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Review Article

Advances in Software-Defined Technologies for Underwater Acoustic Sensor Networks: A Survey

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Underwater Acoustic Sensor Networks (UASNs) are an important technical means to explore the ocean realm. However, most UASNs rely on hardware infrastructures with poor flexibility and versatility. The systems typically deploy in a redundant manner, which not only leads to waste but also causes serious signal interference due to multiple noises in designated underwater regions. Software-Defined Networking (SDN) is a novel network paradigm, which provides an innovative approach to improve flexibility and reduce development risks greatly. Although SDN and UASNs are hot topics, there are currently few studies built on both. In this paper, we provide a comprehensive review on the advances in software-defined UASNs. First, we briefly present the background, and then we review the progress of the Software-Defined Radio (SDR), Cognitive Radio (CR), and SDN. Next, we introduce the current issues and potential research areas. Finally, we conclude the paper and present discussions. Based on this work, we hope to inspire more active studies and take a further step on software-defined UASNs with high performances.

1. Introduction

The Earth is a water-rich planet with 71% of its surface covered by oceans, which are the largest ecosystems determining the survival and development of humanity. With the increasing requirements of resources, developing and utilizing oceans have become hot topics.

In traditional underwater systems, devices are usually deployed in fixed regions [1] which can be salvaged later. Such devices are bulky, and their deployments are generally implemented by ships, gliders, and AUVs (Autonomous Underwater Vehicles) or robots. After being placed, data can be acquired and stored. Then, data recovery and analysis are performed later based on salvaging the systems manually. They are off-line systems [2] despite that the real-time requirements are relatively high; this is because reliability and feasibility cannot satisfactorily be achieved.

With the advances in techniques, online systems based on sensor networks can be achieved. Underwater Acoustic Sensor Networks (UASNs) are composed of nodes with acoustic communication and computation capabilities. It is known that an UASN is a real-time system [3]. Once deployed, an ad hoc network is formed automatically and related technologies are employed, such as location, synchronization, clustering algorithms, and routing protocols.

UASNs are a multidisciplinary integration of computer, marine, electronics, underwater acoustic communication, and other technologies. They have broad application prospects in ocean data acquisition, environmental monitoring, earthquake and tsunami monitoring, auxiliary navigation, robotics [4], and AUV control. Compared to the traditional systems, UASNs have the advantages of a simple infrastructure and low cost, and they have gained great attention all over the world.

UASNs are deployed in shallow oceans where the environments are time varying. Studies demonstrate that RF (Radio Frequency) can be propagated at a very low frequency (30 Hz-300 Hz) [5] for a long distance with a large antenna array and extremely high transmission power in oceans. Optical communication [6] is also strongly affected by scattering, together with the high-precision alignment of a narrow-band laser beam. In contrast, acoustic communication is more suitable.

The frequency of UASNs is commonly at 10-40 kHz [7]. Unlike Wireless Sensor Networks (WSNs) deployed on land, there are many problems in UASNs, including excessively high path loss [8], severe multipath effects [9], Doppler spread [10], limited bandwidth [11], and extremely fast channel variation. The traditional UASNs greatly rely on hardware infrastructure. It is necessary to preset the corresponding protocols and applications in nodes before being deployed. All nodes are charged by batteries. Once a battery is exhausted, a node will fail.

Compared with WSNs, the costs of manufacturing and deployment are quite expensive in UASNs. Taking into consideration the deployment environments and the practical applications, they are typically arranged in redundant manners. For example, an application that lasts for three months generally requires about 300 sensors. To ensure reliability, the service duration is estimated 2-3 times, and more than 600-900 nodes are deployed [12]. In general, UASNs will still survive until being completely abandoned, which is of enormous waste. Due to the different data formats, protocols, and service constraints in varied applications, it is difficult for an UASN to be reused for other services in the identical underwater region, which apparently results in the repeated deployment [13]. Furthermore, limited acoustic channels are shared by a large number of marine mammals, sensor nodes, and sonar devices. Thus, it is a key issue to implement a flexible UASN architecture on the basis of avoiding waste and signal interference.

In recent years, the development of Software-Defined Networking (SDN) has received extensive attention from industry and academia. SDN is an emerging networking paradigm that can hopefully change the limitations of current network infrastructures [14]. It represents an innovative architecture, which is used to abstract devices and applications and then manages networks by controllers. SDN implements the separation of the data plane and the control plane [15] and builds a programmable hardware infrastructure through an open standardized interface and uses controllers to define the behavior and operation of networks. OpenFlow [16] is a popular communication protocol of SDN, by which controllers add, delete, or modify the entries of a flow table [17] to switches. The switches forward packets according to the flow table [18].

Kreutz et al. [19] offer a comprehensive survey of SDN covering its context, rationale, main concepts, distinctive features, and future challenges. Haque and Abu-Ghazaleh [20] evaluate the use of SDN in four classes of popular wireless networks: cellular, sensor, mesh, and home networks. The authors classify the different advantages that can be obtained by using SDN across this range of networks. Kobo et al. [21] present a comprehensive survey on the emerging Software-Defined Wireless Sensor (SDWSN) and give potential importance to SDN in addressing WSN's inherent challenges. Duan et al. [22] provide a review of SDWSN and analyze the current integrated scheme in several aspects, such as in architecture, network topology, routing protocol, node scheduling and energy conservation, data transmission, and load balancing, as well as in network security.

With the rapid progress of network technology, SDN-based UASNs gradually appear. Luo et al. [23] provide a comprehensive review of novel software-defined techniques and paradigms towards realizing next-generation UASNs, such as the Software-Defined Radio (SDR), Cognitive Acoustic Radio (CAR), Network Function Virtualization (NFV), SDN, Internet of Underwater Things (IoUTs), and sensor cloud.

Studies show that SDN provides innovative solutions to UASNs [24]. In SDN, an underwater node is designed as a switch and the sink node (a surface buoy or float) as a controller. Based on the general protocol and service interface, centralized management can be implemented. In theory, the nondifferentiated services [25] can be realized based on SDN. It solves the redundancy of repeated deployment and maximizes the applications. To propel the progress of UASNs further, an SDN which is robust [26], flexible [27], adaptive, able to utilize energy and resources efficiently, and easy to manage and evolve has been proposed recently.

Nevertheless, there are some difficulties in SDN for underwater acoustic sensor networks. Although SDN of wired networks and terrestrial wireless networks provide valuable experience, there are still major gaps in the SDN of UASNs.

First, RF is generally used in terrestrial cable/wireless networks. The signal propagation velocity is 3.0×10^8 m/s [28] and that of the acoustic is about 1500 m/s [29]. The acoustic communication underwater will bring out other problems such as a large delay and noise interference. Second, an UASN is an ad hoc network composed of multiple nodes [30] powered by batteries. To extend the survival time of the system, a switching mechanism for the node state (active, sleep) is usually considered. Furthermore, some nodes may fail, due to the exhaustion of the energy source. Therefore, the topology of UASNs is time varying, and energy conservation and topology control are taken as the primary causes [31]. Third, the underwater conditions are harsh, and the acoustic signal is easily subjected to interference from the natural environment (such as marine animal communication and ocean currents) and other artificial acoustic systems [32]. Fourth, the traditional terrestrial wired/wireless network based on SDN is usually reckoned as the three-layer structure of "controller-switch-host" [33]. On the other hand, in SDN-based underwater acoustic sensor networks, a two-tier structure of "controller-switch" [34] is realized, and the number of switches to be processed is relatively more. As a result, the system bottleneck can be resolved by deploying multiple controllers.

Although many studies in different areas of UASNs and SDN have been presented, there are relatively few works built on the combination of the two [35]. To the best of our knowledge, it is the second paper to review SDN-based underwater acoustic networks except the study of Reference [23] currently. However, we attempt to conduct an in-depth investigation from another perspective. The main contribution of this paper involves the following parts.

Firstly, we introduce the preliminaries and background of UASNs and SDN briefly. Secondly, we provide a comprehensive review on the progress of software-defined underwater acoustic sensor networks, which contain a Software-Defined Radio (SDR), Cognitive Radio (CR), and SDN. Thirdly, we offer the current issues and potential research areas for SDN-based UASNs. Finally, we present discussions for future research.

Based on this work, we hope to inspire more active studies and take a further step towards realizing software-defined UASNs with high performances.

The layout of the paper is outlined as follows: Section 2 introduces the preliminaries and background. Section 3 describes the progress on software-defined underwater acoustic sensor networks. Section 4 depicts current issues and potential research areas. Section 5 concludes the paper.

2. Preliminaries and Background

2.1. Underwater Acoustic Sensor Networks. In 1998, Argo, a global ocean observation project led by the US was launched, in which a profile float was deployed every 300 km crossing over the oceans. As of Nov. 19, 2018, the total number of buoys was 3,959 [36]. It is a large, worldwide, ocean observation system applied to measure temperature, salinity, and currents in the oceans up to the depth of two kilometers, to help humans cope with climate change and improve disaster prevention and resilience. In 2000, more than 30 countries joined in the project. Currently, Argo has become the standard of developing other ocean observation systems. China joined Argo in 2001, and as of Sept. of 2018, 430 profile floats [37] had been deployed in the Pacific and Indian oceans and the Mediterranean Sea, and more than 38,000 temperature and salinity profiles had been acquired cumulatively, accounting for approximately 11% of Argo.

Seaweb [38] is another UASN conducted by the US Naval Research Bureau and the Air-Sea Battle System Center. It is a battery-charged system and designed for coastal Antisubmarine Warfare (ASW) sensor networks such as DADS (Deployable Autonomous Distributed System) [39], also used to implement offshore-based sensor systems like Kelp and Hydra.

WHOI (Woods Hole Institute of Oceanography) [40], established in 1930, is a well-known institution in the field of marine and related Underwater Acoustic Communication (UAC) science. The works of UAC mainly focus on the WHOI Acoustic Communications Group (ACG) [41] and the Ocean Acoustics and Signals Lab (OASL) [42]. ACG has developed a powerful acoustic modem, which was named Micromodem. It offers a complete solution for analyzing and modeling underwater channels. OASL focuses on studies in areas such as sound propagation modeling in shallow seas and underwater signal processing. It has led and completed some representative marine experiments, such as SW06 [43] and ASIAEx 2001 [44], which provided important support for the subsequent development of UASNs.

As an internationally renowned conference, OCEANS [45] is annually held by the IEEE Oceanic Engineering Society [46] and the Marine Technology Society (MTS) [47], in which the topic of underwater communication and the latest relevant works are announced. In 2006, WUWNET (Workshop on Under Water Networks) [48] was established in the international conference of ACM MobiCom [49], by which the recent progress of UASNs had been paid close attention to and significant achievements had been accomplished.

UbiNet [50] and UASN Laboratories [51] led by Professor J. H. Cui [52] developed a series of simulation platforms, hardware, and software. The National Science Foundation (NSF) of the US has also provided substantial funding for UASN projects in recent years, and a number of representative works have emerged.

The WiNES [53] of the Laboratory of Northeastern University has achieved breakthrough works in underwater networks. The internet-based architecture of UASNs is designed, and a network protocol stack based on IP compatibility is developed. At present, SEANet G2 [54], a mobile high-rate platform of UASNs based on IP compatibility is completed.

In addition, some studies of UASNs have also been achieved at the University of Washington, the University of California, Los Angeles, and Texas A&M University. Meanwhile, the University of Rome and the University of Padova in Italy have strong capabilities for designing network simulators and testbeds for UASNs and have implemented several well-known simulators, such as SUNSET [55], DESERT [56], and WOSS [57].

2.2. Software-Defined Networks. SDN is a novel network paradigm, which originated from the Clean Slate project of Stanford University. McKeown et al. released OpenFlow [58] in 2008, and the SDN concept was proposed in the conference of INFOCOM, 2009. SDN separates the forwarding hardware from control decisions [59], which greatly simplifies network management and realizes innovation and evolution.

Both ForCES [60, 61] and OpenFlow [62, 63] are well-known SDN frameworks, which separate the control plane from the data plane and standardize the exchange of information. OpenFlow is proposed to standardize the communication between the switches and controllers in SDN-based systems [64]. The Open Network Foundation (ONF) [65] is just an industry-driven organization created by network operators, service providers, and suppliers to promote SDN. ONF established the Optical Transport Working Group (OTWG) [66] in 2013, which defined the OpenFlow standard for Optical Transport Networks (OTNs) [67]. Academically, the Open Networking Research Center (ONRC) [68] focuses on the architecture design of SDN. Furthermore, IETF, IRTF, and other organizations carry out some SDN standardization works.

Hot topics of SDN are in terrestrial wired networks and wireless networks [69]. Nowadays, B4 [70] is the most important commercial system of Google in the world. It is built on OpenFlow, and the operations indicate that the link utilization increases from 30% to 70% on average, sometimes even reaching 100%. Meanwhile, other SDN-based networks are also in line with full swing around the world. Large-scale networks often need to ensure strict security and reliable QoS [71, 72]. These requirements can be satisfied based on SDN, and many other functions such as NAT [73], firewall [74], load balancing [75], and ACL [76] can be implemented.

Currently, Data Centers (DCs) have increased at an alarming rate. According to the statistics, DCs do not always run at their peak power despite that all the nodes are active, which is a great waste due to the huge energy consumption. Studies have proven that the energy consumption of DCs can be reduced based on SDN. Heller et al. [77] proposed an energy-saving mechanism for DCs. In this method, the minimum number of nodes that satisfy the current traffic is activated by SDN, while the other nodes are set to the sleeping mode. In this way, energy consumption can be controlled between 25 and 62% under different traffic models.

The infrastructure of wireless networks, such as cellular networks and WiFi, is constructed with the advances of SDN. In the OpenRoads [78] project, an SDN-based wireless network is proposed, which is backward compatible and can be shared with different providers and OpenFlow-based devices. In [79], an Odin-based SDN programming method for WLAN (Wireless Local Area Networks) is presented. Access Points (APs) are abstracted as controllers, in order to separate the association status from the physical APs and enable mobility management and load balancing without changing clients. Open Radio [80] is devoted to designing a programmable wireless data plane based on SDN. It provides flexibility at the PHY and MAC layers and meets strict performance requirements simultaneously. In [81], the network architecture of circuit switching and packet switching based on wavelength selection is implemented by OpenFlow and a control plane based on OpenFlow is proposed in [82] for OTNs.

Additionally, a number of SDN-based SOHO (Small Office Home Office) networks have been mentioned. Mortier et al. [83] designed a home network that provides services to customers based on SDN while offering a single controller. Mehdi et al. [84] implemented an Anomaly Detection System (ADS) in SDN-based home networks, which provides more accurate identification capabilities for malicious activity detection than systems deployed in ISPs (Internet Service Providers).

3. Progress on Software-Defined Underwater Acoustic Sensor Networks

At present, studies of software-defined underwater acoustic sensor networks have been concentrated in the following fields.

3.1. Underwater Acoustic Sensor Networks Based on Software-Defined Radio. The key idea of a Software-Defined Radio (SDR) is to construct an open, standardized, modular, general-purpose hardware platform with various functions, such as the frequency control, modulation and demodulation, encryption, and changing protocols based on a wireless communication system with flexibility. SDR is a multiband, multimode radio with a dynamic capability defined through software covering all layers of the OSI model [85]. It provides reliability in a fast time-varying environment. Therefore, UASNs based on SDR have attracted a great deal of attention.

Demirors et al. [86] designed an SDR-based architecture for underwater acoustic communication and constructed a prototype of a software-defined modem. The results demonstrate that the effective recognition of the spectrum is achieved. Sheikh et al. [87] developed an open-source acoustic modem (named Coralcon) based on SDR to build a system of underwater IoT (Internet of Things) [88]. Wolff et al. [89] proposed an underwater acoustic FH-FSK system based on the Goertzel algorithm and SDR. Potter et al. [90] implemented a Software-Defined Open Architecture Modem (SDOAM), which combines numerous protocols to work jointly according to the OSI model. Abbas et al. [91] developed a system named UPPER (Underwater Platform to Promote Experimental Research) and designed an underwater acoustic modem based on the SDR-GNU Radio [92]. Experiments demonstrate that the development cost is greatly reduced, and the flexibility is improved.

Al-Halafi et al. [93] designed a communication system using PSK (Phase Shift Keying) and QAM (Quadrature Amplitude Modulation), then constructed a transmitter based on SDR and realized video streaming communications for short distances on underwater optical links. Torres et al. [94] used SDR to design an acoustic network platform which has strong adaptability and flexibility, making it easy to implement related protocols of PHY and MAC layers in underwater networks. Li and Huang [95] designed a software-based radio-acoustic modem (named SDA) and deployed it in Qiandao Lake of China to verify its performance.

In summary, SDR offers an important foundation for subsequent studies of UASNs. Nevertheless, SDR mainly concentrates on the PHY and MAC layers, and there are still several defects. On one hand, the SDR-based infrastructure relies heavily on physical devices and requires high-performance underwater nodes. With the increase of applications, the execution efficiency of systems will be greatly reduced, and it will lead to the rapid exhaustion of energy, which is fatal for UASNs. On the other hand, the implementation of SDR will increase the development costs for the chip selection. In a word, SDR cannot achieve all the technologies of SDN for underwater acoustic sensor networks.

3.2. Underwater Acoustic Sensor Networks Based on Cognitive Radio. Cognitive Radio (CR) is defined as an intelligent software-defined radio that senses the environments for detecting available channels and accordingly changes its transmitter or receiver parameters such as operating frequency, bandwidth, modulation, and transmitting power [96]. CR realizes a highly reliable communication and increases the utilization of spectrum resources. The core of

CR is DSA (Dynamic Spectrum Allocation) [97] and spectrum sharing [98] through spectrum sensing [99] and intelligent learning.

Alfahham and Berekovic [100] revealed that CR is the most promising technology to resolve the spectrum resources and prolong the survival time of WSNs. However, there is a serious defect in the huge energy consumption. Kaschel and Toledo [101] introduced the cooperative and noncooperative sensing technologies in CR-based sensor networks and make a classification of the relevant spectrum management methods in detail. Luo et al. [102] proposed a CR-based underwater acoustic network named UCAN, and simulations show that the performance of UASNs is improved greatly through the cooperation of PHY and MAC layers.

Based on the Wigner-Ville transform and CR, Biagi et al. [103] presented a method to extract the time and frequency characteristics of underwater acoustic channels. Thus, signals and interference can be distinguished and the maximum access probability can be reached. Wang et al. [104] proposed a FO-based (Frequency Offset) estimation algorithm for cognitive underwater acoustic systems through exponential modulation. Simulation shows that the algorithm offers reliable performance within the expected estimation range. Ghafoor et al. [105] presented a spectrum-aware routing algorithm based on OFDM and CR for UASNs and performed spectrum sensing through an energy detector. Experiments demonstrate that the date rate increases as nodes increase, and the delay is smaller.

Li et al. [106] designed a cognitive transmission scheme named DAD-Tx (Dolphin-Aware Data Transmission) in which a probabilistic method is used to capture the stochastic features of dolphin communication and describes it mathematically. DAD-Tx is designed to maximize the end-to-end throughput based on the constraints of dolphin perception and wireless acoustic transmission. Results show that it greatly improves the spectrum performance of UASNs.

Luo et al. [107] developed a MAC protocol for a distributed acoustic cognitive network, namely DCC-MAC. In this protocol, nodes dynamically adjust and allocate bandwidth according to the traffic. Results demonstrate that DCC-MAC greatly reduces the collision probability between control messages and has advantages in throughput and energy efficiency. Yan et al. [108] provided a solution to the joint relay selection and power allocation in a cognitive acoustic network. Results show that the feedback mechanism based on limited bits improves the performance of the system significantly.

All in all, CR is a mature technology in terms of spectrum sensing and resource management for underwater acoustic systems. Nonetheless, studies on hardware algorithms of CR are relatively scarce [109]. Therefore, the design of the hardware algorithm is crucial. In addition, the front-end noise should be as small as possible, not to influence the performance of spectrum sensing. Nevertheless, it is hard to solve these issues for the terrestrial WSNs, let alone for UASNs. In conclusion, there are still significant challenges in the implementation of CR in underwater acoustic sensor networks.

3.3. Underwater Acoustic Sensor Networks Based on SDN. Compared to SDR and CR, SDN is less studied in UASNs. Akyildiz et al. [110] defined the basic architecture of underwater acoustic sensor networks based on SDN, which is named SoftWater, where the main advantages of SDN and the relevant challenges are presented. Fan et al. [111] designed an SDN-based architecture in which an acoustic system is used in the control plane for long distances and an optical system is used in the data plane for short distances. However, the implementation of the communication mechanism has significant obstacles.

Fan et al. [112] designed an SDN-based AUV system and implemented a test bed on WaterCom [113], in which the performance of the slotted FAMA [114] and UW-ALOHA [115] is tested and compared. Ghafoor and Koo [116] considered the natural and artificial acoustic systems as the two Primary Users (PUs) of UASNs and designed an SDN-based architecture in which buoys are treated as the Main Controllers (MCs) to maintain the global view of the network. The AUVs act as Local Controllers (LCs), which are set to move in a fixed range, and they communicate directly with MCs. Underwater nodes within the motion trajectory of AUVs are set as gateways; these nodes collect data from all their neighbors, then store and transmit data to a LC. All nodes update their status periodically. All LCs share their localized views with a MC, so that a global view can be established. Experiments prove that it has benefits in terms of end-to-end delay, data delivery rate, and overhead.

Lal et al. [117] designed a system model that incorporates SDN for the security of UASNs, considering the deployment and functional issues. Torres et al. [118] proposed security countermeasures to reduce the risk of security attacks and discuss routing configuration, node trajectory optimization, and node buffer management for SDN-based UASNs.

Recently, we offered an SDN-based architecture [119] for UASNs and implemented the hardware of underwater nodes based on OpenFlow. We proposed a multiuser detection algorithm [120] based on convex optimization. The results show that the algorithm is suitable for the MC-CDMA (Multi-Carrier Code-Division Multiple Access) systems of UASNs. Considering that single controllers in large-scale UASNs will cause the bottleneck, we present an SDN-based framework with multiple controllers [121]. Results reveal that the performance of UASNs can be greatly improved.

In summary, studies on SDN-based UASNs have not formed a complete knowledge system. Some works only give the definition of SDN, but they do not give overall solutions. Therefore, it is imperative to carry on comprehensive studies based on SDN.

4. Current Issues and Potential Research Areas for SDN-Based UASNs

In this section, the following current issues and potential research areas of UASNs are presented.

4.1. Inherent Flaws of Underwater Acoustic Sensor Networks

(1) In a traditional UASN, no trade-off can be formed between the repeated deployment of multiservice requirements and the redundant deployment guaranteeing reliability.

Taking into account the issues of nodes (such as performance and energy), only few services can be offered in an UASN of normal conditions. Therefore, multiple systems are deployed in the same region for different applications, which will lead to the repeated deployment.

The redundant deployment is another important technical means to ensure the reliability of UASNs. Nevertheless, the coexistence of multiple systems will lead to serious signal interference [122] in a designated underwater region. SDN implements flexible applications, solves the repeated deployment, reduces waste and saves costs.

(2) In traditional UASNs, multiservice multiplexing technologies are difficult to achieve.

Although the cost of manufacturing and deploying UASNs is expensive, it is impossible to deploy a huge amount of services in a system, due to the limitations of energy and performance. Moreover, there is a great randomness in actual applications, and even if multiple systems can be integrated, there are extreme deficiencies in the function division and scheduling. That is, service multiplexing and resource allocation strategies have not been considered based on the traditional networks. However, software-defined NFV (Network Function Virtualization) [123, 124] leverages network virtualization and logically centralized intelligence to minimize the service-providing cost and maximize the utilization of network resource. Based on NVF, it is feasible to make reasonable service multiplexing and resource allocation in UASNs.

(3) As disposable systems, UASNs cannot be salvaged and recycled after being deployed. Therefore, the development risk cannot be solved.

For an UASN, it must undergo a large number of testing before being deployed. Once the functional and performance defects are found, it should be timely corrected beforehand. If defects are discovered after being deployed, there is no opportunity to handle them, which will leads to serious consequences. It is necessary to ensure that the design of the system is absolutely perfect before being deployed. Nevertheless, it is impossible to do this at all. Therefore, modifications after the system is deployed are an important topic on UASNs, which can be treated based on SDN conveniently.

(4) As an interdisciplinary technology, the research directions of UASNs are extremely wide. Nevertheless, they lack a complete knowledge system, and there are big gaps between the theoretical studies and practical works.

UASNs are emerging multidisciplinary technologies related to ad hoc networks [125, 126]. The interests of distinctive research directions are very different. For example, more considerations (like clustering, location, and synchronization) based on ad hoc networks are given to the deployment of UASNs. The studies based on sensor networks mainly focus on the design of devices, such as the underwater nodes, sensors, buoys or floats [127], and anchors. In addition, it also includes the design of pressure-resistant waterproof batteries [128]. In the acoustic communication science, it chiefly involves the communication techniques, such as MIMO [129–131], cooperative communication [132–134], and cross-layer optimization [135, 136], while marine science pays more attention to the modeling of underwater channels.

In academic terms, various works have greatly promoted the development of UASNs. Due to the failure to form a complete knowledge system, there will be situations where, when a problem is solved, more serious issues will be generated. For instance, an algorithm is used to reduce BER (Bit Error Rate) but this greatly increases the computational complexity, resulting in a significant reduction in the survival time of UASNs. In a sense, these studies alone have no strong research significance. Therefore, it is expected to make a trade-off among multiple indicators based on SDN for UASNs.

(5) Due to the diversity and extensiveness of applications, it has not formed a unified standard in UASNs, and the interconnectivity is weak. Poor interactivity causes the technical blockade.

For now, the deployment of large-scale underwater acoustic sensor networks is relatively rare. It is well known that Argo should be the largest project in the world. However, various technologies of UASNs are not concerned with Argo. In addition, there is often a huge gap between UASNs and the wired sensor networks with underwater drag cables. Currently, surveillance systems [137] can be found in coastal waters, such as submarine exploration and marine biological monitoring, while each system is isolated with others and the interoperability is very weak.

Considering the deployment cost and environment, UASNs have been tested gradually in different regions, such as water tanks, pools, lakes, rivers, and oceans. Actually, UASNs suffer serious signal interference from environmental noise and artificial acoustic systems. In addition, channels in distinct regions are quite different and there will be a great impact on the actual applications due to the time-varying environmental factors, like temperature, salinity, pH, depth, and pressure. Nonetheless, no standards have been established for these impacts. Fortunately, WUWNet is preparing to establish international standards and solutions for UASNs. It is expected to ease the technical blockade and accelerate development efforts.

With the rapid progress of simulation and emulation techniques, combining the disclosed ocean dataset (such as Ocean Observatories Initiative project) [138] becomes an important breakthrough tool for UASNs. Furthermore, with the advance of IoT (the Internet of Things), the underwater IoT systems [139] based on IPv6 should be a new direction.

However, it seems that an all-IP architecture has not yet been realized in underwater acoustic sensor networks.

4.2. Key Issues for SDN-Based Underwater Acoustic Sensor Networks. As an industrial network, an UASN mostly ensures availability, but there are some defects in performance, service quality, and security. We can see that SDN is only a conceptual prototype for underwater acoustic sensor networks. It is not widely implemented based on the following issues.

4.2.1. Design of the Architecture by Software Processing for SDN-Based UASNs. A reasonable infrastructure support is the foundation of UASNs. Currently, various works are presented for software-defined networks. Nevertheless, there is no uniform standard, and chips that are purely SDN supported are rare. Several so-called SDN devices or chips only encapsulate part of the software-defined functions on the original systems and are of poor flexibility.

Underwater nodes are usually developed by dedicated SCM (Single-Chip Microcomputer) systems. Due to the redundant deployment, many issues (like development cost, energy conservation, and performance) must be carefully considered. It means that traditional UASNs which support SDN are extremely limited.

The SDN flow table based on ASIC is usually limited to the KB level [140]; thus, the reliable isolation of multiservices cannot be implemented for UASNs of large scales. In addition, it is difficult to overlay more service identifications and additional functionalities on the existing flow tables. Although the NPU (Network Processing Unit) [141] has high flexibility, the bandwidth is restricted. Therefore, the concurrent processing of a large-scale flow table cannot be supported.

The query efficiency of flow can be improved based on the architecture of FPGA + TCAM [142, 143]. Nevertheless, the energy consumption is extremely high and considerable hardware resources are occupied at the same time, which will increase the design difficulty of board levels in UASNs.

In a word, hardware architecture (ASICs, NPUs, FPGAs, and others) is not ideal for SDN support, and it has no advantages in terms of energy conservation and development cost. Therefore, the design of architecture based on software processing is an important solution for SDN-based UASNs.

4.2.2. The Reasonable Assessment of Isolation Items for Implementing SDN-Based UASNs. In order to realize multiplexing technology, NVF is used to implement the integration of various applications in SDN-based underwater acoustic sensor networks. It is a technique that isolates network traffic from nodes, ports, and other physical elements. Thus, multiple virtual networks can be formed, independently deployed, and managed on a shared system. To form reliable virtual networks, the isolation items (data, CPU, bandwidth, and flow table) must be fully evaluated. Nonetheless, it is difficult to satisfy all isolation items simultaneously on the performance-constrained UASNs. Therefore, it is important to make a reasonable assessment of the isolation items, which can quickly adapt to the deployment and load changes of the physical networks, and offer a stable response to meet the requirements. It is another fundamental issue.

4.2.3. A Reasonable Load-Balancing Technique for SDN-Based UASNs. Generally, a single-sink (single controller) architecture is usually used in UASNs. For a small-scale underwater network, a single controller can indeed undertake management tasks and reduce overhead. Nevertheless, there are plenty of nodes in large-scale UASNs. If a single controller shoulders the centralized management, the following problems will be encountered.

Firstly, all flow is forwarded to a single controller. In a large-scale UASN, the flow of a controller will increase rapidly as nodes increase. Therefore, a single controller will be the bottleneck of the system. Secondly, since the network is extremely extensive, the underwater nodes far from the controller cannot get the feedback in time. It is a fundamental issue for data exchange and synchronization. Thirdly, when the controller fails or is attacked, all nodes will lose connection. It will result in paralyzing the system. Therefore, a multicontroller architecture is a better choice.

Controllers on the ocean surface implement uniform deployment based on buoys or floats, cruise ships, or other equipment, while underwater nodes carry out a random deployment. Therefore, the number of nodes managed by each controller is different, and the load of each controller will be greatly uneven. The load-balancing mechanism among controls becomes the focus. Unfortunately, there is no standard for the horizontal deployment of controllers [144]; thus, the data consistency and East-West interface (the interface between controllers) [145] for communication between controllers have not yet been resolved. All in all, implementing a reasonable load-balancing technique [146] is the third key issue for SDN-based underwater acoustic sensor networks.

5. Conclusion

Compared with WSNs, underwater acoustic sensor networks are relatively closed. The systems do not realize full IP management in common, and based on the industrial infrastructure, it only guarantees usability and performance, but QoS, security, reliability, flexibility cannot be fully guaranteed. UASNs rely heavily on the hardware infrastructure and have poor flexibility. Redundant deployment is an important measure to ensure the reliability of systems. However, no trade-off can be formed between the redundant deployment and the repeated deployment. Furthermore, the repeated deployment is a huge waste, due to the high costs of UASNs. Based on SDN, an innovative network architecture focused on applications can be designed, and OpenFlow is used to construct multiple virtual networks and build the management of all-IP systems. Nevertheless, a single controller may cause serious network bottlenecks for a large-scale UASN. Therefore, a multicontroller architecture is a better choice for SDN-based underwater sensor acoustic networks.

In this paper, advances in software-defined UASNs were presented. First, we introduced the preliminaries and background. Then, we presented the progress of software-defined UASNs, which included SDR, CR, and SDN. Next, we proposed the current issues and potential research areas. The review showed that both UASNs and SDN are hot topics, and they have been transferred from theoretical studies into actual engineering applications. Studies also proved that there is an improvement in the flexibility, realization of multiple service reuse, and great reduction in the development risk based on SDN. Nonetheless, designing an architecture based on software processing, making a reasonable assessment of isolation items, and proposing a flexible load-balancing mechanism were the most urgent tasks. Based on this work, it is hoped that important theoretical and technical support for SDN-based UASNs of high performance can be provided.

Conflicts of Interest

Authors declare that there is no conflict of interest regarding the publication of this paper.

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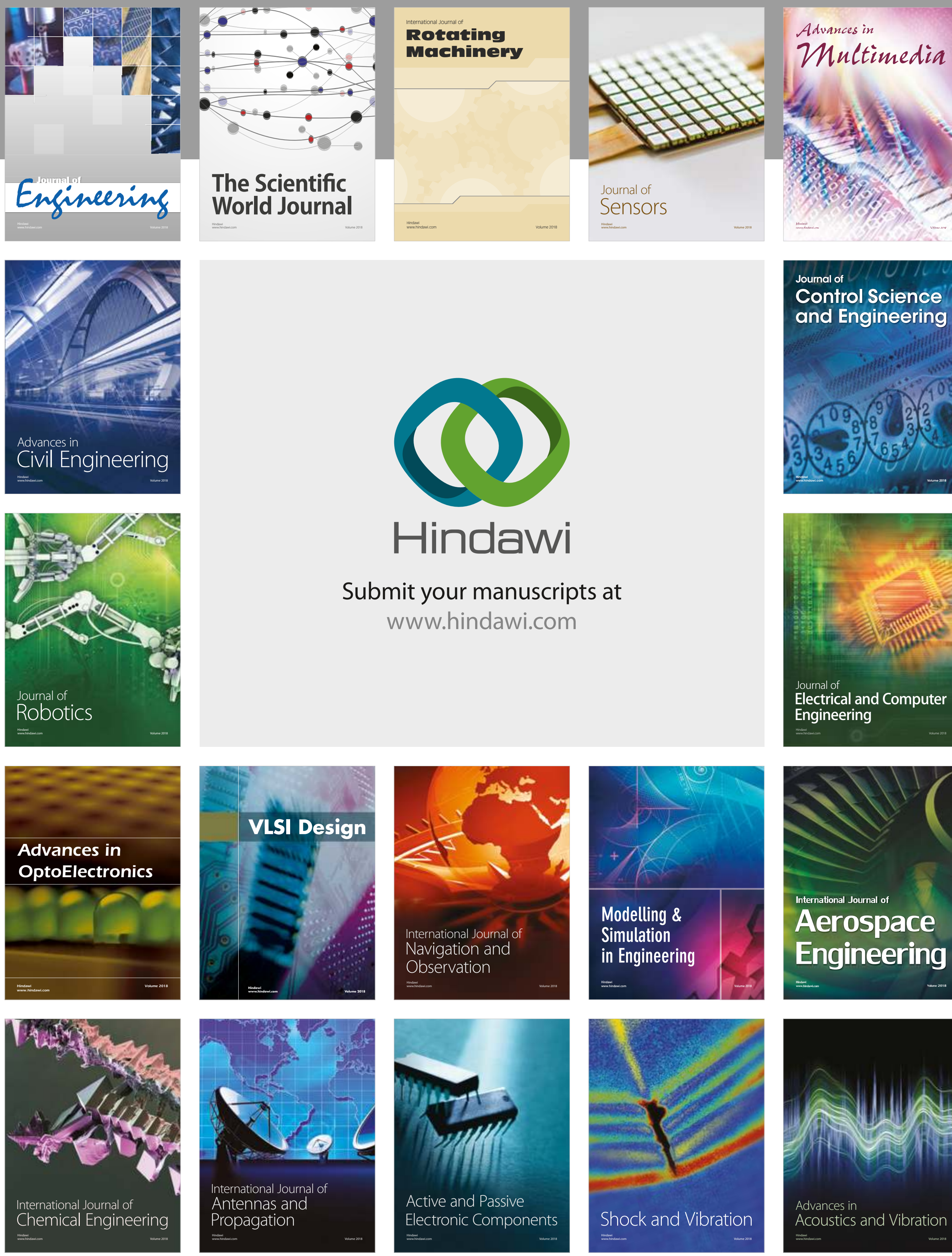
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