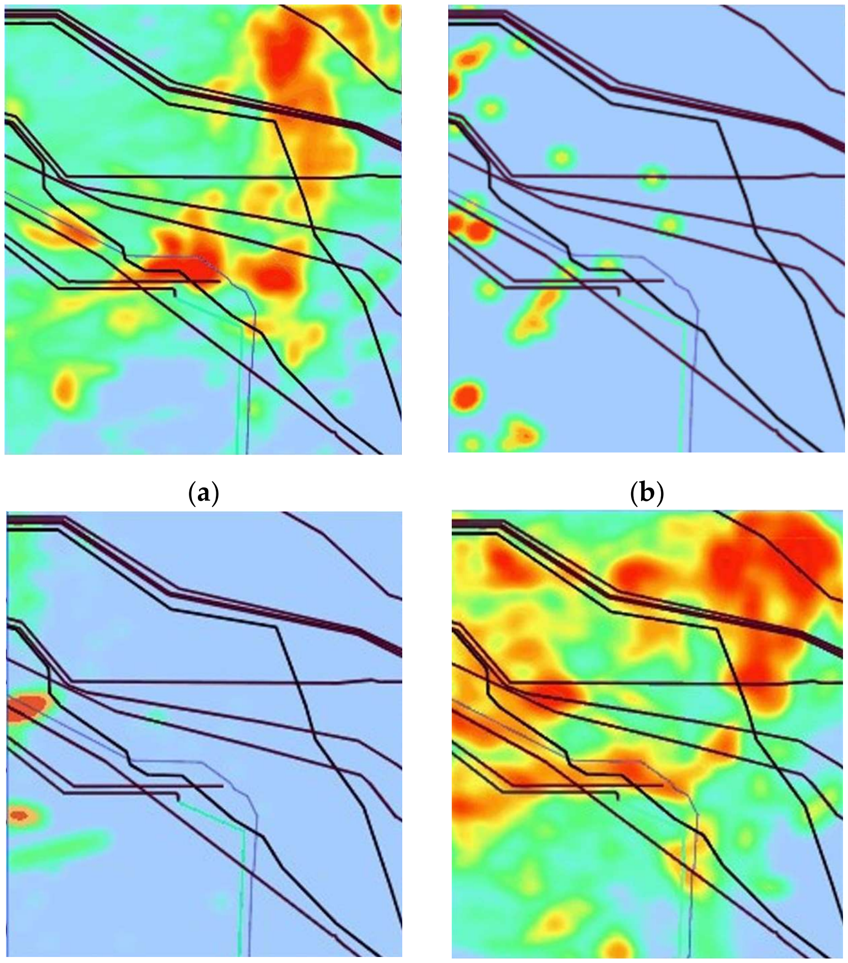
The optical amplification function module amplifies the power of the optical signal of the line to meet the signal transmission requirements of a given span. Owing to the distinct settings of each span in the optical pathway, it is necessary to provide optical amplification functional modules with different gain saturation outputs. The main function of the multiplexer module is to combine multiple optical signals that meet the wavelength division multiplexing (WDM) standard requirements into a single optical signal. The main function of the de-multiplexing module is to split an optical signal into multiple optical signals that meet the WDM standard requirements. The ROADM module is the core module of the backbone node. It reconfigures the wavelength by blocking or crossing the waves, thereby transforming static wavelength resources into dynamic allocation. It then facilitates the multidimensional flexible optical layer scheduling of the optical pathway of the integrated information transmission network.

3.1.2. Optimizing the Routing Design

Evaluation of the faults in COOs and submarine communication systems has revealed that failures in these systems are primarily caused by human activities. Taking NEPTUNE Canada as an example, in February 2011, the cable near the Barkley Canyon node was damaged by a trawl, resulting in data interruption for more than a year [14,16].

Approximately 150 to 200 submarine cables fail every year worldwide, and over 70% of these failures are related to human activities, particularly fishing and anchoring [68]. To cope with cable failures, monitoring systems can be built in the routing area to obtain the GPS trajectories and activities of vessels in the area. Moreover, the seawater near cables produces vibrations with various frequencies and amplitudes due to activities, such as vessel anchoring, excavation, or crustal movement near the cables. These vibrations represent external forces that can disturb the optical fibers in submarine cables and change the phase of the backward Rayleigh scattering. Φ-OTDR technology can be used for vibration localization via multiple-beam interference of backward Rayleigh scattering in optical fibers to prevent cable failures [69–71]. In addition, for large-scale networks, it is reasonable to join the international submarine cable maintenance area nearby for increased reliability of the maintenance system of telecom operators.

Many articles have proposed ways to mitigate cable failures [72–79], and therefore, these topics are not explored further herein. We propose only one routing design concept in this review, which can be used to collect data from fishing authorities, maritime supervision, and other related units to account for the activities of ships in the routing sea area. For example, the international submarine cable monitoring system on Chongming Island in China monitors the activity of ships nearby to determine whether they may pose a threat to submarine cables. Figure 3 shows heat maps of vessel activity captured by this system. The activity of seafaring vessels in this region has a seasonal pattern. If similar information can be obtained during the construction of COOs, it can be used to avoid laying cables in areas with frequent fishing vessel activity, thereby improving the potential long-term safety of the cable.



(a) (b) (c) (d)

Figure 3. Heat map of seafaring vessel activity. (**a**) January and (**d**) October are fishing seasons; (**b**) June and (**c**) September are the off-seasons for fishing. The colored lines (including black, blue and green et al.) represent the submarine cables in the region.

3.1.3. Using Telecom Cables

Most existing COOs are not far from the shore (usually <500 km). The number of optical fibers linking repeaters and BUs has recently reached 64 [80,81], and the communication capacity of a single optical fiber has also increased to single-wavelength 400 Gb $\times$ 64 waves [82,83]. Therefore, it may be possible to consider reserving branch interfaces for scientific observation networks when constructing transoceanic submarine cable communication systems and connecting them after the scientific observation network is completed (Figure 4). The optical path through the BU uses OADM or ROADM technology, and the additional insertion loss should be considered during the design. Specifically, the BU should have electrical switching capabilities. The backbone supplies power (turn on S1), and the branch is looped back normally. If the branch circuit is connected, the backbone will be disconnected (turn off S1), and the current will flow back to the backbone from the branch.

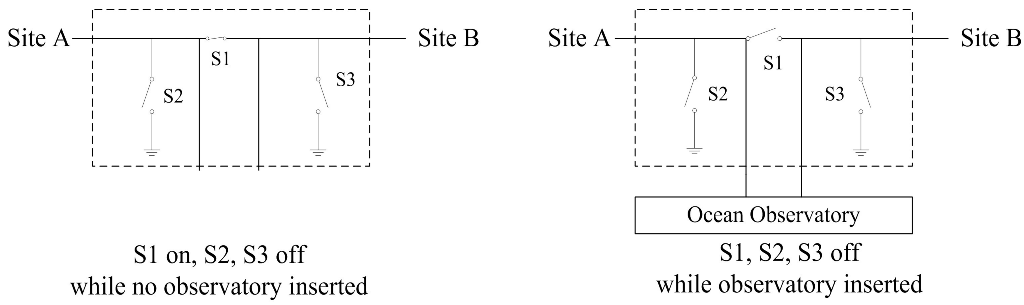


Figure 4. Schematic diagram of branching network principles.

3.2. Power Supply

The debate about CC versus CV has been ongoing for years [35,84,85]. Most of the stable COOs around the world use the CV mode, which is highly suited to the application requirements. Because COOs typically need to connect hundreds or even thousands of instruments, and remove or add new instruments, it is crucial that the network can flexibly configure the loads. The parallel relationship between loads in the CV mode can satisfy this requirement. The advantage of flexible access in a CV system is reflected in the access of instruments, although it also increases the scalability of the network, thereby making it easier to establish complex network topologies. However, the current in the CV system decreases at each step, resulting in low line power loss despite relatively high power supply efficiency. This advantage is particularly prominent in high-power systems.

However, CV systems have undeniable shortcomings. For example, once a shunt fault occurs in the submarine cable, if the potential at the location of the primary junction box does not reach the starting voltage and there are no fast protective measures, then the entire system will fail and will need to be restarted after fault isolation by BUs.

In contrast, CC systems have a higher tolerance for the most common shunt faults of submarine cable systems. After such a fault, the power supply can flow back through the ocean ground, and the operation of the unaffected section can be maintained for a short time, even if the fault is not repaired. In addition, the underwater link current of the system remains constant, and there is no complicated power supply allocation management required. Meanwhile, it is necessary to consider various fault situations when configuring and constructing a CV system, which makes the design process more difficult. Typically, specialized software is used in conjunction with simulations for such designs.

The disadvantage of CC systems is that they have poor network scalability, and thus, most of the COOs that need to support various equipment use the CV mode. In CC systems, two submarine cables (or dual-conductor submarine cables) are required to form a power supply circuit between each BU and primary junction box, leading to complex branch systems. Moreover, the power of primary junction boxes must be maintained constantly by using bypass regulators to compensate for dynamic load variations. When there is a low load or a significant load change, a significant amount of energy will be consumed in the form of reactive power, resulting in lower electrical energy efficiency. Additionally, the transmission power can only be increased by increasing the shore-based power supply current. If the power supply line is too long or the current is too high, the power loss of the line will be more significant. Therefore, the power loss of the line in a CC system is greater than that in a CV system, and this is a bigger issue for large-scale or complex networks.

Considering these features and potential challenges, we propose several ideas and suggestions in the following subsections.

3.2.1. Standardization of Critical Equipment

Currently, the scale of most COOs is much smaller than that of transoceanic submarine communication systems, and the technology related to underwater networks mainly relies on the development of communication systems, such as repeaters and BUs (mostly CC mode products). As a result, much of the equipment used for COOs needs to be customized, and generally in small quantities, which leads to high equipment costs and long development times. In addition, the operating environment of such devices is harsh, and their reliability is relatively low owing to the lack of large-scale application and verification. Therefore, it is recommended that the construction and maintenance units of COOs cooperate with a submarine system or equipment manufacturers in advance. Moreover, considering the ever-expanding scope of applications, such as ocean disaster warning systems, the development, productization, and standardization of critical equipment is crucial.

3.2.2. Using Dual-Conductor Submarine Cables

Modern COOs adopt unipolar high-voltage DC power supply technology; therefore, two submarine optical cables are needed between a primary junction box and a secondary junction box to establish a power feeding loop, and grounding electrodes must be installed at both ends. Owing to the electrochemical corrosion of the anode, this component might need to be replaced regularly, which increases the system maintenance costs and reduces the system reliability. Meanwhile, the introduction of electrodes increases the time required for integration and construction and increases the difficulty of manufacturing the access node equipment, as well as system construction and maintenance. Common structures of these cables are shown in Figure 5. Figure 5a shows that a layer of copper tube conductors is added in common repeated submarine cables, and the two layers of copper tubes are insulated by adding a polyethylene layer. Figure 5b shows the structure often used in optoelectronic composite cables [86], which can withstand relatively high voltage levels but also have a larger diameter.

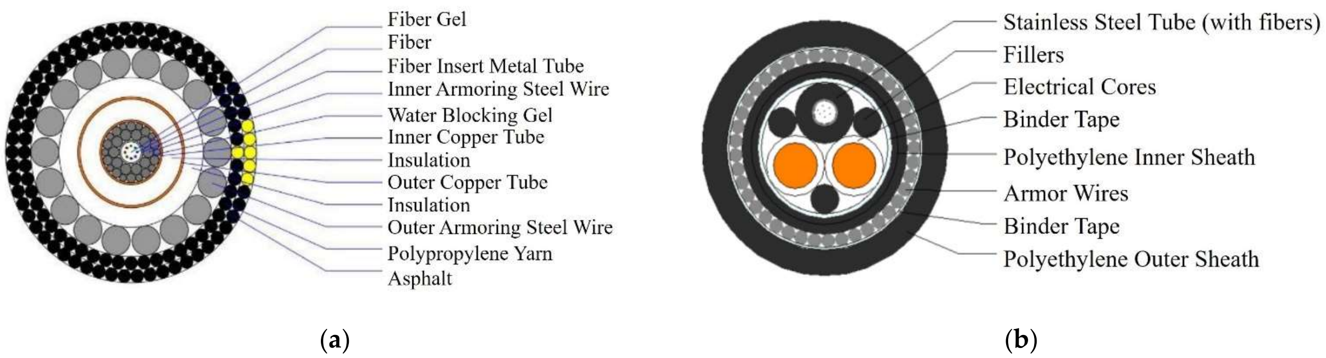


Figure 5. Schematic diagrams of dual-conductor submarine cables structures: (**a**) typical cable structure with two copper tubes; (**b**) typical cable structure with two electrical cores.

Input and output of the branch current are enabled by the double conductors of dual-conductor submarine cables, and thus, the power–information loop can be obtained using a single submarine cable. This design avoids the need to lay two submarine cables and the introduction of grounding electrodes, while reducing the BU construction and maintenance challenges.

Compared with submarine cables containing a single conductor, the application scope of dual-conductor submarine cables is limited. There is a need for further development in terms of insulation and heat dissipation in the inner layer, voltage resistance between two insulation layers, and insulation of matching junction boxes. When the inner and outer layers have different polarity, the voltage between the inner and outer layers will be double that of conventional cables.

The structure in Figure 5b has better voltage resistance and heat dissipation. This composition increases the diameter of the cables because the structure has three cores that need to be made separately and then twisted together during production. Because the size of the reel for storing a core is limited, the maximum length of this type of cable structure is typically less than 5 km. Therefore, the manufacturers of structure (b) are considering expanding the capacity of the storage reels. Meanwhile, they are also trying to improve the production line efficiency to reduce the restriction from storage reels.

The structure in Figure 5a is widely used when a long cable is necessary. Ideally, the thickness of the insulation layer should to be increased while improving the voltage resistance level; however, this will increase the diameter of the cables and affect the heat dissipation. Therefore, the current developmental goal is to improve the stability of production processes, e.g., by avoiding tip discharge caused by the edge warping of the outer conductor.

In addition, junction boxes matched with dual-conductor cables have two layers of insulation, and some manufacturers adopt the method of double injection molding. The high temperatures generated by injection molding will soften the inner insulation, and the state of the inner insulation will be uncertain. Some manufacturers can complete two-layer insulation via single injection [87], which is an important advancement. However, it is still not possible to ensure that the inner insulation remains intact. Therefore, the structure of the junction boxes must be improved further to eliminate this risk.

However, dual-conductor submarine cables are often used as spur cables between the primary and the secondary junction boxes, rather than as backbone cables. In the DONET system, where the voltage of the backbone cables is 3 kV DC, the current is 1 A, and the dual-conductor submarine cables are used between scientific nodes and BUs, with a DC resistance of <1.0 Ω/km [44]. Therefore, individual segments are usually short, and there are fewer requirements for the production technology.

3.3. Communication Capacity

3.3.1. Upgrade the Communication Capacity Gradually

The potential communication capacity has grown from 10 G to 100 G or even larger; meanwhile, the power feeding requirements are decreasing, leading to heating reduction. Therefore, COOs meet the technical conditions for upgrading. The 100 G system has unique advantages compared with the 10 G system. The 10 G system is based on the on-off keying (OOK) mode and has a low tolerance in terms of dispersion in the system. The dispersion tolerance of a typical 10 G module is between 800 and 1600 ps/nm·km, and such systems require dispersion compensation to meet transmission requirements. Single-wave compensation may also be implemented in more complicated configurations. As a result, the cost of amplifier configuration for the insertion loss introduced by the dispersion compensation module increases. In contrast, 100 G systems are based on the coherent mode, where the algorithm compensates for dispersion in the electrical domain. The dispersion tolerance of these systems is very high, usually greater than tens of thousands of ps/nm·km, and there is no need for dispersion compensation in the optical domain.

A large-scale COO cannot be upgraded as a whole because it would be unavailable for a long time. Therefore, a step-by-step upgrade method should be considered, i.e., upgrading each main node one-by-one. To minimize the impact on the overall system, the upgrade work can be conducted synchronously with maintenance work on the main node. When a node needs to be recovered for maintenance, its communication module can be replaced with 100 G at the same time, and the corresponding communication equipment in the shore station can also be upgraded simultaneously. When the upgrade is completed, a mixed transmission method of different rates (10 G/100 G) can be applied by the system until all communication modules in all nodes are replaced. Notably, hybrid transmission has nonlinear effects, and therefore, further wave spacing between 10 G and 100 G is desirable [88]. For example, it may be best to concentrate 10 G on the first few waves and 100 G on the last few waves and to insert protective wavelengths (e.g., waves used for switching) in the middle to ensure communication stability.

The construction of cabled observatories involves many aspects, e.g., scientific research, engineering, technology, technique, funds, and policies. There is no perfect solution, and it is not necessary to pursue a one-step solution. The pursuit of the latest technology may lead to system unreliability. Therefore, it is recommended to prioritize reliability in the initial design. For example, in NEPTUNE Canada, although the capacity of mainstream communication systems was already 40 G, the capacity of 10 G was sufficient and remains sufficient in that case. Moreover, communication modules with large capacity inevitably lead to higher power demands, which increase heat generation and reduce system reliability. In this situation, it is advisable to prioritize availability and reliability, and then to gradually update and upgrade the system as conditions evolve; these processes can be combined with system maintenance and other opportunities.

3.3.2. Using OADM or ROADM Technology

For branched systems, especially those with many branches, OADM or ROADM technology can be employed to allocate the spectral resources of backbone fiber pairs to the branches [89], thereby achieving bidirectional communication between the branches and the backbone cable.

The OADM BU supports up- and down-going wave switching of specific wavelengths or bandwidths between the branch and the backbone [90]. Figure 6 shows the working principle of the OADM BU's up- and down-going wave switching. The yellow bandwidth represents the up- and down-going wave, the red bandwidth represents the primary wave, and the gray bandwidth represents the dummy light channel. Taking the transmission direction from site A to site B in Figure 6 as an example, the BU receives the optical signal of the backbone from site A, which includes the up- and down-going wave, the primary wave, and the dummy light channel. The optical filter inside the BU separates the down-going wave from the backbone optical signal and transmits it to branch site C. The primary wave and dummy light channel from the backbone pass through the filter directly and then combine with the up-going wave from the branch site. They continue to transmit to site B on the backbone, thus achieving optical communication between the backbone site and the branch site.

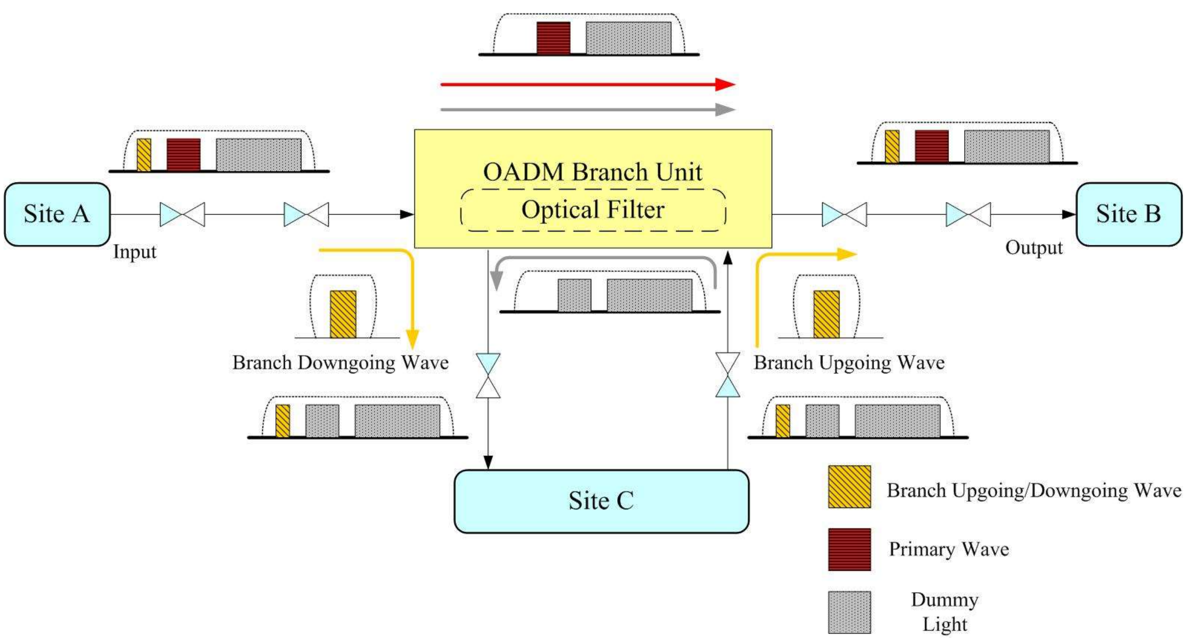


Figure 6. Working principle of the up- and down-going waves of OADM branches.

The ROADM technology is more flexible because it supports bidirectional communication between backbone sites A and B and branch site C [90]. A fiber pair in the backbone corresponds to two fiber pairs in the branch, and the wavelength is reused for the branch, as shown in Figure 7. Both OADM and ROADM technologies can ensure that the optical fibers in the backbone do not need to branch out to the branch lines and are instead used entirely for backbone transmission. Including more redundant optical fibers in the backbone increases the system reliability.

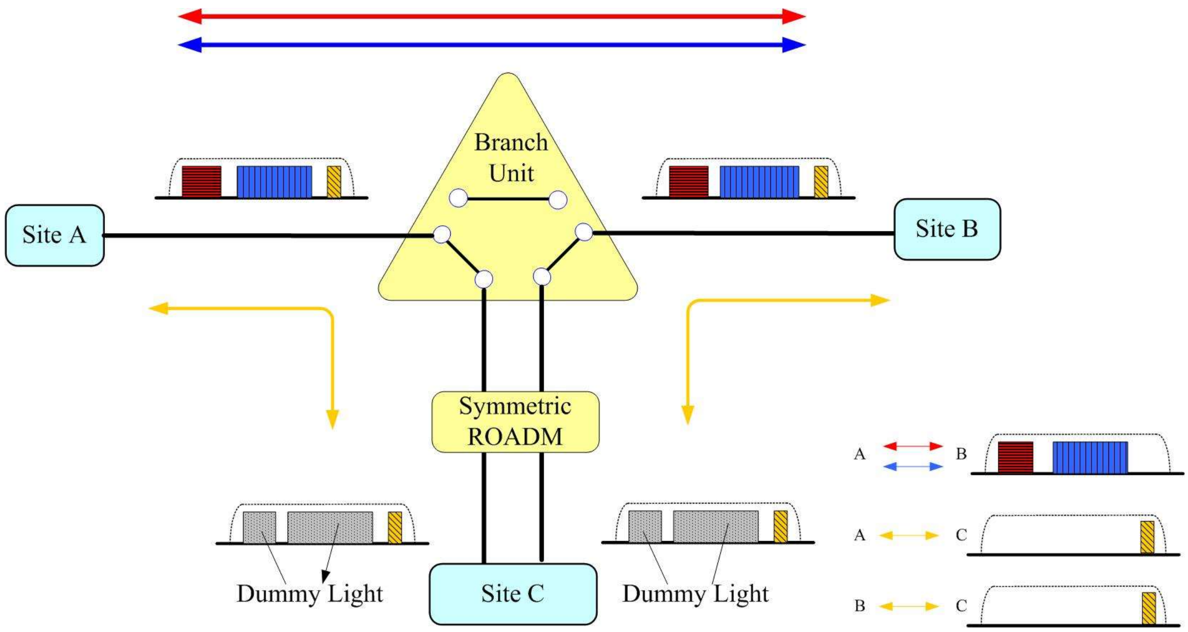


Figure 7. Working principle of the up- and down-going waves of ROADM branches.

4. Summary and Outlook

Owing to the increasing attention on ocean environment conservation, large-scale COOs with advanced technologies have been constructed, and the implementation of grid networks will become more feasible. The power switching BU and OADM/ROADM have made it possible to integrate scientific observation systems with commercial communication systems. This will also promote the standardization of related equipment and expand its application scope. In the future, scientists will have the opportunity to extend their observation areas to the high seas at much lower costs. At the same time, the massive communication capacity will enable more diverse data collection. This will significantly expand the spatial scale of ocean observations and widen the scope of research objectives, from initial earthquake detection to global climate issues and marine disaster monitoring/early warnings, as well as scientific research in other disciplines.

We predict that these developments will also allow the COOs to be interconnected with observation systems in the sea, on land, and eventually in the air. Numerous COOs have developed from independent systems to subsystems of global observation plans. This approach optimizes the conditions for collecting a wide range of data and promoting interdisciplinary research and development. The EMSO (European Multidisciplinary Seafloor and water column Observatory) [4] in Europe is an excellent example.

The operation of established COOs highlights significant advantages, including continuous high power supply and large-capacity communication. However, most systems face certain problems, such as poor maintainability, failure susceptibility, and difficulty in expanding the observation range. Therefore, reducing maintenance challenges, improving system reliability, scalability, and fault tolerance, and reconfiguring the systems to facilitate updates are the current developmental goals in the field. The specific research content includes the distance, capacity, and quality of communication systems; isolation and recovery of cables and nodes faults; the types of access services, access methods, access protocols; remote management of various services; and reliability research of complex engineering for long-term service in extreme underwater environments. Top-level design and coordination should also be considered in the future to gradually establish a standardized system for COOs and to achieve interconnectivity between different systems.

With the increasing scale of COOs, there are still many challenges that are expected to arise. Table 2 outlines some of these challenges and related aspects that merit further investigation.

Table 2. Challenges facing COO construction.

No.	Challenges	Future Directions
1	Long-term maintenance	Establish an effective prognostics and health management system that can alert users of system threats quickly, locate faults accurately, and repair them quickly.
2	System extension	Overcome issues, such as system scalability, network reconfigurability, interface universality, and system compatibility.
3	Interconnection of different systems	Establish common protocols, data standards, and interfaces.
4	Expanding the observation range	Establish a distributed and interactive observation network; integrate observation stations, nodes, satellites, and buoys through universal data standards.
5	Large-scale network monitoring	Establish a digital twin platform for online analytical methods to monitor the operational status of power and communication systems in COOs.
6	Emergency solutions for faults	Use marine energy and energy storage to react to sudden failures temporarily.
7	Data sharing	For common data, a unified data format, data standard, and transmission mode should be considered; for personalized data, data demand planning should be performed, and different types of data should be handled by relevant departments.
8	Deep data processing	Use artificial intelligence to explore marine data deeply to reveal the mechanisms of marine phenomena.
9	International cooperation	Establish a framework with good compatibility. The management and maintenance of sites should also be more flexible.
10	Standardization	Draft relevant standards for applications involving marine observation, the internet of things, big data, artificial intelligence technology, etc., in COOs.

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