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Review

Application Prospects and Challenges of VHF Data Exchange System (VDES) in Smart Fisheries

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Abstract: Smart fisheries are an important way to promote the sustainable development of fisheries, and efficient and reliable marine communication systems are the key to realizing smart fisheries. As an emerging marine communication technology, the VHF Data Exchange System (VDES) has the advantages of a high data transmission rate, large communication capacity, and wide coverage, providing new opportunities for the transformation and upgrading of smart fisheries. This paper introduces the technical architecture and functions of the VDES, compares it with existing marine communication technologies, analyzes the key requirements of a smart fishery, and assesses how the VDES meets these requirements. The potential application scenarios of the VDES in smart fishery fields such as fishing vessel monitoring, fishery resource management, and maritime security are discussed. The challenges faced by the VDES in the application of smart fisheries, such as technology, policies and regulations, and construction cost layout, are analyzed, and its future development trend is prospected. Suggestions such as its integration with emerging technologies, the realization of global seamless coverage, and the strengthening of international cooperation and data sharing are proposed. This paper aims to provide theoretical guidance and scientific reference for the promotion and application of the VDES in smart fisheries.

Keywords: smart fishery; VDES; maritime communication; internet of things; big data

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1. Introduction

With the growth of the global population and the increase in consumption demand, overfishing, environmental pollution, and climate change, the sustainability of fishery resources is facing increasing pressure [1]. Factors such as overfishing, environmental pollution, and climate change have led to the depletion of fishery resources and the destruction of ecosystems [2]. In order to achieve sustainable fishery development, smart fisheries have become a global consensus. The core of smart fisheries lies in using modern information technology to improve fishery production efficiency, the resource management level, and environmental protection capabilities [3,4]. Real-time data acquisition and efficient information transmission are the prerequisites for realizing the intelligent application of smart fisheries.

Real-time data acquisition and efficient information transmission at sea rely on a variety of methods, including satellite communications (such as the Inmarsat, Iridium, Very Small Aperture Terminal (VSAT)), the VDES, enhanced application of the Automatic Identification System (AIS), and hybrid architectures combining multiple technologies, so as to achieve ship–shore interconnection and maritime Internet of Things (IoT) applications [5,6]. Mobile network communications provide high-speed, high-bandwidth, and relatively low-cost communications services in coastal areas, but their coverage is limited by coastal base stations and cannot be used far from the coast [7]. Satellite communications provide voice, data, and internet access across the world's oceans, making them particularly suitable for ocean-going vessels, but they are expensive and susceptible to weather and signal delays [8]. Traditional maritime communication methods such as Very-High Frequency (VHF), Medium-Frequency (MF), and High-Frequency (HF) radio, AIS, Wireless Local Area Network (WLAN) and Wi-Fi, and the Beidou Navigation System (BDS) have their own limitations, either due to distance restrictions, insufficient bandwidth, or susceptibility to interference [9,10].

As an emerging marine communication technology, the VDES is the mainstream technology for future marine communications due to its advantages of broadband, high speed, and wide coverage. Although Hu et al. explored the application of the VDES in maritime safety [11] and Alissa et al. examined its potential in shipping data exchange [12], existing research on the VDES mainly focuses on the maritime application technology level. The application of the VDES in the diverse and complex smart fishery environment is still in its infancy, and its specific applications in fishery production management, resource conservation, and environmental monitoring have not been fully explored [13].

In order to make up for the lack of VDES application in smart fisheries, this paper adopts the method of subject classification, takes "VDES" and "smart fisheries" as keywords, and uses 133 documents retrieved from the "Web of Science" and "CNKI" document databases as materials to analyze the application prospects and challenges of the VDES in smart fisheries. First, Section 2, "VDES Technology Overview", will comprehensively introduce the VDES technology from two aspects: the technical architecture and functions of the VDES (Section 2.1) and a comparison between the VDES and existing communication technologies (Section 2.2). Secondly, Section 3, "Demand Analysis and Countermeasures for Smart Fisheries", will focus on analyzing the key demands of smart fisheries (Section 3.1) and explain how the VDES supports these needs (Section 3.2). Finally, Section 4, "Potential Application Scenarios of VDES in Smart Fisheries", will specifically explore the various application possibilities of the VDES in smart fisheries and provide a reference for the application of the VDES in this field. Through in-depth analysis of these three topics, this paper aims to reveal the application potential of VDES technology in smart fisheries and point out the challenges facing its development.

2. VDES Technology Overview

2.1. Technical Architecture and Functions of VDES

The VDES is a new maritime communication system based on Very High Frequency (VHF) that aims to enhance and expand the functions of the existing Automatic Identification System (AIS) and provide higher data transmission rates, greater communication capacity, and a wider range of applications [14]. The technical architecture and system functions of the VDES are shown in Figure 1. The VDES is designed to achieve efficient data exchange between ships and shore users. The core of the VDES is to use ground or satellite links, under the management of the control station, or autonomously to achieve automated or manual data exchange. The VDES uses designated VHF channels to minimize crew intervention and is compatible with existing AIS and Application Specific Messages

(ASMs) applications. The VDES also supports Very High Frequency Data Exchange (VDE) functions, language-independent communications, data integrity monitoring, network security measures, and machine-to-machine communications. Through these key functions, the VDES ensures high availability and is committed to providing a clear and easy-to-understand information exchange experience to promote the intelligent development of maritime communications.

The VDES relies on three application services, ASMs, VDE, and Ground Distribution Messaging (GDM, also known as ABM), to work together to build a comprehensive and flexible maritime communication system. These services provide seamless data exchange via terrestrial and satellite links, bringing significant advantages to a variety of maritime applications, including smart fisheries [14,15]. ASM is similar to an enhanced version of AIS, broadcasting safety-related information and application-specific data, and is capable of handling larger and more diverse data sets. ASM provides a shared situational awareness platform that supports applications such as collision avoidance, local weather updates, and fishery activity reports and is essential for establishing initial contact and rapidly disseminating critical information. VDE provides a medium-bandwidth two-way communication link and is the main data transmission force of the VDES system. VDE supports large file transfers, real-time sensor data exchange, remote diagnostics, and even video streaming and is the backbone of applications that require continuous data exchange. ABM uses satellites to extend the reach of the VDES beyond terrestrial networks and is essential for communicating over long distances and serving vessels on the high seas or with limited ground infrastructure. ABM can broadcast wide-area information such as weather forecasts, navigation warnings, and search and rescue information.

These three services work together to achieve a variety of collaborative scenarios [16–18]. ASM provides initial contact and basic vessel information, while VDE further exchanges more detailed data such as precise position, speed, heading, and even video data, enhancing the situational awareness of nearby vessels and shore-based operators. In search and rescue scenarios, ABM can broadcast distress calls received through ASM to a wider area, while VDE facilitates direct communication between distressed vessels, rescuers, and coordination agencies to achieve efficient and accurate rescue [19]. In data-driven fisheries management, sensors on fishing gear transmit data to buoys equipped with the VDES (using VDE) through the IoT, and the buoys forward these aggregated data to shore stations through VDE or forward them via satellite using ABM when out of range. Even in remote areas, fishery managers can monitor fishing activities, assess fish stocks, and enforce regulations in near real time [20]. ABM can also provide weather forecasts and ocean data to fishing vessels, combined with real-time fishing data and vessel performance information transmitted through VDE, to help captains make more informed fishing decisions and optimize operations.

The VDES is designed to enable seamless switching between ground and satellite communications. This is made possible by the integrated management of channels and resources by the VDES control station, which ensures efficient use of the spectrum, minimizes interference, and routes data between ground stations and satellites as needed. Standardized protocols and message formats ensure interoperability between different VDES components, whether communications are conducted over ground or satellite links [21]. Adaptive modulation and coding techniques optimize data transmission based on channel conditions, ensure reliable communications even in harsh environments, and automatically switch between ground and satellite links to adapt to changes in signal strength.

By combining the strengths of ASM, VDE, and ABM and leveraging ground and satellite infrastructure, the VDES creates a powerful and flexible maritime communications system. This integrated approach facilitates seamless data exchange, supports a wide range of applications, and is a valuable tool for improving safety, efficiency, and sustainability in the maritime domain, especially in the field of smart fisheries.

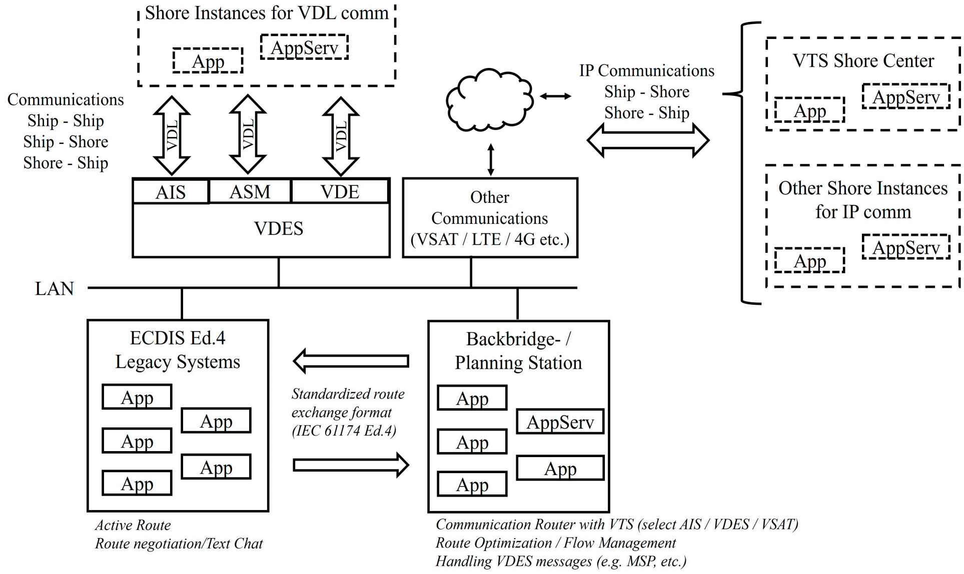

Figure 1. Technical architecture and system functions of VDES [22].

2.2. Comparison Between the VDES and Existing Communication Technologies

Existing maritime communication technologies cover a variety of systems to meet the needs of different distances and functions. Short-range communications mainly rely on VHF, which supports voice, digital selective calling (DSC), and AIS and is an important part of the Global Maritime Distress and Safety System (GMDSS) [23,24]. MF is used for medium-range communications, also supports voice and DSC, and is also part of the GMDSS [25]. HF can be used for long-distance and even global communications [26]. In terms of satellite communications, Inmarsat and Iridium provide global coverage, while VSAT enables high-speed internet access [27]. In addition, mobile communication networks can be used in near-shore areas, while BDS provides positioning, navigation, timing, and short message communication services [28]. Ships usually use ship-based local area networks (LANs) for internal communications [29].

A comparison of the functional characteristics of existing maritime communication technologies is shown in Table 1. VHF, MF, and HF are GMDSS components, which are suitable for short-, medium-, and long-distance communications, respectively, but the data transmission rate is low, and they are easily affected by interference or the ionosphere. AIS improves navigation safety, but the information is easily be tampered with. Satellite communications such as Inmarsat, Iridium, and VSAT provide wider coverage and higher data rates, but at a higher cost. Wi-Fi and mobile communications are limited by coverage. BDS provides reliable navigation and timing and supports limited short message communications [5,30].

Table 1. Comparison of functional characteristics of VDES and existing maritime communication technologies [25,27,30–32].

Technology	Functional Integration	Data Transmission Rate	Spectrum Utilization	Security	Compatibility	Application Scope	Disadvantages
VDES	Voice, data, AIS, safety-related information	Medium	High	Medium	Compatible with VHF	Broadcast of maritime safety information, two-way data exchange	New technology, high equipment cost, coverage still needs to be expanded
VHF	Voice, DSC	Low	Medium	Low	Good, GMDSS components	Short-range communications, maritime distress and safety calls	Communication range is limited, susceptible to interference
MF	Voice, DSC	Low	Medium	Low	Good, GMDSS components	Medium-range communications, maritime distress and safety calls	Communication distance is limited and susceptible to interference and weather
HF	Voice, data, DSC	Low	Low	Low	Good, GMDSS components	Long distance communication	Communication quality is unstable and easily affected by the ionosphere
AIS	Automatic vessel identification information	Low	High	Low	Good	Improve navigation safety and traffic management efficiency	Reliance on accurate vessel information input, vulnerable to interference and spoofing
BDS	Navigation, timing, short message communication	Low (short message)	High	Medium	Compatible with other navigation systems	Global navigation, positioning, timing, and short message communication in emergency situations	Short message communication capacity is limited, and voice and high data volume transmission is not possible
Inmarsat	Voice, data, Internet	Medium to high	High	Medium	Good	Global satellite communications	The cost is high, and signal coverage may be limited in some areas
Iridium	Voice, data, Internet	Medium	High	Medium	Good	Global satellite communications	Higher cost and relatively low data transfer rate
VSAT	Voice, data, Internet	High	High	Medium	Good	High-speed maritime communications	High cost, requires professional installation and maintenance, and is greatly affected by weather
Wi-Fi	Data	High	High	Medium	Good	Wireless network inside the ship	Limited coverage and vulnerable security
Mobile network communications	Voice, data, Internet	Medium to high	High	Medium	Good	Nearshore communications	Signal coverage is limited to coastal base stations and cannot be used far from the shore

Compared with traditional maritime communication methods such as VHF, MF/HF, AIS, WLAN/Wi-Fi, and BDS, VDES technology stands out. The VDES integrates voice, data, AIS, and safety-related information. Through advanced modulation technology and channel access schemes, the VDES achieves a higher data transmission rate and spectrum utilization and supports larger capacity data transmission, such as real-time video and remote diagnosis. More advanced error correction coding and modulation methods enhance the anti-interference ability and reliability of the VDES. Functionally, the VDES is not only compatible with traditional voice and DSC but also integrates AIS and other safety information, which can realize more comprehensive maritime safety information broadcasting and two-way data exchange, such as ship traffic management and collision warning. The VDES is compatible with existing VHF systems, reducing upgrade costs, and supports interconnection with other communication systems to build a more flexible and efficient maritime communication network. The VDES has good scalability and flexibility, supports the development of future maritime communication technologies, such as the IoT and autonomous navigation, and is expected to become the mainstream technology for future maritime communications [30,33,34].

In summary, VDES has made significant progress in maritime communications, providing the bandwidth, coverage, and flexibility required for the evolving needs of smart fisheries. The next chapter will analyze the key requirements of smart fisheries and how the VDES meets these requirements.

3. Demand Analysis and Countermeasures for Smart Fisheries

3.1. Key Demands for Smart Fisheries

Implementing a smart fishery is a process of using modern information technologies such as the IoT, big data, Artificial Intelligence (AI), satellite remote sensing, and the mobile internet to develop and utilize fishery information resources and comprehensively improve the productivity and management efficiency of fisheries through smart breeding such as environmental monitoring, automatic feeding, fish behavior monitoring, disease prevention and control, and smart facilities; smart fishing such as fishing forecasts, fishing vessel positioning monitoring, smart fishing gear, and illegal fishing monitoring; fishery resource management such as resource assessment and monitoring, ecological and environmental protection, and data analysis and decision-making; fishery market and services such as aquatic product quality traceability, online trading platforms, and fishery information services; as well as smart fishing port construction and fishery safety production management [35–37]. Smart fisheries are an important means and effective way to promote the structural reform of the fishery supply side and accelerate the transformation and upgrading of fisheries.

The demand analysis of smart fisheries reveals their key needs in real-time monitoring, data sharing, remote management, security and reliability, and interoperability [37–41]. Real-time monitoring requires high-frequency data transmission and real-time update capabilities to ensure the safety and efficiency of fishery activities; data sharing requires an efficient data exchange platform and standardized data format to improve decision-making quality and resource utilization efficiency; remote management requires stable remote communication capabilities and efficient command transmission mechanisms to achieve remote control and task allocation; security and reliability require strong data encryption and anti-interference capabilities to prevent data leakage and communication interruption; interoperability requires the system to be compatible with existing technologies and equipment to ensure a smooth transition and wide application. These requirements together constitute the comprehensive requirements of smart fisheries for efficient, reliable, and secure communication technologies.

3.2. The VDES Supports the Needs of Smart Fisheries

The VDES is an integrated space–ground system that organically integrates space-based and shore-based systems. With the continuous development and improvement of technology and standard systems, the VDES can meet the needs of large-scale, dense ships and two-way data exchange between ships and shores in nearshore and port areas through the VHF frequency band which is applicable to any weather conditions [22]. In the vast sea and air areas, it can realize global information broadcasting and two-way data exchange through a low-orbit satellite network covering the world, meeting the needs of integrated space–ground communication and information transmission of all things required in the internet application scenarios of maritime safety communication, global stereoscopic observation, energy exploration, and environmental monitoring (Figure 2) [34].

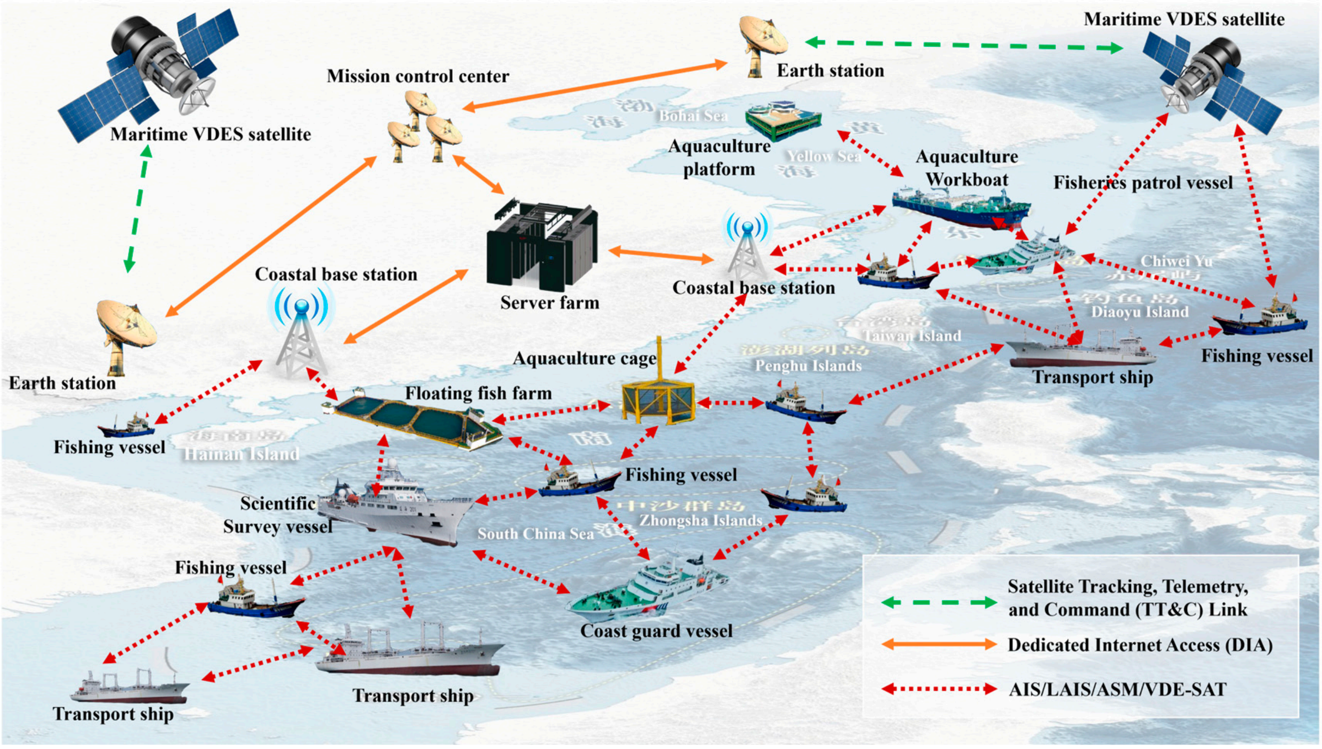

Figure 2. The space–ground architecture of the VDES system.

The use of the VDES provides a much-needed improvement to the current AIS-based vessel traffic service. With a bandwidth 32 times higher than AIS, the VDES will support a wider range of applications such as fisheries, maritime surveillance, encrypted communications, logistics, search and rescue, etc. [22]. By adding space-based capabilities to the VDES, the use of the system is extended from the coastline to anywhere in the ocean. The VDES is integrated with electronic navigation systems to improve navigation, increase safety, and save up to 25% in costs [42]. This increase in space and reduction in cost capabilities will expand the scope of the VDES from the coastline to anywhere in the ocean, providing strong support for the development of smart fisheries at sea.

Table 2 summarizes the service support relationship of the VDES for smart fisheries. The VDES is not only powerful in itself but can also be deeply integrated with other technologies, especially IoT technology, to further expand its application potential. Taking fishing gear sensors as an example, it is envisioned that various sensors are installed on the fishing net to monitor key data such as temperature, pressure, and position in real time. These data are transmitted to the buoy equipped with the VDES via a low-power wide area network (LPWAN). Due to the low power consumption characteristics of LPWAN technology, the sensor can operate for a long time without frequent battery replacement. The buoy acts as a data transfer station and transmits the collected data to the shore base station or satellite via the VDE link. If the buoy is located in the nearshore area, the data are transmitted to the shore station via the VDE ground link to achieve real-time monitoring; if the buoy is located in the open sea, the data are forwarded via a satellite link (ABM) to ensure the continuity of data transmission. In this way, fishery managers can monitor fishing conditions, environmental conditions, and fishing gear status in real time, thereby optimizing fishing strategies, reducing bycatch, and protecting marine ecology [43–45].

Table 2. VDES service support relationship for smart fisheries.

Smart Fisheries Content	VDES Service Support	Description
Smart fishing	Strong support	Fishing forecast: the VDES can receive and send fishing forecast information. Fishing vessel positioning and monitoring: the VDES can provide more accurate positioning and more reliable communication, supplementing the shortcomings of AIS. Smart fishing gear: the VDES can communicate with smart fishing gear to collect and transmit data. Illegal fishing monitoring: the VDES can assist in monitoring and reporting suspicious fishing activities.
Fisheries resource management	Support	Resource assessment and monitoring: the VDES can transmit monitoring data to management departments. Fishery ecological environment protection: the VDES can be used to report pollution incidents and environmental anomalies. Fishery data analysis and decision-making: the VDES serves as a data transmission channel to support data collection and analysis.
Smart breeding	Partial support	Environmental monitoring and control: the VDES can transmit sensor data to a shore-based control center, but nearshore aquaculture may rely more on other networks. Automatic feeding: the VDES can be used to remotely control feeding equipment, but nearshore aquaculture may use other LAN technologies. Fish behavior monitoring: If offshore cages are involved, the VDES can transmit monitoring data. Disease diagnosis and prevention: the VDES can transmit diagnostic data and expert guidance. Smart aquaculture facilities: the VDES can be used to remotely monitor and manage offshore aquaculture facilities.
Fisheries market and services	Limited support	Aquatic product quality traceability: the VDES is mainly used for data transmission in the offshore part, and the land part relies on other networks. Online trading platform: the VDES can provide data connection for offshore transactions, but the main trading platform relies on land-based networks. Fishery information service: the VDES can be used as a channel for publishing and receiving fishery information.
Other	Partial support	Smart fishing port construction: the VDES can support communication and data exchange between fishing ports and ships. Fishery safety production: the VDES can be used for maritime safety communications and emergency rescue.

The data provided by the VDES can be combined with satellite images, oceanographic data and other data sets for big data analysis. This helps to gain a more comprehensive understanding of the marine environment and the distribution of fish resources and provides a more scientific basis for decision-making in fishery management. Combining the location and fishing data of fishing vessels provided by the VDES, the sea surface temperature and chlorophyll concentration provided by satellite images, and the ocean current information provided by oceanographic data, it is possible to predict the movement trajectory of fish schools and guide fishing vessels to conduct more effective fishing operations [46]. AI and machine learning technologies can also play an important role in VDES data analysis. Through in-depth mining of VDES data, AI can be used for predictive maintenance of ships, predicting potential failures based on engine operation data, arranging repairs in advance, and avoiding losses caused by failures at sea. In addition, AI can also be used to optimize fishing routes, plan the best fishing path based on fish distribution, ocean currents, and weather information, improve fishing efficiency, and reduce fuel consumption [47]. AI can also perform anomaly detection, identify abnormal situations such as illegal fishing or loss of fishing gear, and take timely response measures.

Although the role of the VDES in offshore aquaculture and market services is relatively limited, it can still provide certain support. In intelligent aquaculture, the VDES can transmit the monitoring data of offshore cages, disease diagnosis information, and be used for remote management of offshore aquaculture facilities; in terms of fishery markets and services, the VDES can support data connections for offshore transactions and serve as a channel for publishing and receiving fishery information [48]. However, since there is usually more convenient land-based network coverage near the coast, the VDES is more of a supplementary means in these areas, combined with other communication technologies to form a more complete smart fishery system.

In short, the integration of the VDES with technologies such as the IoT, big data analysis, and AI provides strong technical support for the development of intelligent fisheries. Through real-time data collection, transmission, and intelligent analysis, the VDES helps the field of fishery management achieve a more efficient, sustainable, and scientific development and contributes to protecting the marine ecology and ensuring the sustainable development of the fishery economy.

4. Potential Application Scenarios of the VDES in Smart Fisheries

VDES technology is currently in the early stages of active development and application, especially in the large-scale application of smart fisheries, and related research and practical cases are still being accumulated. Although the VDES has shown certain application value in maritime surveillance, encrypted communications, logistics, search and rescue, etc. [21,28,49], its specific application scenarios in fisheries, especially its integration with existing systems and operating procedures, still need further exploration and improvement. However, based on the powerful functional characteristics and technical advantages of the VDES, such as higher bandwidth, more reliable communication, and more accurate positioning, we can reasonably speculate on the important role it may play in the future development of smart fisheries and preliminarily outline some potential application scenarios. These scenarios cover fishing vessel monitoring, resource management, maritime safety, data analysis, and other aspects, providing new possibilities for improving fishery production efficiency, ensuring the safety of fishermen and promoting sustainable development.

In terms of fishing vessel monitoring, the VDES will go far beyond simply providing basic information such as location, speed, and heading. Through real-time monitoring, the VDES can collect and transmit various key status information such as engine speed, fuel consumption, and fishing gear operation for fishing vessels, thereby fully understanding the operating status of the fishing vessels [43]. Its high data transmission rate and real-time update capability enable fishery managers to accurately grasp the dynamics of each fishing vessel, detect abnormal situations in a timely manner and take corresponding measures, effectively reduce accidents, and improve operational efficiency. Furthermore, through the analysis of historical data, the VDES can identify abnormal navigation trajectories and berthing behaviors, assist in determining whether there is illegal fishing or other illegal activities, and provide strong support for fishery law enforcement [15]. At the same time, the fuel consumption monitoring function can help captains optimize route planning, reduce operating costs, and contribute to reducing carbon emissions. For different types of fishing vessels such as trawlers, purse seine fishing vessels, and fishing gear fishing vessels, the VDES can set differentiated monitoring parameters and warning thresholds to achieve more refined monitoring management.

The application of the VDES in the field of fishery resource management can bring data exchange and sharing to a new level. Managers and scientific research institutions can collect and obtain key data such as fish distribution, catch monitoring, and environmental parameter records in real time, which can not only optimize fishing plans and promote sustainable fishery development but also provide a deeper understanding of marine ecosystems. By combining marine environmental data and fish behavior models, the VDES can predict the distribution and movement trends of fish schools, guide fishing vessels to conduct precise fishing, improve fishing efficiency, and reduce ineffective operations and the impacts on the marine environment [50]. Real-time monitoring of a catch and comparing it with the set quota can promptly remind fishing vessels to avoid overfishing and ensure the sustainable use of fishery resources. In addition, by monitoring the environmental parameters and fish activities of key habitats, the VDES can assess the health of habitats and provide a scientific basis for the formulation of protection measures. Through the onboard video monitoring system and edge computing equipment, combined with AI technology, video images can be analyzed to identify fishing species, determine whether fishing behavior is compliant, and estimate catch. The VDES can transmit effective data information on fishing vessels in real time, provide more accurate data for fishery resource assessment, and optimize the smart supervision methods of fishery management departments [51].

The VDES can provide more comprehensive and timely protection for maritime safety. In addition to quickly and reliably transmitting fishing vessel distress alarms, distress position reports, and emergency assistance requests, the VDES can also receive and broadcast more detailed weather warning information to help fishing vessels avoid bad weather in advance and ensure navigation safety [43]. By integrating and analyzing multi-source data such as meteorological and sea conditions and using the two-way communication function of the VDES, real-time assessment of fishing vessel operation risks and the interconnection of avoidance suggestions can be achieved, thereby assisting fishing vessels in making safer and more efficient decisions. Using the precise positioning information of the VDES, collision warnings between fishing vessels can be achieved to avoid maritime collision accidents [52]. In the event of a maritime accident, the VDES can provide more accurate information on the location of the distressed vessel, provide key support for search and rescue operations, and minimize casualties and property losses.

Its data recording function can be used for accident investigation and suspicious vessel screening, promoting the transformation of fishery safety management from passive post-event disposal to active pre-event prevention and risk control. In addition, the VDES can effectively monitor and warn of illegal operations, such as deliberate dismantling and blocking of positioning signals, and monitor whether fishing vessels enter no-fishing zones or other restricted areas through electronic fences [45]. The analysis reports provided by the VDES can provide data support for the daily supervision and maritime law enforcement of the fishery department and can be combined with other law enforcement measures to build a more effective law enforcement system, thereby improving the efficiency and effectiveness of supervision and ensuring the rational use of fishery resources.

In addition to the above points, the VDES can also play an important role in fishery supply chain management and the in-depth mining and analysis of fishery scientific research data, which can promote the comprehensive and sustainable development of fisheries [53]. By tracking the entire process of fish catch from fishing to landing, the quality and safety of aquatic products can be guaranteed, and the efficiency of the supply chain can be improved. The communication method and transmission capacity of the VDES can broaden the channels and data volume for fishery scientific research institutions to obtain marine data, which is conducive to the in-depth mining and analysis of fishery data.

5. Challenges and Development Trends

5.1. Challenges

VDES technology has great application potential in the field of smart fisheries, but it also faces many challenges on its development path. From a technical perspective, the limitation of network coverage is an urgent problem that the VDES needs to solve. Although the VDES has a wider coverage area than AIS, there are still signal blind spots in the open sea and polar regions. This requires further improvement of the layout of ground base stations and the strengthening of integration with satellite communications, especially low-orbit satellite constellations, to truly achieve global seamless coverage [54]. The reliability of the VDES in harsh sea conditions is also a key issue. Extreme weather such as storms and sea fog can seriously affect signal transmission. Therefore, it is necessary to improve the anti-interference ability and robustness of the VDES to ensure that it can operate stably in various complex environments [55]. For small fishing boats, the power consumption of terminal equipment is also an important consideration. Only by developing low-power equipment and optimizing energy management strategies can the endurance time and operating costs be effectively extended. The VDES generates a large amount of heterogeneous data. How to efficiently integrate and analyze these data and extract valuable information from them is also a major challenge facing the development of VDES technology. This requires the development of specialized data processing tools and the establishment of a unified data standard interface to better support smart fishery decision-making [56].

In terms of policies and regulations, the deployment and application of the VDES also face some challenges. Spectrum management is the key to VDES deployment. Due to the different spectrum allocation policies of various countries, it is necessary to strengthen international cooperation, coordinate spectrum resources, avoid mutual interference, and ensure the interconnection and interoperability of the VDES worldwide [57]. At the same time, the fishing vessel operation and catch data collected by the VDES involve commercial secrets and national security. Therefore, it is crucial to establish clear data ownership, usage rights, and sharing rules, which requires finding a balance between data security and data utilization.

Cost and personnel training are also difficult problems that need to be overcome in the promotion and application of the VDES. For small fishery enterprises, the initial investment cost of the VDES is relatively high, including terminal equipment, ground base stations, and software platforms, which require capital investment. This requires exploring more flexible business models or government funding support for system upgrades and renovations. The long-term maintenance and upgrades of the system also require continuous capital investment, so it is necessary to optimize the system design, reduce maintenance costs, and provide convenient upgrade services [58,59]. The skills gap of personnel is also a major obstacle to the application and promotion of the VDES. It is crucial to bridge the digital divide, especially in some developing countries. It is necessary to strengthen digital literacy education and improve the acceptance and application capabilities of new technologies among governments, scientific research institutions, and fishermen.

5.2. Future Development Trends

In September 2021, the precision intelligent control system for fishing vessel safety in Zhejiang Province, China, was put into operation. The system realizes sea–land interconnection through "broadband access to the sea" and relies on satellite broadband communication networks, smart fishing port networks, and production safety early warning networks to achieve real-time monitoring and early warning and management of fishing vessels and crew members [60]. The precision intelligent control system for fishing vessel safety has greatly improved the inherent safety level of provincial-level offshore fishing vessels and accelerated the modernization of Zhejiang's marine fishery governance system and governance capabilities.

Through the construction of ground base stations, satellite communication integration, and the deployment of low-orbit satellite constellations, the VDES will gradually achieve seamless coverage around the world and provide real-time and reliable information services for distant-water fishing vessels. In the future, the VDES will be deeply integrated with technologies such as the IoT, big data, and AI to build a more intelligent fishery management system and form a "smart fishing sea" network with wider coverage and more powerful functions. The VDES-based fishery safety intelligent control system can promote the sustainable use of global fishery resources and the modernization of fishery management by building international cooperation and data sharing mechanisms. However, the premise of the concept is to improve the VDES standard system and enhance interoperability, break down the data barriers between different systems, and realize information sharing and collaborative work.

With the maturity of technology and large-scale application, the deployment and operation costs of the VDES will gradually decrease, making it easier for small- and medium-sized fishery companies to accept. The VDES will also provide more refined data services, supporting applications such as high-definition video transmission and real-time marine environment data collection. The openness and flexibility of the platform will give rise to more customized services to meet the specific needs of different fishery scenarios.

International cooperation and data sharing are crucial to the global application of the VDES. Countries need to work together to promote VDES technology to play a greater role globally. The development of the VDES also needs to consider integration with existing maritime communication systems, achieve data sharing and collaborative work between different systems, avoid information islands, and formulate long-term development plans to ensure the sustainable development of the system.

6. Conclusions

This paper discusses the application prospects and challenges of the VDES in smart fisheries. With its advantages of high bandwidth, wide coverage, and high speed, the VDES has shown great potential in improving fishery production efficiency, resource management level, and maritime security. Its application scenarios cover real-time monitoring of fishing vessels, fishery resource assessment and management, maritime safety communication and early warning, illegal fishing monitoring, and other aspects, providing new technical means for achieving the sustainable development of fisheries. By achieving more refined data collection and transmission, the VDES can provide fishery managers, researchers, and fishermen with richer and more timely information support, thereby optimizing fishing strategies, improving resource utilization efficiency, reducing operating costs, and enhancing maritime safety.

However, the widespread application of the VDES in smart fisheries still faces many challenges. At the technical level, it is necessary to solve the problems of network coverage limitations, reliability in harsh environments, power consumption of terminal devices, and fusion and analysis of massive heterogeneous data. At the policy and regulatory level, it is necessary to coordinate international spectrum management, establish data ownership and sharing mechanisms, and regulate cross-border data flows. In terms of cost and personnel training, it is necessary to reduce the deployment and maintenance costs of the VDES and bridge the digital skills gap of fishermen. In addition, the integration of the VDES with existing maritime communication systems and long-term sustainable development are also key issues that need attention.

This study currently focuses on the theoretical analysis of the application of VDES technology in smart fisheries and the exploration of potential application scenarios. Since actual experiments and simulation studies require a lot of resources and time, they have not yet been carried out. This limits our in-depth understanding of the performance of the VDES in complex real-world environments. However, we believe that this preliminary study has laid an important theoretical foundation for more in-depth experimental and simulation work in the future. Future research will focus on the performance verification and optimization of the VDES in actual fishery scenarios. We plan to carry out a series of experimental and simulation studies to evaluate the key performance indicators of the VDES, such as data transmission rate, latency, coverage, and anti-interference ability under different weather conditions and sea conditions. Specifically, we will build a simulation platform that simulates a real fishery environment, simulating different numbers of fishing vessels, buoys, and other offshore equipment, as well as various weather and sea conditions, to evaluate the capacity, coverage, and anti-interference ability of the VDES network. In addition, we also plan to conduct offshore field tests to deploy VDES devices and IoT sensors on actual fishing vessels, measure data transmission rates and latency in actual fishing scenarios, and verify the compatibility and interoperability of the VDES with other maritime communication systems. Furthermore, we plan to develop a small prototype system to demonstrate the integration of the VDES with IoT sensors on fishing gear, explore the feasibility of using the VDES to monitor fishing conditions, environmental conditions, and fishing gear status in real time, and evaluate its potential contribution to improving fishing efficiency and protecting marine ecology. These experimental and simulation studies will provide a stronger scientific basis for the practical application of the VDES in smart fisheries.

In short, the VDES, as an emerging marine communication technology, has brought new opportunities for the development of smart fisheries. By effectively responding to challenges and giving full play to its technical advantages, the VDES will play an increasingly important role in promoting the sustainable development of fisheries, ensuring the safety of fishermen and improving the economic benefits of fisheries. Future research should focus on the evaluation of the application effect of the VDES in specific fishery scenarios and explore innovative applications based on the VDES to provide strong support for the sustainable development of smart fisheries.

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