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Review

A Survey on Air-to-Sea Integrated Maritime Internet of Things: Enabling Technologies, Applications, and Future Challenges

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Abstract: Future generation communication systems are exemplified by 5G and 6G wireless technologies, and the utilization of integrated air-to-sea (A2S) communication infrastructure is employed to extend network coverage and enhance data throughput to support data-driven maritime applications. These ground-breaking techniques have promoted the rapid development of the maritime internet of things (MIoT). In particular, the integration of air base stations (ABSs) in the MIoT can achieve broadband, low-delay, and reliable wireless transmissions. Considering the potential of ABS-enabled communications, this survey presents the state of the art in the A2S integrated MIoT. More specifically, relevant A2S integrated MIoT architectures are discussed together with the role of their building blocks. Next, we introduce the enabling technologies, including the sensor, communication, data processing and storage, and security and privacy protection techniques. Then, resource allocation, cloud/edge computing and caching, routing protocols, and spatial location optimization in the maritime environment are discussed and grouped based on their performance targets. Additionally, we also show the potential applications of the A2S integrated MIoT in marine environment monitoring, traffic, navigation safety, and resources management. Finally, several future challenges in the area of the A2S integrated MIoT are given, related to the technical security, reliability, and energy efficiency, etc.

Keywords: air base stations (ABSs); air-to-sea (A2S) integrated communication; future generation communication systems; maritime internet of things (MIoT)

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1. Introduction

1.1. Background

Currently, marine equipment and vessels are often isolated, they cannot effectively exchange information, hence they cannot work together effectively. The construction of the maritime internet of things (MIoT) enables real-time connectivity and information sharing among various devices, thereby enhancing the efficiency and security of marine equipment [1]. The MIoT refers to a network system that connects ships, marine equipment, and sensors, etc., and utilizes modern communication and information technologies to realize the interconnection between marine equipment and other equipment [2]. By collecting, transmitting, processing, and applying data, the MIoT provides the real-time monitoring, remote control, and intelligent decision support to achieve comprehensive awareness, intelligent management, and collaborative work of maritime objects. The MIoT stems from the development of modern science and technology and the need for in-depth development and utilization of marine resources [3,4]. With the vigorous development of artificial intelligence, big data, the internet of things (IoT), and other technologies, the MIoT has become an important force driving the development of the marine economy [5].

Wang et al. [6] showed that the MIoT is a special kind of IoT system and is very different from the IoT on land in terms of connection methods, device types, data transmission, and so on. The complexity and variability in the marine environment make the construction and application of the MIoT more extensive and has far-reaching significance [7]. Xvz et al. [8] showed that the MIoT needs to consider the particularities of limited maritime communication, the complex maritime environment, and the operator safety. Moreover, the application field of the MIoT is expanding day by day, which has become an important supporting force for promoting the transformation and upgrading of the marine economy and building maritime power [9].

Since air-to-sea (A2S) integrated communication is crucial in the MIoT, we introduce A2S integrated communication technology. This technology seamlessly connects air resources such as aircraft drones and marine equipment, ships, and other ground resources [10]. Madha et al. [11] relied on traditional coastal base stations (CBSs). The signal coverage was limited thus transmission efficiency was low and the flexibility was poor. But A2S integrated maritime communications have the following advantages:

- Wide coverage: Through satellite communication (SC) technology, A2S integrated communication can achieve global coverage, even in the deep-sea area far from the land, and can also carry out communications and data transmission (DT), effectively solving the problem of limited maritime communication [12].
- Strong real-time capabilities: A2S integrated communication provides real-time DT and communication capabilities, minimizing DT delays and ensuring real-time monitoring, control, and decision support for the MIoT [13].
- High bandwidth and large capacity: A2S integrated communication provides broadband and large-capacity communication channels, meeting the needs of high-speed DT for the MIoT and supporting large-scale DT and application among marine equipment [14].
- Flexible and schedulable: A2S integrated communication possesses flexible scheduling capabilities, allowing communication resources to be allocated to different areas or tasks as needed, ensuring the communication quality and reliability of each node of the MIoT [15].

In summary, the introduction of A2S integrated communication in the MIoT greatly expands the communication coverage, improves the communication quality and data transmission capacity, and provides strong support for the construction and application of the MIoT.

1.2. Related Works

1.2.1. Maritime Internet of Things (MIoT)

With the increasing frequency of maritime activities, the development of maritime communication technology has an immense strategic importance [16]. However, due to the complex and variable maritime environment and inconsistent communication system standards, the development of maritime communication lags behind that of land-based communication significantly. The MIoT relies on reliable communication networks for the transmission and exchange of data [17]. The network can include SC, wireless sensor networks, cellular networks, and other technologies to cover vast ocean areas [18]. An efficient communication network can realize real-time DT and remote control between nodes and supports the needs of different application scenarios. In [19], the MIoT is mainly driven by marine resource development and management, maritime shipping safety, marine environment monitoring and protection, the cross-border cooperation and sharing economy, and scientific and technological progress and application needs [20]. With the continuous development of related technologies and the continuous expansion of application scenarios, the MIoT plays an increasingly important role in the marine industry and marine environmental protection [21].

The MIoT is widely used in marine resource exploration and development, ship safety management, marine environment monitoring, fishery management, marine disaster early warning, and other fields. For example, the MIoT enables real-time monitoring of the marine meteorological and environmental conditions, providing decision support to fisheries managers; ships can be tracked and monitored in real time to improve the safety and efficiency of ship operations; the exploitation of marine resources can be monitored to support sustainable development [22–24]. MIoT technology and applications are used, through the combination of sensors, communication networks, and data processing platforms, to achieve the monitoring of the marine environment, resource management, and security [25]. MIoT technology has broad application prospects and can provide strong support for the development of the marine industry and environmental protection [26].

1.2.2. A2S Integrated Communications

With the continuous development of information technology, the spatial scope of information services continues to expand, various space-based, sea-based, and ground-based network services continue to emerge, and the demand for multi-dimensional comprehensive information resources is gradually increasing [27,28]. An A2S integrated network can provide seamless information services for land, sea, air, and space users, and meets the needs of the future network demand for the full-time all-space communication and network interconnection. A2S integrated communications can realize instant communication and DT on a global scale, connecting the rest of the world and promoting globalization [29]. Through terrestrial radio and optical fiber communication technologies, high-speed and large-capacity DT can be achieved, meeting the needs of various application scenarios [30]. For example, global positioning systems such as aviation, shipping, and vehicles, and data acquisition systems such as weather forecasting and earthquake early warning. Using the terrestrial radio technique, A2S integrated communications can realize global television broadcasting and live video broadcasting, which has greatly improved the coverage and influence of the media [31]. A2S integrated communications can promote the process of informatization, accelerate the development of the digital economy and intelligent manufacturing, further improve production efficiency, and reduce costs [32]. A2S integrated communication has achieved many results and has broad development prospects. A2S integrated communications play an important role in globalization, informatization, security, and sustainable development. Table 1 is a review of the A2S integrated MIoT.

Table 1. Overview of the A2S integrated MIoT.

Reference	Short Summary	Introduction
[33]	A survey on the concept of A2S integrated communications.	The basic concept and technical system of the MIoT.
[34]	A survey to explore strengths and application areas.	In the field of communication of A2S integrated networks, it has also been widely used in the past.
[35]	A survey that analyzes key technologies.	The wireless communication technology, network protocol, and wireless design are important technologies.
[36]	A survey to introduce the technical systems of the MIoT.	A2S integrated technologies, including the sensor technology and communication technologies, will work together.
[37]	A survey that explores the drivers and concerns of the development of the MIoT.	The potential role of the MIoT in energy conservation, emission reduction, ship safety, and other aspects is emphasized.
[38]	A survey illustrating the application advantages of this communication system.	It can realize the transmission of data on a global scale, connect the rest of the world, and promote the development of globalization.

Table 1. *Cont.*

Reference	Short Summary	Introduction
[39]	A survey on the demand for maritime communications enabled by state-of-the-art hybrid satellite-terrestrial MIoT.	The external auxiliary information can used to build up an environment-aware, service-driven, and integrated satellite–air–ground MIoT.
[40]	A survey on UAV-aided maritime communications.	The state of the art in UAV-aided maritime communications is presented.
[41]	A survey on communication and networks for autonomous marine systems.	The major advancements on state-of-the-art autonomous maritime vehicles and systems are reviewed.
[42]	A holistic overview of the different forms of maritime communications is presented.	The latest advances in various marine technologies and some emerging use cases of the MIoT are provided.

1.2.3. Synthesis

Although many articles have been written about the prospects of A2S integrated maritime communications, there are still many shortcomings in maritime communications. The first issue is that due to the distribution and transmission distance limitations of ground base stations (BSs), A2S integrated communications in the MIoT may be limited by maritime coverage. In areas far from land or offshore, connectivity becomes unstable or unavailable. The second problem is that there are many sources of interference in the marine environment, such as atmospheric influence, surface reflection, and ship structures. These factors lead to signal attenuation and interference, which affect communication quality, and reliability. The third challenge is that offshore equipment usually needs to operate for a long time, but the energy supply is limited. In order to achieve durable A2S integrated communications, the challenges of equipment energy consumption and power supply need to be addressed to ensure the reliable operation of equipment and meet communication needs. The fourth challenge is that DT in the MIoT involves sensitive information, such as ship location and sailing plans. Ensuring the security and privacy of communications is an important challenge that requires effective encryption and authentication mechanisms to prevent data breaches and unauthorized access. Finally, a variety of devices and platforms are involved in the MIoT, such as sensors, communications equipment, data processing systems, and so on. Ensuring interoperability and seamless integration between these devices and platforms is a complex task that requires addressing issues such as standardization and protocol unification. These remaining questions prompted this survey.

1.3. Contributions

Interest in maritime activities has been increasing in recent years, and the currently deployed communications infrastructure (CI) cannot meet the needs of emerging use cases. In this case, A2S integrated maritime communication technology complements the ground and satellite parts, bringing unique advantages in terms of coverage, transmission efficiency, and so on. Considering the integration of A2S integrated technology into MIoT, this survey provides relevant supplements to the A2S integrated MIoT technology, introduces the key technologies applied therein, and analyzes their algorithms. In more detail, our contributions are as follows:

- This paper introduces the MIoT and A2S integrated technologies in detail, and discusses the types and functions of sensor technologies applied to various applications, emphasizing the wide application of air base stations (ABSs).
- We summarize the technology and propose the cloud/edge computing algorithm, analyze and discuss the algorithm, further introduce the routing protocol (RP), and optimize the spatial position and trajectory (SPAT).
- Then, in order to illustrate the wide application of A2S integrated MIoT in the world, some specific cases are provided to demonstrate the role of MIoT in different fields.

We also analyze the challenges faced by the current technology, discuss the development prospects of the future MIoT, and finally put forward solutions.

1.4. Structure

The structure of this survey is as follows. First, the second section introduces the key technologies of the MIoT and A2S integrated techniques in the A2S integrated MIoT, and gives the structure of the A2S integrated MIoT. Then, the third part introduces the key technologies for A2S integrated MIoT applications, including resource allocation, cloud computing, caching applications, and RP and their spatial location optimization to improve the application performance of the MIoT. The fourth part introduces the application of the MIoT in different fields, focusing on three aspects: marine environment monitoring, maritime traffic and navigation safety, and maritime resource management. Then, the fifth part introduces the challenges and future development of the MIoT, and puts forward relevant solutions. Finally, the sixth part gives the conclusions. Overall, the survey structure is shown in Figure 1, and Abbreviations contains a list of abbreviations used in this survey.

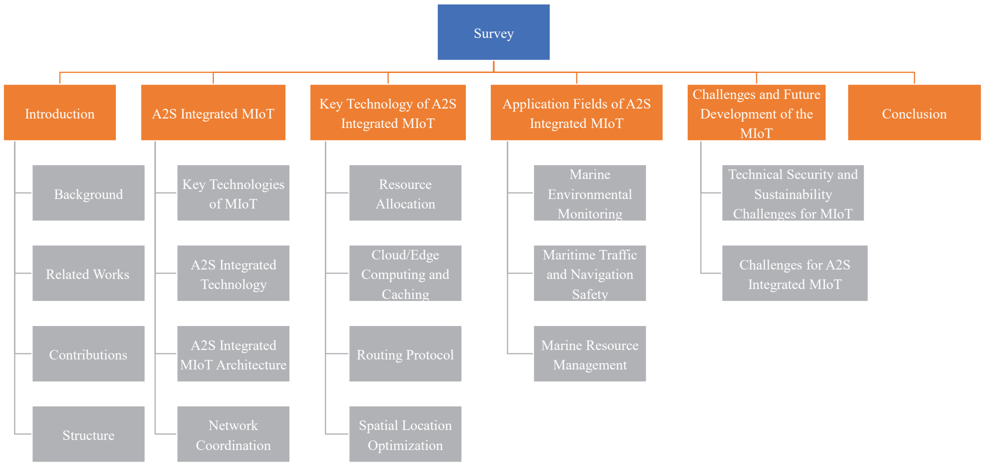

Figure 1. Survey structure.

2. A2S Integrated MIoT

Maritime activities rely on heterogeneous network topologies to enable secure and reliable communications in highly mobile and unstable environments. Next, we introduce the key technologies in the MIoT, the wide application and the role of ABS, and analyze the architecture of the A2S integrated MIoT while describing its specific application.

2.1. Key Technologies of the MIoT

Due to the heterogeneity of maritime communication network segments, in order to better monitor, collect, and disseminate relevant information, different sensor technologies (STs) and communication technologies (CTs) are often used to adapt to different environments and propagation characteristics [43]. IoT technology integrates the sensor technology, communication technology, embedded technology, and other technologies. The IoT also has its own unique methods in relevant data processing and storage. We will focus on the relevant functions of some key technologies for the MIoT, and analyze the security challenges that exist in order to solve the processing [44].

(1) Sensor technology (ST)
The MIoT is a system based on ST which is used for monitoring and collecting marine environmental data. Sensors are installed in various locations and devices in the ocean to sense different parameters and conditions [45]. These parameters can include ocean temperature, salinity, pressure, water quality, light, and more [46]. At the same time, ocean sensors have a variety of types and functions for monitoring and

collecting marine environmental data. Here are some common ocean sensor types and their features:

- Temperature sensor: Used to measure the temperature distribution of the ocean [47]. Common STs include resistive temperature sensors and thermal conductivity sensors.
- Salinity sensor: Measures the salinity distribution of the ocean. A conductivity sensor is one of the commonly used salinity STs [48].
- Pressure sensor: Used to measure the depth and pressure distribution of water in the ocean. Pressure sensors are widely used in marine scientific research and marine engineering.
- Light sensor: Measures light intensity and spectral distribution in the ocean. This is important for understanding phytoplankton distribution, photosynthesis, and ecosystem function [49].
- Water quality sensor: Used to monitor dissolved oxygen, chemical concentration, nutrients, toxic substances, etc., in water. They help to assess the state of marine water quality and environmental health [50].
- Sonar sensor: Uses sound waves to measure and detect marine life, seafloor terrain, and obstacles. These sensors are commonly used in marine ecological research and ocean navigation [51].
- Oxygen sensors: Used to measure the amount of dissolved oxygen in the ocean, which is essential for biological survival and biogeochemical processes [52].
- Video and image sensors (VAISs): Video and images in the ocean are recorded using camera equipment for monitoring marine life, the marine substrate, and human activities [53].

Overall, MIoT ST can help us to better understand and monitor the marine environment, providing important support for marine scientific research, resource management, and marine environmental protection.

(2) Communication technology (CT)

With the increasing frequency of maritime activities, the development of maritime CT has an important strategic position [54]. However, due to the complex and variable marine environment, inconsistent standards of communication systems, and other factors, the development of marine communication lags behind land-based communication systems. Therefore, in order to adapt the marine communication to different environments and communication characteristics, different CTs are usually adopted. At the same time, the CT of the MIoT plays a crucial role in transmitting sensor data and realizing the functions of the MIoT. Below, we introduce the communication protocols and technologies used for the MIoT.

- Cellular network: A cellular network is a wireless CT that enables communication with the internet by connecting MIoT devices to BSs on land. This communication can use different communication protocols such as 2G, 3G, 4G, and 5G. Cellular networks feature wide coverage and high-speed data transmission for a wide range of MIoT applications [55].
- SC: SC is a CT widely used in maritime dense communication environments. MIoT devices can communicate with networks on land via satellite. SC has wide area coverage and global characteristics, suitable for MIoT applications far from land and ocean navigation.
- Radio-frequency identification (RFID): RFID technology uses radio-frequency signals to identify and communicate with items or devices. In MIoT, RFID tags can be attached to goods, equipment, or individuals to transmit relevant information to data collection systems by interacting with RFID readers [56]. This CT is widely used in supply chain management (SCM), ship tracking, and item security [57].

- Wireless sensor network (WSN): A WSN is a technology that enables the widespread deployment of sensor devices in the MIoT. The WSN uses wireless communication protocols such as Wi-Fi or Bluetooth to connect sensor devices to a network for communication and data transmission among devices. These sensor devices can self-organize into networks that transmit data via repeaters to BSs or data collection systems.
- Submarine optical cable (SOC): An SOC is a CT that enables communication among devices by transmitting optical signals in an undersea cable. This CT is characterized by a high data transmission speed and reliability, and is suitable for MIoT applications that require large bandwidth and long-distance communication. SOCs are commonly used to connect MIoT devices to terrestrial networks and enable data transmission and remote control [58].

The application of these communication technologies in the MIoT depends on the specific needs and environment, and can be selected and combined according to the actual needs to meet the communication needs of the MIoT.

(3) Data processing and storage

Data acquisition, processing, and storage in the MIoT are complex and critical processes. MIoT systems typically consist of sensors and devices that monitor and collect various maritime environmental data, such as meteorological conditions, marine life, vessel status, etc. [59].

Data collection is the first step in the process. Sensors and equipment measure and monitor environmental parameters at sea and transmit these data to a central data processing system [60]. These sensors can be mounted on boats, buoys, pontoons, and even marine organisms to enable comprehensive data collection [61].

Once the data has been collected, the next step is data processing. This includes cleaning, validating, converting, and correcting the original data. The cleansing process helps remove noise and outliers from the data, ensuring the data's accuracy and reliability [62]. The checksum remediation process is used to handle erroneous data caused by sensor failure or other problems. The conversion process may include data format conversion, unit conversion, and data standardization for further analysis and application.

Once data processing is complete, the next step is data storage. Data in the MIoT are often large-scale and real-time, requiring robust storage systems to house and manage these data [63]. Cloud computing platforms and distributed storage systems are among the commonly used solutions, which can provide highly scalable storage and processing power [64]. In addition, data backup and redundancy mechanisms are also indispensable to ensure the security and durability of data [65].

In MIoT systems, data collection, processing, and storage need to consider factors such as resource constraints, data transmission, and security. In order to achieve effective data utilization, data analysis, and mining, visualization and monitoring operations are also needed [66]. The combination of these steps can help to achieve a comprehensive understanding of the offshore environment and support decisions.

(4) Security and hidden dangers

When it comes to the MIoT, security and privacy issues are important issues to be seriously considered. The following lists some challenges and privacy issues that may be faced in the MIoT and provides some solutions, which can be seen in Table 2 [67].

(a) Security challenges:

- Authentication and device security: Ensure that only authorized devices can connect to the network and take appropriate measures to prevent unauthorized access.
  Solution: Adopt strong authentication mechanisms, such as two-factor authentication, and use data encryption to secure devices and communications [68].

- Data integrity and confidentiality: Ensure that data are not tampered with or stolen during transmission [69].
  Solution: Use end-to-end encryption to protect the data transmission and implement effective data-integrity checking mechanisms.
- Physical security: Protect the device from malicious damage, physical intrusion, or damage to the device.
  Solution: Provide appropriate physical protection, such as security facilities and monitoring measures, to ensure the physical security of equipment and infrastructure [70].

(b) Privacy issues:

- Personal privacy: Ensure that data collected, transmitted, and stored do not reveal personally identifiable or sensitive information [71].
  Solution: Use data masking techniques to minimize the collection of personally identifiable information, and take appropriate access control and privilege management measures.
- Location tracking and behavior monitoring: Tracking and recording an individual's location and behavior can be a privacy violation [72].
  Solution: Clearly inform users that data are being collected and provide users with options to opt in, such as authorizing or disabling location tracking.
- Data sharing: Ensure that data collected from the MIoT is only shared where necessary and with appropriate anonymization and security safeguards in place [73].
  Solution: Establish clear data sharing policies and legal frameworks, limit the collection and use of data, and ensure that data sharing complies with privacy regulations.

(5) Channel modeling
In the A2S integrated MIoT, channel modeling is important for network deployment and the accurate prediction of wireless conditions, especially considering the existence of aerial nodes [74]. Specifically, the A2S integrated MIoT represents an advanced network architecture that tightly integrates the realms of the sky and the ocean. The successful implementation of such networks requires establishing reliable communication connections in different environments [75]. Channel modeling plays a crucial role in this context by studying the mathematical models of signal transmission processes to optimize channel transmission performance, enhance data transfer reliability, and adapt to changes in diverse environments [76].

- First, channel modeling in A2S integrated MIoT contributes to understanding and analyzing the channel characteristics in the atmosphere and the ocean. The atmospheric and oceanic environments exert unique influences on the propagation of electromagnetic waves, involving phenomena such as multi-path propagation, fading, and scattering. By establishing accurate channel models, researchers can better comprehend the propagation characteristics of signals in these complex environments, providing robust theoretical support for network design.
- Second, channel modeling aids in optimizing the communication system parameters of A2S integrated MIoT. Through simulation and analysis of channel transmission performance, the optimal parameters for modems, power control strategies, and spectrum allocation schemes can be determined, enhancing the efficiency and performance of the communication system. This optimization ensures that the network maintains high-quality communication connections under different atmospheric and oceanic conditions.
- Third, channel modeling is crucial for the security of A2S integrated MIoT. By modeling the propagation paths of signals, potential sources of interference and security threats can be identified. This helps in designing and implement-

ing effective security protocols and protection mechanisms, ensuring that the network remains stable and reliable in the face of malicious attacks.

Table 2. Security risks and solutions in the A2S integrated MIoT.

Security Risks	Solutions
Identity authentication and device security	Advanced encryption technologies and two-factor authentication can be employed to ensure the secure and reliable transmission of data and communication between devices.
Physical security	Tamper-resistant sensors and physical security infrastructure can be deployed to ensure the resilience and reliability of the A2S integrated MIoT in real-world environments.
Personal privacy	Robust privacy regulations and the implementation of anonymization techniques can be enforced to ensure effective protection of individual information during data collection and transmission processes.
Location tracking and behavior monitoring	Differential privacy techniques can be implemented to protect location information privacy, based on which the compliant data collection and usage standards can be adhered to ensure lawful and transparent behavior monitoring.
Data sharing	Secure data sharing protocols and decentralized blockchain techniques can be adopted to ensure trustworthy and efficient data exchange and collaboration.

In summary, channel modeling plays a vital role in the A2S integrated MIoT. A deep understanding and accurate modeling of channel characteristics provides the foundation for network design and optimization, ensuring that the network can deliver efficient, reliable, and secure communication services even in extreme atmospheric and oceanic conditions.

2.2. A2S Integrated Technology

In an A2S integrated network, the communication equipment built by UAVs is used as the ABS, which has the characteristics of being low cost, easy to deploy, and being capable of on-demand deployment, and is widely used in military rescue, emergency communication, commercial aviation, and other fields. An ABS is a device used to provide wireless communication services, usually installed on an aircraft or other aerial platforms. An ABS usually consists of an antenna, a transmission device, a frequency converter, a processor, and a communication interface [77]. Its main function is to connect mobile communication devices (such as mobile phones) with ground BS or SC networks, allowing users to maintain communication connections during flight. The following introduces the categories of A2S BSs, their applications in various fields, and the role and advantages of ABSs in MIoT [78].

(1) Classification:

- Mobile communication BS: This is the most common type of ABS used to provide mobile communication services. It connects the aircraft's mobile communications equipment with ground BS or SC networks, enabling passengers and crew to make voice calls, send text messages, and use the internet during flight, among other things [79].
- Other dedicated ABSs: In addition to mobile communication BSs, there are also some ABSs specifically designed for specific purposes. For example, military aircraft may be equipped with military communication BSs for military command and control communications; public safety BSs on aircraft may be used for emergency communications and rescue operations [80].
- Satellite communication BS: This BS provides air communication connection through a satellite network. SC installs satellite dishes and terminal equipment

on the aircraft for communication with satellite communication systems, thus enabling long-distance communication in flight [81].

- UAV communication BS: UAVs can also be equipped with communication BSs for communication and control with ground control stations or other UAVs. This BS enables two-way communication between the drone and the operator, and supports DT and sensor information sharing [82].

(2) Application of ABSs in various fields:

- Commercial aviation: ABSs play an important role in commercial aviation. They enable passengers to maintain mobile phone signals during the flight, make voice calls, send text messages, and use the internet. This provides a better passenger experience and communication connectivity, while also providing value-added communication services for airlines.
- Military and security applications: ABSs play a key role in the military and security fields. ABSs on military aircraft provide military communications capabilities, support command and control, and share battlefield information. This is essential for coordination and decision-making in military operations.
- Emergency rescue and disaster relief: ABSs provide critical communications support during emergency rescue and relief operations. They allow rescuers to maintain contact with ground command centers and share rescue information. This helps to improve rescue efficiency and the safety of rescue operations [83].
- UAV applications: ABSs are also widely used in UAV applications. The BS equipped with the UAV can realize the communication and control between the UAV and the ground control station, as well as the collaborative operation among UAVs. This allows UAVs to play an important role in surveillance, logistics, agriculture, security, and other fields [84].
- Satellite communications: ABSs are used in conjunction with SC systems to provide long-range communication connectivity in aviation services. Through SC, ABS can realize broadcasting, DT, and remote control on a global scale to meet the communication needs of aircraft and passengers [85].

(3) The role and advantages of ABSs in the MIoT

- ABSs can be used as wireless communication BSs to provide stable networking connectivity for MIoT devices. By incorporating radio equipment and antennas, they enable efficient communication with IoT devices far from shore [86].
- Air-based warfare can provide greater coverage. Their height and flexibility allow them to provide the signal coverage over a wider range than land BSs or SCs. As a result, more MIoT devices can be connected, enabling a wider range of data transmission and communication.
- Air-based warfare also offers the advantages of rapid deployment and flexibility. They can move from one place to another at a relatively fast pace, providing communication support in different areas at sea depending on demand [87]. This flexibility can play an important role in situations of emergency, temporary assignment, or specific needs [88].

In summary, the role of ABSs in the MIoT is to provide stable communication connectivity, extended coverage, rapid deployment, and flexibility. These advantages make them an important part of enabling efficient MIoT communications.

2.3. A2S Integrated MIoT Architecture

Figure 2 depicts an illustrative A2S integrated MIoT architecture. Specifically, the A2S integrated MIoT is based on the internet and connects a network of various objects and devices in the ocean, land, and air. Its architecture is a system architecture for realizing marine environment perception and DT [89]. It connects sensor devices in the air and on the ground, data centers, communication networks, and MIoT devices, and enables data acquisition, processing, and distribution through IoT platforms [62]. Below, we analyze the main architectural parts shown in the diagram, as well as the success stories of A2S integrated networks in the MIoT.

(1) Perception layer: The perception layer refers to sensor nodes and IoT devices. Sensor nodes include various environmental detectors, position and attitude sensors, cameras, etc., which are connected to the MIoT through IoT devices and collect data and upload the data to the next layer of the network. It consists of various sensor devices deployed in the air, on the ground, and at sea, such as meteorological sensors, ocean sensors, position sensors, etc. These sensor devices transmit the collected data to the data center via wireless communication [90].
(2) Transport layer: The transport layer refers to the interaction of various communication networks. Including satellite positioning system, SC of the wireless network, etc., used to connect the various components. These communication networks provide reliable data transmission channels that support real-time marine environmental awareness and data exchange [91].
(3) Processing layer: The marine environmental data obtained from the perception layer are centrally stored and processed for cloud computing. A cloud-based service enablement platform is used to manage and operate the entire MIoT system [92]. The platform provides the equipment management, data management, and other functions, and supports the real-time monitoring, analysis, and sharing of the marine environmental data. At the same time, the IoT platform can also be integrated with other systems, such as shipborne navigation systems, maritime supervision systems, etc. Data centers are typically equipped with HPCAS devices and utilize data processing algorithms to analyze, mine, and visualize ocean data.
(4) Application layer: This refers to various specific application scenarios and business requirements, such as smart ports, marine environmental monitoring, ship safety, fisheries resource management, etc., which exchange data and share information through the MIoT. Based on the MIoT, various marine environment application services, such as marine early warning, marine resource management, route planning, etc. These application services use the marine environmental data provided by the IoT platform to provide decision support and information services for users in maritime, fisheries, energy, tourism, and other fields [93].
(5) Space segment: This segment aims to establish a security monitoring system, real-time monitoring of the security status and abnormal conditions of the IoT system, security protection and privacy protection, and timely warning and appropriate protective measures [94].
(6) Specific cases: Through the A2S integrated MIoT architecture, we can achieve comprehensive perception and monitoring of the marine environment, improve the safety and efficiency of maritime transportation, promote the sustainable development and utilization of marine resources, and provide decision-making support and services for relevant industries and government departments [95].

One of the successful examples of the A2S integrated MIoT is China's "Nanhai No. 1" research ship. The ship is equipped with a large number of sensors and monitoring equipment that can monitor and collect data in real time on the marine environment, weather conditions, and the status of the ship. At the same time, the "Nanhai No.1" research ship can also upload data to ground BSs or central servers for processing and analysis through SC systems and its own data processing equipment [96]. These data can provide a scientific basis for related fields, such as marine environmental protection, fishery resource management, etc.

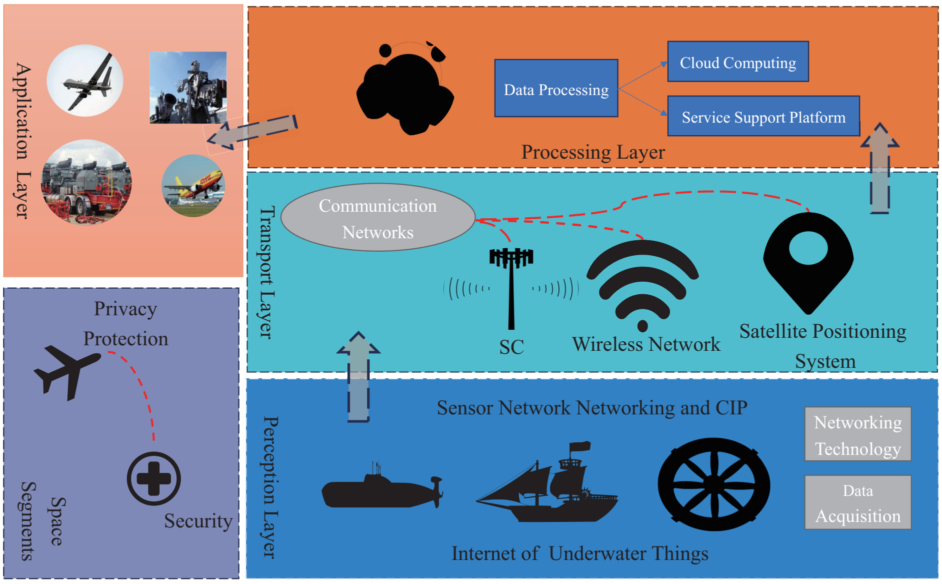

Figure 2. A2S integrated MIoT architecture.

Another example is the port of Zhuhai in China. Zhuhai Port adopts A2S integrated MIoT technology and is equipped with a large number of sensors and monitoring equipment, which can conduct real-time monitoring and management of vessels, cargo, traffic conditions, environment, and other aspects in the port [97]. BSs and wireless network facilities are also set up in the port to facilitate the collection and transmission of information. These data can be used to optimize vessel entry and exit processes, improve the efficiency of cargo transportation, protect the environment, and more [98].

In addition, there are many other cases of A2S integrated MIoT applications around the world, such as the “Cape Town Underwater Cable” project in the United States, the “MOSES” project in Europe, and the “Marine Resource Utilization System” in Japan. These cases demonstrate the potential of the A2S integrated MIoT to improve the efficiency of marine resource utilization, improve transportation safety, and protect the marine environment.

3. Key Technology of the A2S Integrated MIoT

3.1. Resource Allocation

In order to better support the large amount of DT and communication required for the marine equipment and sensors in the MIoT, two key technologies are being used. Device-to-device (D2D) and non-orthogonal multiple-access (NOMA) techniques will be introduced next.

3.1.1. D2D Technique

The D2D technique in the MIoT refers to the ability to communicate and exchange information directly between marine devices and sensors, and its model is shown in Figure 3. The D2D technique allows point-to-point communication among devices without a central server, improving the efficiency and reliability of communications [99].

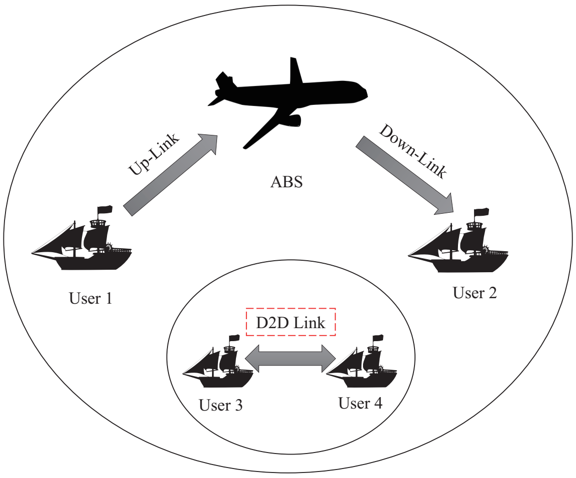

Figure 3. D2D model.

In the maritime environment, the D2D technique has many advantages. First, D2D communication can provide faster response times because devices can communicate directly via short-range communication, reducing the latency required to pass through a central node in the traditional way. Secondly, the D2D technique can reduce the probability of network congestion and reduce the delay of information transmission. In addition, D2D communications can also enhance the reliability and stability among devices, as devices can cooperate with each other to maintain communication in the event of unstable network connections. As data in D2D communications in 5G networks are transmitted through connected devices, new possibilities for potential security breaches (such as data hacking) increase [100]. This implies a violation of privacy and confidentiality, and attacks can be classified according to access control, accessibility, authenticity, confidentiality, and integrity. Detailed security threat issues for D2D are given in Table 3.

Table 3. Detailed security threat issues for D2D.

Security Threat	Specific Situation
Eavesdropping	Through eavesdropping and recording data, private data can be obtained.
Man-in-the-middle attack	The attacker secretly takes control of the communication channel, intercepts the message from the sender, modifies it, and forwards it to the recipient.
Private viewing	During the device monitoring phase, attackers use verified anonymous identities for malicious activities.
Disturb	An attack that interferes with operations, shuts down D2D, and disables the communication itself.
Inference attack	Through peers, logical analysis to obtain private information.

In the MIoT, the D2D technique is widely used. China Mobile uses the D2D technique to launch the "HeWO network" service, enabling users to share information and resources through the direct communication among mobile phones, file transfer, and other ways; Mazda uses the D2D technique to establish a communication network among vehicles in a vehicle ad hoc network, and realizes real-time data exchange and traffic information sharing among vehicles in the intelligent transportation system. Various emergency relief agencies are also leveraging the D2D technique to enhance disaster management and relief efforts, such as using D2D communication equipment to set up temporary communication networks during disasters to facilitate rapid information sharing and collaborative action. IoT devices can be interconnected through the D2D technique, for example, for directing communication and intelligent control among devices in the field of smart homes [27,44,101,102]. In the fisheries industry, the D2D technique allows the sensor on the fishing boat to directly communicate with nearby fishing nets, fishing gear, and other equipment, enabling the real-time monitoring of fishing conditions and sea conditions. In the shipping industry, ships communicate directly with port facilities and other vessels through the D2D technique, improving the efficiency and safety of collaborative operations. In summary, the D2D technique plays an important role in the MIoT by providing fast, reliable, and efficient direct communication capabilities among devices, bringing innovation and convenience to the marine industry by enabling the seamless connectivity and information exchange [103].

3.1.2. NOMA Technique

The NOMA technique in MIoT technology is a key technique for increasing spectral efficiency and connectivity capacity. A schematic diagram of a NOMA link is shown in Figure 4. The NOMA technique achieves this by transferring data for multiple users simultaneously on the same time and frequency resource. Unlike traditional frequency division multiple access (FDMA) and time division multiple access (TDMA), the NOMA technique allows multiple users to share the same spectrum resources in parallel [104].

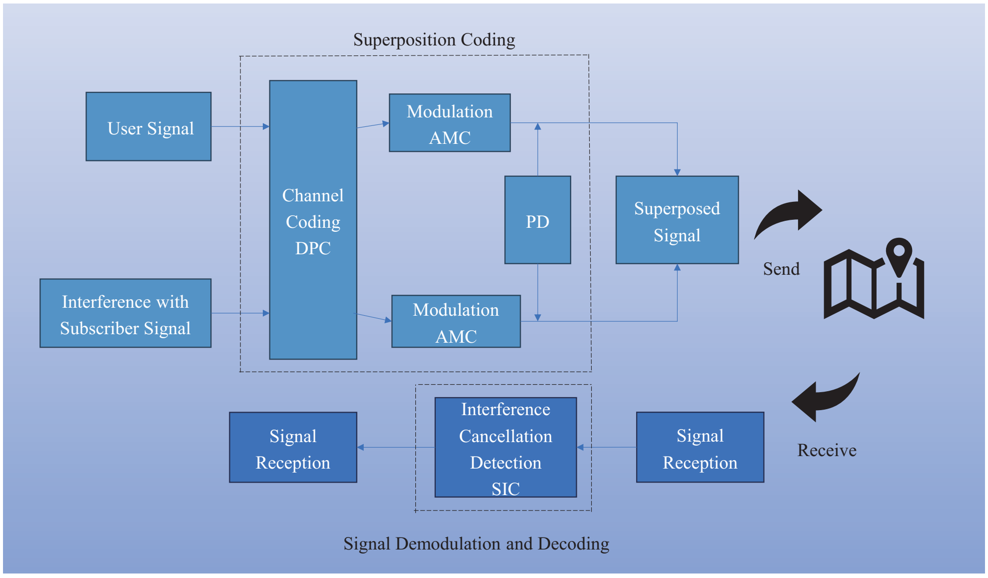

Figure 4. A diagram of the implementation of NOMA.

The NOMA technique enables the simultaneous transmission of data from multiple users at the same time and frequency resources by distributing data from different users to different power levels [105]. This power allocation can be dynamically adjusted based on the user's channel conditions and transmission needs to achieve a higher spectral efficiency and connection capacity. The NOMA technique can also efficiently distinguish and decode simultaneously transmitted user data through superior multiple access (SMA) decoding. At the receiving end, the data of the strong signal user is decoded first, and then the data of the weak signal user is decoded using channel estimation and interference cancellation (CEAIC). This interference cancellation technique can significantly improve the reception performance and system capacity.

In the MIoT, the NOMA technique is also widely used. The NOMA technique can be used to improve the reliability of the system through the power allocation and channel scheduling. If one of the users has an interruption or other problem, the system can quickly reallocate the other users' signals and resources, thus ensuring the stability of the entire system [48]. As one of the major mobile operators in China, the China Mobile Communications Corporation has begun to adopt the NOMA technique in its network architecture.

The NOMA technique is being used in next-generation wireless communication networks to improve the spectrum utilization, enhance system capacity, and support diverse application scenarios. Tencent Cloud, a well-known cloud computing service provider in China, is also exploring the application of the NOMA technique in its IoT platform. They are using the NOMA technique for communication among IoT devices to enable more efficient DT and connectivity, and to promote the application of the IoT in the integration of land and ground; NTT DOCOMO, one of the largest mobile operators in Japan, is also using the NOMA technique in research and practice [106–108]. They are applying the NOMA technique to 5G networks to increase network capacity and coverage, and support A2S integrated applications including smart cities, connected vehicles, and industrial automation. Some European telecom companies are also actively exploring the application of the NOMA technique. For example, companies such as Vodafone in the UK and Deutsche Telekom in Germany are looking into applying the NOMA technique to their communications networks to provide more efficient wireless connections and services [109].

In general, the NOMA technique can provide a higher spectral efficiency and connectivity capacity in the MIoT, thus supporting more DT and communication needs of maritime devices and sensors. The NOMA technique is a technique with great potential to improve the performance and reliability of MIoT systems.

Additionally, machine learning plays a crucial role in enhancing the resource allocation performance of the MIoT. By leveraging big data and advanced algorithms, machine learning technologies can analyze the complex scenarios of maritime traffic, enabling more efficient resource utilization [110]. In particular, machine learning algorithms can be integrated in MIoT deployments, for example, to improve the communication performance or support a specific application [111]. First, machine learning, through in-depth analysis of historical data, can identify potential patterns and trends in maritime traffic systems. This helps in predicting future demand and traffic distribution, allowing managers to better plan resource allocation strategies. Second, machine learning can adjust resource allocation plans in real time through continuous monitoring and feedback mechanisms. For example, when maritime traffic systems encounter unforeseen events or abnormal situations, machine learning can quickly respond by re-optimizing resource allocation, ensuring the efficient operation of the traffic system in complex environments. Furthermore, machine learning can optimize ship navigation paths and berthing locations, reducing congestion and waiting times, to improve overall traffic efficiency. By continuously updating models in real time, the system can adapt to changing conditions, making resource allocation more flexible and intelligent. In conclusion, the application of machine learning in the MIoT, through deep learning and intelligent optimization, enhances the efficiency and accuracy of resource allocation, making maritime traffic safer, more reliable, and sustainable.

3.1.3. Network Coordination

Achieving network coordination in the A2S integrated MIoT with a multitude of airborne, surface, and underwater nodes, users, and vessels poses a complex and critical challenge [112–114]. Effective network coordination not only requires the consideration of multi-layered, multi-modal communication requirements, but also adaptation to dynamically changing maritime and atmospheric environments. The following are some solutions on how to achieve network coordination.

- First, introducing intelligent sensing and decision-making systems is a crucial step in achieving network coordination. By deploying advanced sensing technologies, including radar, sonar, and cameras, among others, across various nodes and users, the system can acquire real-time environmental information. This information can be used to perceive network status, identify node positions, and capture vessel dynamics, providing real-time input for network coordination. Intelligent decision-making systems can then utilize this information to make informed decisions, optimizing network resource allocation, path planning, and communication parameter settings to meet the diverse needs of users and nodes.

- Second, adopting adaptive communication technology is essential. Considering the involvement of multiple communication media in the A2S integrated MIoT, including wireless communication, acoustic communication, etc., communication technology needs to be adaptable to different environments and node types. Adaptive communication technology can dynamically adjust based on network status and requirements to ensure communication reliability and efficiency. For example, when an underwater node needs to communicate with an airborne node, the system can automatically choose the appropriate communication mode and frequency to maximize communication success.
- Third, establishing cross-layer communication protocols and standards is crucial for achieving network coordination. In the A2S integrated MIoT, communication spans multiple layers, including airborne, surface, and underwater. To achieve effective network coordination, consistent communication protocols and standards need to be developed to ensure seamless information interaction and collaboration between different layers. This helps improve system interoperability, reduce communication complexity, and make the network more scalable and flexible.
- Fourth, employing advanced data management and processing techniques is necessary. Due to the involvement of a large number of nodes and users, the network generates a vast amount of data. Effective data management and processing techniques can help the system efficiently collect, store, process, and analyze these data, providing more accurate information support for network coordination. This includes the use of big data technologies, artificial intelligence algorithms, etc., to unearth potential patterns and trends in the data, providing a more scientific basis for decision-making.
- Finally, simulation and testing are essential means to achieve network coordination. Implementing network coordination in a real environment may pose risks and cost issues. Therefore, before actual deployment, verifying network coordination strategies and algorithms through simulation and testing is crucial. This can help identify potential issues, adjust system parameters, and enhance the robustness and performance of the system.

In conclusion, achieving network coordination in the A2S integrated MIoT requires comprehensive consideration of sensing, decision-making, communication technology, protocol standards, data management, and simulation testing, among other aspects. Only through the integrated application of these approaches can the system achieve efficient, reliable, and intelligent network coordination in a complex environment.

3.2. Cloud/Edge Computing and Caching

3.2.1. Mobile Edge Computing (MEC)

In the A2S integrated scenario, several organizations and entities are currently using MEC for different applications. China Mobile Communications Group, one of the major mobile communication operators in China, is actively exploring and applying the MEC technique in A2S integrated systems [115]. They use MEC to push computing resources and services to the edge of the network to meet users' demands for low latency and high throughput. For example, with MEC support, they provide intelligent traffic management systems that enable the intelligent traffic monitoring and optimization through real-time data processing and decision-making on edge servers. Ullens Group, a German technology company, has carried out a research project using the MEC technique in A2S integrated systems [116]. They have combined MEC with the UAV technology to achieve the real-time image processing and analysis of drones. By carrying out image recognition and target tracking on edge computing nodes, they can achieve the intelligent navigation, target detection and capture of UAVs, further supporting A2S integrated applications. The FCC also recognizes the potential of MEC in the A2S integrated scenario and supports related research and pilot projects [117]. They encourage operators and technology providers to leverage MEC to push computing and storage capabilities to the edge of the network, enabling applications such as smart cities, IoT, and virtual reality. These measures are designed to enhance the performance and user experience of wireless networks and promote the development of A2S integrated systems. As one of the major mobile operators in Japan, NTT DOCOMO is also applying the MEC technique in A2S integrated systems. They use MEC to place computing and storage resources at the edge of the network, supporting diverse application scenarios including intelligent transportation, intelligent healthcare, and industrial automation. By processing data and making decisions at edge nodes, they can provide services with low latency and high reliability [118].

Figure 5 shows an MEC architecture in the A2S integrated MIoT. Specifically, the three-tier architecture of edge computing in the A2S integrated MIoT includes the cloud computing layer, the mobile edge layer, and the device edge layer [5,102]. The cloud computing layer enhances the response speed and reduces latency by deploying data processing functions closer to the cloud. The mobile edge layer emphasizes executing edge computing on mobile devices to alleviate the central cloud's burden, adapting to dynamic environments. The device edge layer extends computing capabilities to IoT devices, enabling localized data processing, reducing reliance on the network, and enhancing system stability and efficiency.

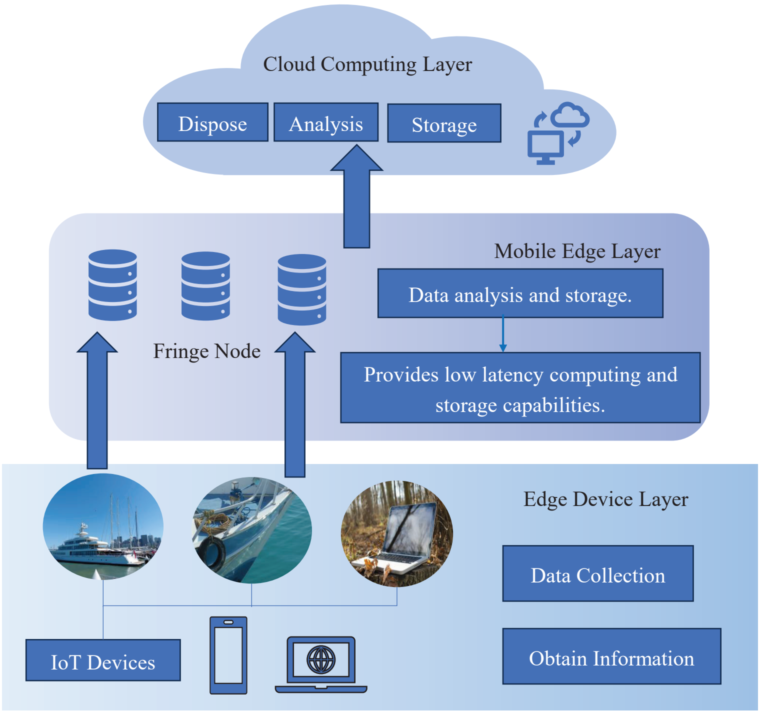

Figure 5. MEC architecture diagram.

(1) Edge device layer: This is the lowest level and it includes the various physical devices and sensors deployed at sea. These are responsible for collecting data on the marine environment, controlling offshore equipment, and obtaining other relevant information. These devices are typically low-power and have limited computing and storage capabilities. Their main task is to transmit the collected data to the edge node through the wireless network [119].
(2) Mobile edge layer: This layer is located between the edge device layer and the cloud computing layer; it deploys the computing and storage resources at the edge. Mobile edge nodes are similar to the IoT gateways in that they can be placed close to offshore equipment and sensors to provide low-latency computing and storage capabilities [120]. These nodes can be UAVs, floating nodes, or ship-based nodes, among others. The main task of the mobile edge layer is to carry out local data processing, analysis, and storage after receiving the data from edge devices.
(3) Cloud computing layer: This is the highest layer, usually located on a remote data center or cloud server. The cloud computing layer provides more powerful computing

and storage capabilities capable of handling complex data analysis and processing tasks. It takes data from the mobile edge layer and further processes, analyzes, and stores those data [121]. The cloud computing layer can also provide services such as data management, visual analytics, and decision support.

This three-tier architecture based on mobile edge computing brings computing and storage resources closer to offshore devices and sensors, enabling lower latency and faster responses. This architecture can also reduce the dependence on remote cloud computing resources, reduce the DT latency and network congestion, and improve the system reliability [122]. At the same time, this architecture exhibits the good flexibility and scalability needed to adapt to the needs of MIoT applications of different sizes and complexities [123].

Overall, the three-tier architecture based on MEC provides an efficient, flexible, and reliable architecture for the A2S integrated MIoT to support data processing, analysis, and application of the needs of offshore equipment and sensors. By bringing computing and storage resources closer to the edge, more responsive and lower-latency MIoT systems can be achieved.

3.2.2. Data Caching

The main function of data caching is to store frequently accessed data on neighboring nodes to reduce transmission latency when data are accessed. Figure 6 shows the pattern of data caching. When a node needs to access certain data, it first checks whether there is a copy of the data locally, and if there is, it obtains it directly from the local source, thus saving transmission time and energy consumption [124]. If there is no local copy of the data, the node queries its neighbors and caches the data locally for future use.

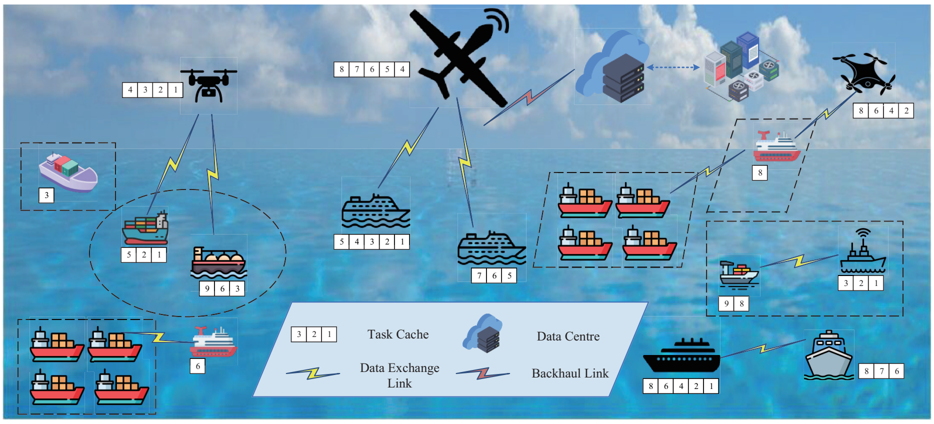

Figure 6. Data cache mode in the A2S integrated MIoT.

Due to the complexity of the marine environment and the instability of communication links, DT often faces many challenges, such as bandwidth limitation and transmission delay. In order to solve these problems, the data caching technique is introduced into the A2S integrated system. Many logistics and distribution companies use data caching to optimize the distribution process in A2S integrated systems. They can deploy data cache nodes in different logistics centers and sorting points to cache commonly used logistics data close to data users. This reduces the latency of remote data access and network traffic, thereby improving the efficiency and accuracy of the logistics distribution. In smart city management, data caching is widely used to provide real-time city information and services. For example, a public transportation system in a city can deploy data cache nodes at different stations and vehicles to cache real-time traffic data [125]. When users need to query bus information, they can directly obtain data from nearby cache nodes, reducing the access to the central server and improving the response speed and availability. In A2S integrated healthcare applications, data caches can be used to store and manage medical data. For example, some hospitals or clinics deploy data cache nodes locally to cache patients' basic information and medical record data [126]. In this way, when doctors need to access patient data they can quickly obtain it from the cache, improving the efficiency and quality of medical services [127].

In conclusion, data caching plays an important role in the application of the A2S integrated MIoT which can improve data access efficiency, reduce energy consumption, and provide better support for marine environmental monitoring and related applications.

3.3. Routing Protocol

3.3.1. End-to-End Transmission and Cluster Routing

When it comes to A2S integrated MIoT routing protocols, the common end-to-end transmission and clustered routing structures are two important concepts.

(1) End-to-end transmission: End-to-end transmission refers to the process of transmitting data from the source node to the target node through the network. In the A2S integrated MIoT, wireless sensor networks are usually used for DT [128]. Data start from the source node, passes through various intermediate nodes step by step through multi-hop mode, and finally reaches the target node. The transmission mode allows there to be a certain distance between the nodes in the MIoT and the target node, with data transmission completed through the cooperation of the intermediate nodes [129]. End-to-end transmission needs to consider factors such as energy efficiency, network topology, and communication quality among nodes.

(2) Cluster routing: Cluster routing is a commonly used routing mechanism in wireless sensor networks, as shown in Figure 7. Due to the large number of nodes and wide network range, the clustering routing structure can improve the scalability and energy efficiency of the network in the A2S integrated MIoT. The structure divides the nodes into several clusters, each with a cluster-head node responsible for coordinating the communication of the nodes within the group [130]. Cluster-head nodes collect data from surrounding nodes and forward them to other cluster-head nodes or the cloud. Other nodes only need to communicate with the cluster-head node, which reduces the communication and energy consumption among nodes. At the same time, the cluster structure can also improve the stability and fault tolerance of the network. When a node fails, it only affects the communication within the cluster, not the whole network.

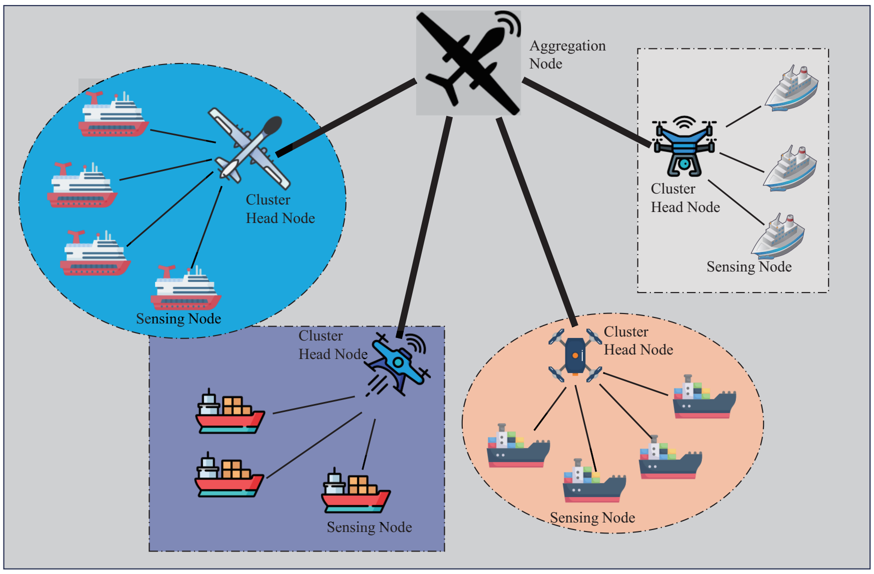

Figure 7. Cluster routing structure.

In A2S integrated scenarios, the clustering routing structure is also a common technical means. NASA's Office of Information Science and Technology conducted a research project called "Fault-tolerant protocols for wind power". The aim of this project was to ensure the safety and reliability of data transmission in wind power systems by using a cluster routing structure and fault tolerance mechanism. By dividing nodes into different clusters and repairing data errors through fault tolerance mechanisms, the reliability and performance of wind power systems can be greatly improved [131]. A study by the Indian Institute of Technology has implemented multi-path DT for intelligent transportation systems using clustered routing structures. By dividing nodes into different clusters and establishing a multi-path routing mechanism, the reliability and robustness of DT can be improved, so as to realize the efficient operation of intelligent transportation systems. The University of Hamburg in Germany has used a clustered routing structure to achieve efficient data collection in wireless sensor networks [132]. By dividing nodes into different clusters, and dividing clusters according to the location and function of nodes, efficient data collection and processing of wireless sensor networks can be realized, so as to support various application scenarios of A2S integrated systems.

Since some of the topics that have been discussed are related to clustering methods, we need to discuss how offering a backup node within the cluster can ensure less latency and further reliability. In [133,134], dynamic self-healing vehicle network organization methods considering the deviation of key network connection components were proposed. The design ideas of these methods can be applied to the A2S integrated MIoT with mobile nodes. Therefore, through the application of end-to-end transmission and clustered routing, the A2S integrated MIoT can achieve effective DT and resource management, improve network reliability and energy efficiency, and meet the needs of various application scenarios of the MIoT.

3.3.2. Opportunistic Routing

When it comes to A2S integrated MIoT routing protocols, opportunistic routing is one of the common routing methods. The schematic diagram in Figure 8 illustrates the opportunistic network. Opportunistic routing refers to a way to realize DT by transmission opportunities when there is no direct communication among nodes in the A2S integrated MIoT [135]. This opportunity can be either an overlap of two nodes in time or an overlap of two nodes in space. Specifically, this routing method can be divided into the following steps:

- Data topology construction: In the A2S integrated MIoT, each node has a data cache to store the received data. When a node receives data, it first stores the data in the local cache, establishes a data topology relationship, and records the source and destination nodes of the data.
- Chance encounter: When two nodes come into proximity, they exchange data in each other's cache. If one of the nodes can forward data to the target node, the data are sent to the target node; otherwise, it continues to be stored in the local cache.
- Data transfer: When the data finally reach the destination node, the entire routing process is completed.

The advantage of opportunistic routing is that in the MIoT, even if nodes cannot communicate directly with each other, data can be transmitted through various opportunities to improve the arrival rate of data [136]. For example, on a ship, direct communication may be unstable due to factors such as geographical location, weather, and sea conditions. However, through the opportunistic routing mode, nodes can make use of opportunities for DT to improve the efficiency and reliability of DT. It is worth noting that opportunistic routing also has some limitations, such as the need for a large cache space, a long time to discover opportunities, and also need to design effective routing protocols to ensure that data can be transmitted in a timely manner [137].

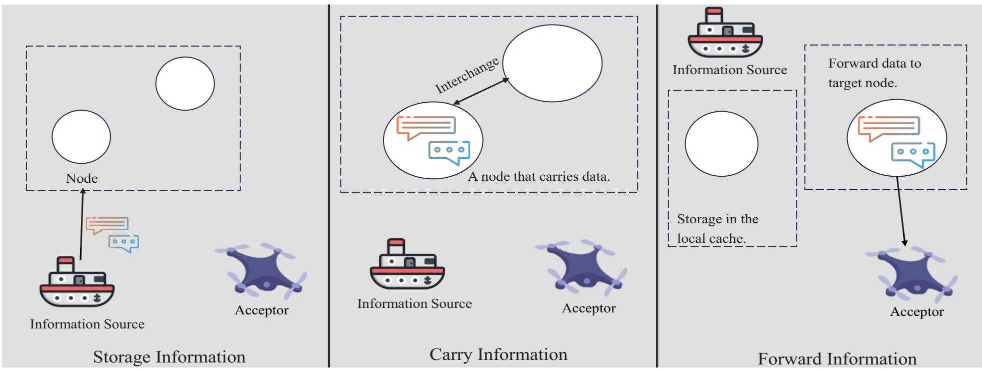

Figure 8. A diagram of an opportunistic network.

In A2S integrated scenarios, the opportunistic routing technique is being used to optimize resource allocation and service scheduling to achieve more efficient operations [53]. Logistics distribution companies can use opportunistic routing technology to improve the efficiency of goods distribution. When new goods need to be delivered, the system can select the best delivery route and truck for distribution based on the destination of the goods, the location, and availability of the vehicles [138]. By dynamically distributing goods to idle vehicles, logistics and distribution companies can reduce idle miles and waiting times, thereby improving distribution efficiency. Opportunistic routing can also find application in intelligent transportation systems to optimize traffic flow and reduce congestion. For example, in urban road networks, traffic management systems can dynamically adjust the timing of traffic lights according to real-time traffic conditions and road condition information [54]. When traffic pressure is detected at a certain intersection, the system can extend the green time through the intersection and adjust the signal timing of the surrounding roads accordingly to optimize the traffic flow and reduce the traffic congestion. Table 4 analyzes and compares typical routing algorithms.

Table 4. Overview of the A2S integrated MIoT.

Algorithm Name	Type	Advantage	Disadvantage
Epidemic	Routing algorithm based on infectious disease model.	Decentralized, adaptive, suitable for network environments with no central control and unstable connections.	High storage overhead and propagation delay.
Direct Delivery	Routing algorithm based on store and forward.	Improves data transfer efficiency and choose the best path.	The connection between nodes has high requirements.
Max Prop	Routing algorithm based on prediction and probability.	Chooses the most reliable path to improve data transmission efficiency.	The prediction information between nodes needs to be maintained.
Spray and Wait	Routing algorithm based on infectious disease model.	Increases the number of data copies and improves data transmission reliability.	High storage overhead and propagation delay.
Prophet	Routing algorithm based on prediction and probability.	Reduces energy consumption by predicting connections between nodes.	The propagation delay is high, and the maintenance costs and storage costs of nodes are high.
BubbleRap	Routing algorithm based on social network.	Considers social network connections and improves data transfer success.	The social network information is incomplete and the calculation complexity is high.

3.4. Spatial Location Optimization

3.4.1. Trajectory Optimization

When it comes to spatial location optimization for MIoT, trajectory optimization is an important aspect. Figure 9 shows the application of trajectory optimization in A2S integrated systems. Trajectory optimization involves optimizing the movement path of

MIoT nodes to enable more efficient data collection, communication, and resource utilization. In the MIoT, various sensor nodes are distributed in the ocean and need to collect marine environmental data or monitor targets. To improve the efficiency and accuracy of data collection, the movement paths of nodes need to be optimized. The goal of trajectory optimization is to find the best node movement path under the premise of satisfying specific constraints in order to achieve the following purposes:

- Shortest path: By finding the shortest path, the movement time and energy consumption of nodes can be reduced, thereby improving the efficiency of data collection.
- Node coverage: The movement path of a node should be able to cover as many critical areas as possible to ensure the comprehensiveness and accuracy of the data.
- Network connectivity: The movement paths of nodes should ensure network connectivity and avoid communication interruptions among nodes. In order to achieve trajectory optimization, a variety of methods and algorithms can be used [139], including heuristics, evolutionary algorithms, simulated annealing algorithms, etc. These algorithms can be adjusted and optimized according to the specific situation to achieve optimal trajectory planning.

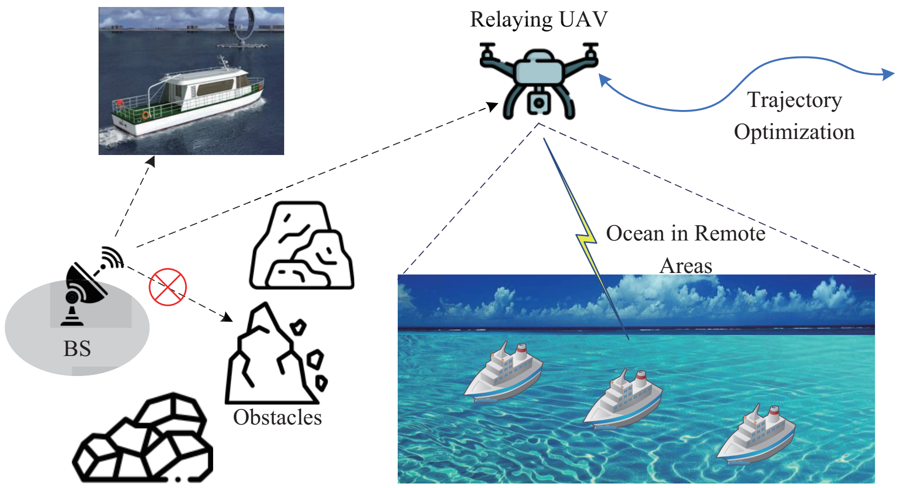

Figure 9. Trajectory optimization model in A2S integrated system.

Trajectory optimization is widely used in many fields in the scenario of A2S integrated systems. UAV delivery service providers can use trajectory optimization to plan the flight paths of UAVs. The system takes into account the destination address, terrain information, flight restrictions, and other factors to generate the best flight path to ensure the delivery of goods safely and quickly to the destination. Taxi companies employ trajectory optimization algorithms to schedule taxi routes [140]. By considering passenger demand, the real-time traffic information, and driver location, the system can dynamically assign orders and generate optimal pick-up routes to improve service quality and passenger satisfaction. In urban planning, trajectory optimization can be used to optimize urban traffic flow and road network design. By taking into account traffic data, people flow data, and urban development needs, the system generates the best road planning scheme to improve traffic congestion and improve traffic efficiency. In the field of equipment inspection and maintenance, trajectory optimization can help plan the travel path of inspection personnel or maintenance personnel. The system can generate an optimal path planning solution based on the device distribution, inspection, or maintenance requirements to improve the work efficiency and resource utilization.

Additionally, in order to improve the energy consumption of both UAV and sensor nodes (SNs), the authors in [141,142] optimized UAV trajectories. Specifically, an SN-and-UAV collaborative communication framework was designed. Such a framework can smooth the trajectory and facilitate the network re-orchestration for a data gathering effort from spatially dispersed MIoT over a large space. Therefore, through trajectory optimization MIoT can enable more efficient data collection and communication and improve resource utilization efficiency, while reducing energy consumption and costs. This is of great significance for marine environment monitoring, resource exploitation and utilization, maritime safety, and other fields.

3.4.2. Deployment Optimization

In spatial location optimization of the A2S integrated MIoT, the deployment optimization of multi-ABSs is an important aspect. The deployment optimization involves deploying multiple ABSs to the optimal location in an MIoT system for efficient communication coverage and DT. Figure 10 shows the deployment model of multiple ABSs in an A2S integrated system. The objective of multi-ABS deployment optimization is to determine the appropriate BS deployment location under the premise of meeting certain constraints, so as to maximize the communication coverage and transmission efficiency. Table 5 is a list of some common optimization goals and methods [143].

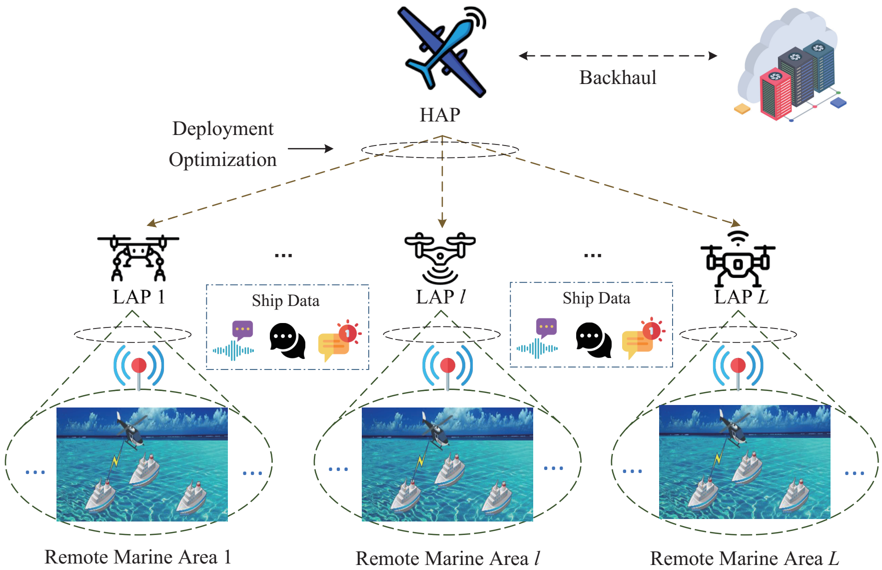

Figure 10. Multi-ABS deployment optimization model.

In A2S integrated scenarios, deployment optimization is widely used in many fields. Wireless communication network operators can use deployment optimization to optimize the location of BSs. By analyzing user needs, geographic information, a signal propagation model, and other factors, the system can generate the best BS deployment plan to improve signal coverage, reduce interference, and optimize network capacity and user experience. In the field of video surveillance, deployment optimization can be used for camera layout planning. The system can generate the optimal camera layout scheme according to the monitoring target area, monitoring requirements, equipment performance, and other factors to achieve comprehensive monitoring coverage, and improve security and monitoring effects. In IoT applications, deployment optimization can help to rationally deploy IoT devices. For example, in the field of smart homes, the system can generate the best device layout scheme according to a user's needs, the IoT device type and communication distance, and other factors to achieve efficient connection and intelligent control among devices.

Table 5. Optimization goals and methods.

Reference	Maritime Topology	BS Deployment Target	Method
[40]	UAV aided MIoT	Achieve maximum-range communication coverage.	Graph theory and convex optimization methods.
[71]	BS aided MIoT	Optimize transmission efficiency.	Particle swarm arithmetic.
[75]	BS aided MIoT	Ensure reliable communication.	Game theory.
[78]	UAV aided MIoT	Network load balancing optimization.	Genetic algorithm.
[88]	BS aided MIoT	Improve network performance.	Heterogeneous network collaboration.
[123]	UAV aided MIoT	Efficient BS distribution.	Mathematical models and optimization methods.
[128]	BS aided MIoT	Achieve optimal network performance.	Clustered deployment strategy.
[136]	A2S integrated MIoT	Achieve maximum capacity.	Genetic algorithms and game theory.

4. Application Fields of the A2S Integrated MIoT

The MIoT has a strong system power and is being applied in many fields, The following introduces some practical cases to demonstrate the application of the MIoT in different fields. Figure 11 shows a comprehensive diagram of the integrated application of the MIoT in the A2S environment.

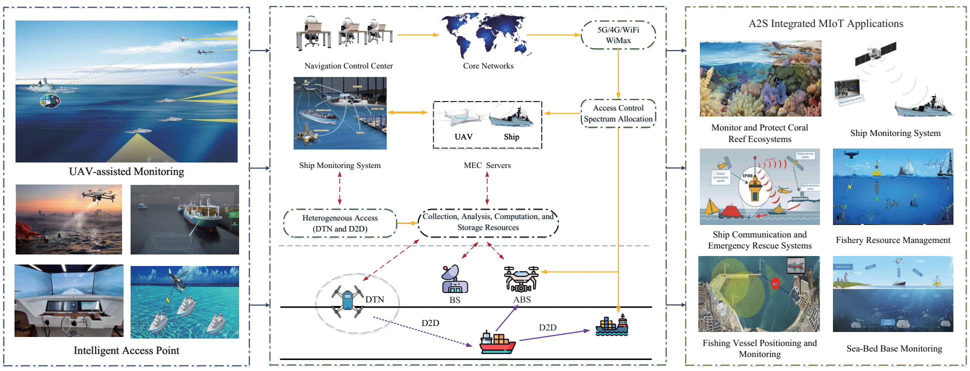

Figure 11. A comprehensive diagram of the application of the A2S integrated MIoT.

4.1. Marine Environmental Monitoring

The use of the MIoT to monitor and protect coral reef ecosystems is a concrete example. Coral reefs are an extremely important part of marine ecosystems, but are threatened by various factors, including climate change, pollution, and human activities. The MIoT can monitor the health and environmental changes in coral reefs by establishing sensor networks and DT systems.

Sensors are mounted on buoys near coral reefs to monitor the reef ecosystem by measuring parameters such as water temperature, water quality, nutrient concentration, pH, and the distribution of marine life. These sensors communicate wirelessly with the UAV, underwater robots, and other devices at sea to collect and transmit data in real time. The collected data are stored, analyzed, and visualized through a cloud-based platform that researchers, conservation agencies, and government departments can use to develop measures to protect and manage coral reefs [144]. For example, if an increase in water temperature or deterioration in water quality is detected, timely alerts can be issued and measures can be taken to reduce further damage. In addition, the real-time video surveillance of coral reefs can also be realized using the MIoT. By installing cameras, it is possible to remotely observe the ecological status of the reef and detect any anomalies, such as illegal fishing or tourist hotspot destruction.

Monitoring and protecting coral reef ecosystems through the MIoT can help scientists, environmental organizations, and government departments to better understand changes in the marine environment and to develop conservation strategies to ensure the health and sustainable development of coral reefs.

4.2. Maritime Traffic and Navigation Safety

(1) Ship monitoring system: By installing sensors and communication equipment on a ship, the real-time monitoring of the ship's position, speed, heading, and other parameters is possible. These data can be transmitted to the monitoring center on land. Such systems provide real-time position information on the vessel, helping to monitor the ship's course and avoid collisions.
(2) Ship health monitoring system: By installing sensors and data acquisition equipment on a ship, the operating status and health status of the ship's mechanical, electrical, and other equipment can be monitored in real time. The system automatically identifies equipment failures and abnormalities, providing early warnings for maintenance and repair to ensure the normal operation and navigational safety of the ship.
(3) Ship communication and emergency rescue systems: By using IoT technology, real-time communication between ships and land or other ships can be realized. When the vessel is in an accident or distress, it can quickly send a distress signal and provide accurate location information so that rescuers can respond quickly and provide assistance.
(4) Intelligent maritime transportation: Global maritime trade inevitably impacts economies, transportation systems, and markets on a global scale [145]. However, centralized optimization for ships underway faces numerous challenges, such as potential breaches in data security, excessive signaling overhead, and delayed responses due to high latency. Facing this challenge, using the federated learning in the A2S integrated MIoT has been proposed as an efficient solution for promoting data privacy, low latency, and high communication efficiency.

4.3. Marine Resource Management

The use of the MIoT can help to better manage fisheries and develop marine resources, reduce resource waste, and promote the sustainable development of fisheries. Specific uses are as follows:

(1) Fishing vessel positioning and monitoring: By installing position sensors and monitoring equipment on fishing vessels, information such as the position, speed, and heading of the fishing vessels can be tracked in real time. This helps to improve the safety and the management efficiency of the fishing vessels, and enables the identification of unusual behavior, such as illegal fishing activities or fishing vessel entry into restricted areas.
(2) Marine environmental monitoring: Various sensors, such as water quality sensors and meteorological sensors, are used to collect data in the ocean, including water temperature, salinity, oxygen content, ocean currents, and more. These data can help scientists to better understand marine ecosystems, assess the health of marine resources, and predict natural disasters such as storms and red tides.
(3) Fishery resource management: With the help of MIoT technology, fishery resources can be intelligently managed. By monitoring data such as fishery activities and fish stock distribution and trends, it is possible to monitor fishing in real time and assess resources. This contributes to sustainable fishery management policies, protects fishery resources, and ensures the sustainable development of fisheries.

5. Challenges and Future Development of the MIoT

5.1. Technical Security and Sustainability Challenges for the MIoT

The MIoT, while connecting ships, buoys, sensors, and shore-based infrastructure, faces a series of challenges in terms of technical security and sustainability. To ensure the reliability of data transmission, exchange, and communication, as well as the sustainability of the system, comprehensive solutions are required. The current technical security and sustainability challenges facing the MIoT mainly include the following aspects:

- Technical security challenges: MIoT systems involve a large amount of data transmission and information exchange, including sensitive fishery resource data, vessel positioning information, and more. Protecting these data from threats such as hacking, data tampering, or data breaches is a significant challenge.
- Communication reliability challenges: The MIoT relies on the wireless communication technique for DT, but in the offshore environment, factors including waves, weather conditions, and other factors can interfere with the transmission of wireless signals. Ensuring the stability and reliability of communication networks is a key challenge.
- Energy supply and sustainability challenges: MIoT devices operate for long periods of time and are often located far from land, so providing a stable energy supply is a challenge. At the same time, in order to achieve sustainability MIoT devices also need to be designed to be energy-efficient and environmentally friendly.

To address the technical security and sustainability challenges of the MIoT, we can consider the following research directions.

1. Reliability of data transmission and communication

- Adopt encryption technology: Implementing robust encryption algorithms during data transmission effectively prevents unauthorized access and tampering with data. This helps to maintain the confidentiality and integrity of information, ensuring its protection during transit.
- Establish multi-path communication: Implementing multi-path communication mitigates potential failures and interruptions associated with a single channel. This can be achieved by utilizing satellite communication, cellular networks, and other communication means to enhance overall communication redundancy.
- Implement fault-tolerance mechanisms: Introducing fault-tolerance mechanisms safeguards continuous operation in the face of faults or attacks. This includes employing redundant devices, alternate pathways, and automatic switching mechanisms to enhance the system's resistance to errors and interference.

2. Security of data exchange

- Utilize secure protocols: Employ secure communication protocols such as TLS (Transport Layer Security) and DTLS (Datagram Transport Layer Security) to ensure data are appropriately protected during transmission and exchange.
- Authentication and authorization: Enforce authentication and assign proper permissions for each device and user. This helps restrict access to critical information, ensuring data can only be accessed by authorized entities.
- Implement blockchain technology: Blockchain technology provides a decentralized, tamper-proof data storage method, enhancing data security and transparency, reducing risks during data exchange.

3. System sustainability

- Energy efficiency and management: Adopt energy-efficient devices, optimize device management, and implement energy recovery technologies to ensure the systems in the MIOT efficiently utilize energy during prolonged operations, reducing the need for frequent maintenance of sensors and devices.
- Regular updates and maintenance: Provide timely updates to software and firmware, and patch potential vulnerabilities to ensure the system operates at the latest security

and reliability standards. Regular maintenance and monitoring are crucial to ensuring the system's sustained normal operation.

- Utilize intelligent analytics and predictions: Utilize machine learning and big data analytics to monitor the performance of devices and sensors in real time, predict potential faults and issues, take preemptive measures, and ensure the sustainability and stability of the system.

According to the above discussion, to comprehensively address the technical security and sustainability challenges in the MIoT, an all-encompassing solution is indispensable. This requires cross-disciplinary collaboration involving hardware, software, networks, and management across multiple levels. Simultaneously, establishing and adhering to relevant industry standards and regulations ensures that the system conforms to best practices in design and operation. Only through global cooperation can a secure, reliable, and sustainable MIoT system be established.

5.2. Challenges for the A2S Integrated MIoT

The development of the A2S integrated MIoT has facilitated the deep integration of aviation and maritime systems, but at the same time, it faces a series of formidable challenges. These challenges include the limited endurance of aerial base stations, a restricted communication range, and data processing issues. To address these challenges, a comprehensive set of technologies and strategies can be employed.

- First, the limited endurance of ABSs is a critical issue restraining the development of the A2S integrated MIoT. To tackle this challenge, more advanced energy management technologies can be introduced. Solar charging and fuel cell technologies are two potential solutions. Solar charging systems can collect solar energy during the day and store it for use during the night or when cloud cover obstructs sunlight. Fuel cells, on the other hand, can provide more sustainable energy, extending the endurance of ABSs for complex and prolonged missions.
- Second, the limited communication range is another challenge that needs to be addressed. To expand the communication range, satellite communication and relaying systems can be utilized. Satellite communication can achieve broader coverage, allowing IoT devices to maintain connectivity in vast ocean areas far from land. Relaying systems can construct a multi-tiered communication network, transmitting signals through relay stations to extend the communication range. This hierarchical communication network structure enhances the reliability and stability of communication.
- Finally, considering the complexity of the maritime environment, optimizing the approach to data processing is essential. Edge computing technology can perform data processing near IoT devices, reducing the dependence on central data centers and enhancing the real-time response of data. This distributed data processing approach effectively alleviates the burden on central servers, improving the overall processing efficiency of the system. Moreover, employing advanced data compression and transmission algorithms can reduce the burden of data transfer and lower the bandwidth requirements for communication.

In conclusion, addressing the challenges faced by the A2S integrated MIoT requires multifaceted technological innovation and strategic responses. By introducing advanced energy management technologies, expanding the communication range, and optimizing data processing methods, we can effectively enhance the endurance, communication range, and data processing efficiency of ABSs, promoting the sustainable development of the A2S integrated MIoT.

6. Conclusions

The introduction of ABSs in the MIoT has allowed increased deployment flexibility and dynamic resource provisioning, aligning with 6G ubiquitous connectivity goals. In the A2S integrated MIoT, the incorporation of ABSs to supplement onshore and satellite deployments establishes an intermediary airborne stratum, addressing the constrained coverage of land-based stations and mitigating the heightened latency and narrow-band links associated with satellites. This survey demonstrates the role of the A2S integrated MIoT. Specifically, the A2S integrated MIoT can connect ships, marine equipment, sensors, etc., to achieve information collection, transmission, processing, and application. By introducing the A2S integrated MIoT, we can further solve problems, including maritime information transmission, computation-intensive task offloading, data-caching mechanisms, relay selection, multi-dimensional resource allocation, information security, etc. Moreover, the A2S integrated MIoT can provide real-time and accurate data support for marine environmental protection and marine resource development, and optimize maritime traffic management and navigation safety. Furthermore, several important open issues towards efficiently integrating and exploiting ABSs for maritime activities in the A2S integrated MIoT have been outlined, aiming to attract high research interest in this important domain. A major takeaway from this survey is that a novel implementation framework is set for the A2S integrated MIoT, optimizing important performance metrics in a wide range of deployment scenarios. Unfortunately, there is a gap among theoretical gains and practical large-scale implementation, as the field of the A2S integrated MIoT has only recently started to gain traction.

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Abbreviations

The following abbreviations are used in this manuscript:

HPCAS	High-performance computing and storage	WSN	Wireless sensor network
MIoT	Maritime internet of things	UAV	Unmanned aerial vehicle
A2S	Air-to-sea	ABS	Airborne base station
IoT	Internet of things	SOC	Submarine optical cable
BS	Base station	D2D	Device to device
CBS	Coastal base station	MEC	Mobile edge computing
SC	Satellite communication	PD	Power distribution
DT	Data transmission	AMC	Adaptive modulation and coding
CI	Communications infrastructure	DPC	Dirty paper coding
RP	Routing protocol	CEAIC	Channel estimation and interference cancellation
SPAT	Spatial position and trajectory	SMA	Superior multiple access

ST	Sensor technology	TDMA	Time division multiple access
CT	Communication technology	FDMA	Frequency division multiple access
VAISs	Video and image sensors	NOMA	Non-orthogonal multiple-access
RFID	Radio-frequency identification	CIP	Collaborative information processing
SCM	Supply chain management	IS	Information source

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