

SoftWater: Software-Defined Networking for Next-Generation Underwater Communication Systems

Ian F. Akyildiz, Pu Wang, and Shih-Chun Lin

Abstract—Underwater communication systems have drawn the attention of the research community in the last fifteen years. This growing interest can largely be attributed to new civil and military applications enabled by large-scale networks of underwater devices (e.g., underwater static sensors, unmanned autonomous vehicles (AUVs), and autonomous robots), which can retrieve information from the aquatic and marine environment, perform in-network processing on the extracted data, and transmit the collected information to remote locations. Currently underwater communication systems are inherently hardware-based and rely on closed and inflexible architectural design. This imposes significant challenges into adopting new underwater communication and networking technologies, prevent the provision of truly-differentiated services to highly diverse underwater applications, and induce great barriers to integrate heterogeneous underwater devices. Software Defined Networking, recognized as the next-generation networking paradigm, relies on the highly flexible, programmable, and virtualizable network architecture to dramatically improve network resource utilization, simplify network management, reduce operating cost, and promote innovation and evolution. In this paper, a software-defined architecture, namely SoftWater, is first introduced to facilitate the development of the next-generation underwater communication systems. More specifically, by exploiting the network function virtualization (NFV) and network virtualization concepts, SoftWater architecture can easily incorporate new underwater communication solutions, accordingly maximize the network capacity, can achieve the network robustness and energy efficiency, as well as can provide truly differentiated and scalable networking services. Consequently, the SoftWater architecture can simultaneously support a variety of different underwater applications, and can enable the interoperability of underwater devices from different manufacturers that operate on different underwater communication technologies based on acoustic, optical, or radio waves. Moreover, the essential network management tools of SoftWater are discussed, including reconfigurable multi-controller placement, hybrid in-band and out-of-band control traffic balancing, and utility-optimal network virtualization. Furthermore, the major benefits of SoftWater architecture are demonstrated by introducing software-defined underwater networking solutions, including the throughput-optimal underwater routing, SDN-enhanced fault recovery, and software-defined underwater mobility management. The research challenges to realize the SoftWater are also discussed in detail.

Index Terms—SDN, Underwater Communications, Virtualization

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I. INTRODUCTION

Existing underwater communication systems are inherently hardware-based and rely on closed and inflexible architectural designs. Such inflexible hardware-based architectures impose significant challenges into adopting new underwater communication and networking technologies to maximize the network capacity, robustness, and energy efficiency, prevent the provision of truly-differentiated services able to adapt to increasingly growing and highly diverse underwater applications, and induce great barriers to integrate underwater devices from different manufacturers or operate on different underwater communication technologies based on acoustic, optical, or radio waves [2][13][5]. The challenges faced by the current underwater communication architecture cannot be solved without a radical paradigm shift in the design of next-generation underwater communication systems. Hence, in this paper, we propose the utilization of software-defined networking (SDN) concept for next generation underwater communication systems, and introduce a new architecture for underwater software-defined networks, called SoftWater.

Software Defined Networking has been recently introduced primarily for data center networks [12] and later extended to support wireless networks such as 5G systems [4]. The main ideas of SDN are (i) to separate the data plane from the control plane; and (ii) to introduce novel network control functionalities based on the abstracted network representation. The ideas of SDN are instantiated by (i) separating control decisions from the network hardware infrastructure, e.g., switches and routers, (ii) enabling the programmable hardware infrastructure via an open and standardized interface, e.g., Openflow [15], and (iii) utilizing a network controller to define the behavior and operation of the network hardware infrastructure. SDN has been recognized as the next-generation networking paradigm with the promise to dramatically improve network resource utilization, simplify network management, ease the interoperability of the heterogeneous devices from different manufacturers, reduce operating cost, and accelerate innovation and evolution.

So far, the majority of SDN developments has concentrated on wired networks and terrestrial wireless networks [4][3]. In this paper, we propose the utilization of SDNs for next generation underwater communication networks, propose a new architecture for software-defined underwater networks, called SoftWater, develop the essential management tools for SoftWater, and present the software-defined underwater

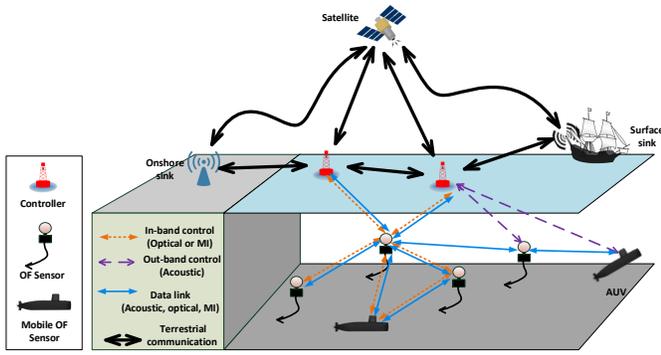


Fig. 1. Overall Architecture of SoftWater.

networking solutions enabled by SoftWater. As shown in Fig. 1, SoftWater is composed of (1) the underwater sensors including anchored stationary sensors and the mobile AUVs, which collect and forward a variety of sensing data using hybrid communication links of acoustic, optical, and MI waves, (2) surface buoys and ships, which act as data sinks to receive and forward the sensing data from underwater devices, and host the network controllers for network management and control, and (3) in-band and out-of-band control channels for exchanging control messages between underwater devices and network controllers, where multi-hop in-band control channel is established by high-bandwidth low-delay short-range optical and MI links, and single-hop out-band control is realized by low-bandwidth high-delay long-range acoustic links. The characteristics of optical, MI, and acoustic communications are summarized in table I.

Different from current underwater communication systems which mainly rely on acoustic technology, the underwater sensors in SoftWater are equipped with multiple hardware frontends, e.g., LED photodiode, acoustic transponder, and coil-antenna, to simultaneously support different underwater communication technologies, e.g., underwater optical communications, acoustic communications, and MI communications. Such feature greatly facilitates the interoperability of underwater devices and enhances the networking performance, in terms of throughput, delay, and reliability, by jointly exploiting the advantages of different underwater communication technologies. Moreover, in SoftWater, the underwater sensors exploit network function virtualization (NFV) concepts by simultaneously implementing the physical, MAC, and network layer functions in the form of software along with unified and open control interfaces, e.g., OpenFlow and SNMP. Such NFV feature considerably increases the architectural feasibility of underwater communication system, which enables the timely adoption of novel communication and networking solutions by simply deploying new software algorithms, allows the systems to be adaptively reconfigured to support different underwater applications under the ever-changing underwater environment by dynamically exploiting different system configurations and different PHY/MAC/NET layer solutions, and facilitates the global optimization of network resources by consolidating any desired network functions, e.g., routing and spectrum manage-

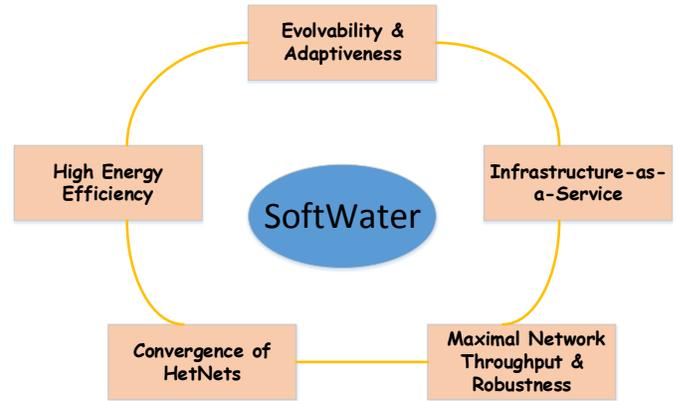


Fig. 2. Key advantages of SoftWater.

ment, at network controller, which can greatly maximize spectrum, computation, and energy efficiency. Moreover, current underwater communications systems are usually application-oriented, where a system designed for one application cannot be applied for other applications. SoftWater adopts the concept of network virtualization to allow multiple underwater applications to simultaneously operate on the same physical underwater communication system without interfering the normal operations of each other.

More specifically, SoftWater can be decoupled into control plane and data plane. The *control plane* consists of network management tools and underwater applications, which are implemented by software in network controllers. The *data plane* consists of software-defined OpenFlow-enabled underwater sensors (OF-sensors), which form the data forwarding infrastructure. As shown in Fig. 2, the proposed SoftWater architecture offers four core properties: (i) *programmability*, i.e., the network functions of OF-sensors, including physical, MAC, and network layer functions, are all implemented in software and thus can be reconfigured on-the-fly by dynamically associating with different network resources and adopting different communication and networking schemes; (ii) *cooperativeness*, i.e., the network management, such as routing and spectrum management, are implemented and centralized at network controllers for achieving globally optimized control to enhance the overall network performance; (iii) *virtualizability*, i.e., multiple virtual wireless networks can be created on a single SoftWater, each of which can host different underwater applications and operates under its own independent network protocols with network resources allocated based on demand; (iv) *openness*, i.e., data plane elements (i.e., OF-sensors), regardless of the underlying forwarding technologies and vendors, have unified data/control interfaces, e.g., OpenFlow [16], thus significantly simplifying the network monitoring and management across heterogeneous underwater devices.

The above four properties can enable the development of next-generation underwater communication systems, which possess the following promising features:

- *Evolvability and Adaptiveness*: Because of the inherent separation between data plane and control plane, in SoftWater, both hardware forwarding infrastructure and

TABLE I
CHARACTERISTICS OF UNDERWATER MI, ACOUSTIC, AND OPTICAL COMMUNICATIONS

Communication Paradigm	Propagation Speed	Data Rates	Communication Ranges	Channel Dependency
MI	$3.33 \times 10^7 m/s$	$\sim Mbps$	10 – 100m	conductivity
Acoustic	1500m/s	$\sim Kbps$	$\sim km$	multipath, Doppler, temperature, pressure, salinity, environmental sound noise
Optical	$3.33 \times 10^7 m/s$	$\sim Mbps$	10 – 100m	light scattering, line of sight communication, ambient light noise

software networking algorithms can easily, continuously and independently be upgraded quickly, which allows to timely adopt emerging radio technologies (e.g., underwater MI technology, acoustic MIMO, and underwater optical communications) in the hardware infrastructure, while deploying novel traffic engineering, application management, and system optimization solutions at controllers. Moreover, the programmable data plane allows controllers to dynamically allocate network resources and adopt new networking solutions, according to the highly variable traffic patterns, unexpected link/node failures in harsh underwater environment, inherent mobility of AUVs, diverse quality of service (QoS) requirements of traffic flows, and different security requirements between civilian and military applications.

- *Infrastructure-as-a-Service*: Emerging and growing underwater applications, such as intelligent fishery management, underwater environment mapping, pollution source seeking, and underwater tactical surveillance, require highly differentiated networking capabilities to be integrated and deployed over the same network infrastructure. The network virtualizability of SoftWater allows the wireless hardware infrastructure to be offered as a *service* rather than as a *physical asset*. Specifically, in SoftWater, the network applications are provided with the ability to control, optimize, and customize the underlying infrastructure without owning it and without interfering with the operations and performance of other network applications, thus leading to more cost-efficient operations and enhanced QoS. Moreover, thanks to the programmable data plane, the network resources can be dynamically shared among the service providers, e.g., virtual network operators.
- *Maximal Network Throughput and Robustness*: By taking advantage of the global view of network controller and its superior computational power, SoftWater greatly facilitates the implementation of large-scale and network-wide resource optimization, which can significantly enhance network throughput and robustness. More specifically, the globally optimal traffic forwarding decisions can be determined to maximize network throughput by utilizing all available routing paths for acoustic, optical and MI underwater technologies. Moreover, for conventional acoustic communications, SoftWater can minimize the end-to-end delay by optimally selecting the delay-minimum routing paths based on the per-link propagation latency information available at network controllers. For underwater optical communication technology, the optimal network topology or/and optimal pointing directions of optical links can be obtained to maximize the availability of the line-of-sight optical links and thus enhance network connectivity. For underwater MI communications, the optimal configuration of underwater MI relay mode (e.g., active relay and passive relay) can be determined to achieve optimal tradeoff between network lifetime and latency. What is more important, is that, the acoustic, optical, and MI technologies can be jointly exploited and optimized globally in order to maximize the network throughput, robustness, and coverage. In addition, fast failure recovery can be realized via real-time rerouting by simultaneously reconfiguring forwarding rules of any subsets of OF-sensors. Seamless mobility management can be implemented by installing predictive data forwarding rules at OF-sensors based on the mobility patterns of AUVs.
- *Convergence of Heterogeneous Networks*: Different underwater communication schemes have their unique advantages and disadvantages. Jointly exploiting multiple communication technologies can greatly improve network capacity, reliability, connectivity, and coverage. For example, acoustic communications are suitable for realizing long-range connections in the cost of low data rate and high propagation delay, while optical and MI communications are desirable for short and medium range data forwarding with high bandwidth and negligible propagation delay. However, current underwater communication networks mainly operate under a single communication technology because of the fundamentally different features of different technologies. By utilizing network function virtualization at physical, MAC, and network layers, SoftWater can enable the seamless integration of multiple underwater communication technologies and promote the unified management among the underwater devices produced by different manufacturers.
- *High Energy Efficiency*: Under SoftWater, the network controller has the global view of the residual energy and the location of the OF-sensors along with the per-link capacity of the whole network. Utilizing those information,

the network controller can determine the most energy-efficient routing paths for each traffic flow in such a way that the network lifetime can be considerably enhanced, while satisfying the per-flow QoS performance. Moreover, utilizing the long-range out-of-band control channels, the optimal roaming paths of AUVs can be determined by the controller to wirelessly charge the anchored underwater sensors for realizing the perpetual underwater operations.

It is important to note that recent ideas on software defined radio technology are being developed for underwater acoustic networks in the research community [8], [24]. However, these ideas focus on the development of software-defined acoustic modems which allow dynamic reconfiguration of the physical and MAC functions for underwater acoustic transceivers. On the contrary, SoftWater introduces a novel underwater networking architecture, which possesses the above five promising properties. More specifically, although these software-defined acoustic modems can be adopted to develop the programmable data plane for SoftWater, they lack the capability to enable the programmable network layer functions, e.g., routing decisions, which is one of the key features and advantages of software-defined networking for maximizing network throughput, robustness, and adaptiveness. Moreover, those software-defined acoustic modems do not support network virtualization and thus cannot support the feature of infrastructure-as-a-service. In addition, those software-defined acoustic modems only support underwater acoustic communications and thus cannot facilitate the convergence of heterogeneous underwater networks.

The rest of the paper is organized as follows. Section II introduces the architecture design of SoftWater. Section III summarizes the essential management tools for SoftWater. Section IV presents the software-defined underwater networking solutions enabled by SoftWater. Section V concludes this paper.

II. SOFTWATER ARCHITECTURE DESIGN

As shown in Fig. 4, the architecture of SoftWater consists of a data plane and a control plane.

- The *data plane* is an open, programmable, and virtualizable network forwarding infrastructure, which consists of open-flow underwater sensors (i.e., OF-sensors), which can be anchored as stationary sensors or act as mobile AUVs. As shown in Fig. 3, each OF-sensor consists of (1) the software radio which implements physical and MAC layer functions in the form of software, (2) the OpenFlow-supported flow table, which defines the routing decisions and can be configured by the network controller through south-bound APIs, e.g., standardized and secure protocols, i.e., OpenFlow, (3) the wireless hypervisor, which allows to create multiple virtual OpenFlow underwater sensors (V-OF-sensors) operating on different underwater technologies or protocols on the same OF-sensor, and (4) multiple hardware front-ends, e.g., LED photodiode, acoustic transponder, and coil-antenna, to

simultaneously support different underwater communication technologies, e.g., underwater optical communications, acoustic communications, and MI communication. Because of the software-defined PHY/MAC/NET layer functions along with the multiple hardware front-ends, OF-sensors can freely communicate with the legacy underwater sensors and thus can be seamlessly integrated with the conventional underwater communication systems.

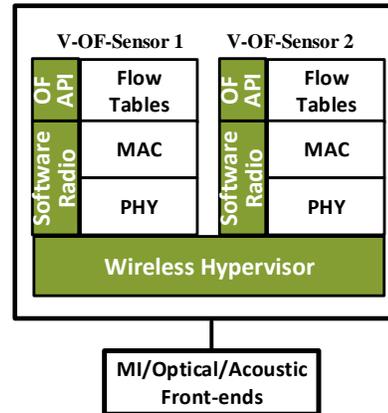


Fig. 3. Abstract Overview of OF-Underwater Sensor Device.

- The *control plane*, realized in the network controller, residing at surface buoys, consists of two key components: (1) network management tools, e.g., routing, control traffic management, mobility management, spectrum management, and network virtualization tools (e.g., network hypervisor) and (2) customized underwater applications, e.g., environment monitoring, fishery management, and underwater surveillance. Moreover, the network controller provides a set of application programming interfaces (i.e., north-bound Open APIs) to allow network management tools and underwater applications to access and manage network resources and devices. As shown in Fig 4, to configure and control OF-sensors, the network controller can either exploit the out-of-band control channel, where the dedicated links are reserved for control traffic forwarding, or utilizes the in-band control channel, where the data and control traffic flows share the same links. In SoftWater, the out-of-band control channel can be realized by long-range acoustic links to guarantee one-hop connections between OF-sensors and network controller. The in-band control channel can be realized by short-range multi-hop connections using optical and MI links because their high bandwidth is suitable for currently supporting data and control traffic.

In the following, we present the SoftWater architecture in detail, explain the network function virtualization and network virtualization, and introduce three essential management tools, namely reconfigurable multi-controller placement, control traffic balancing, and resource-efficient network virtualization.

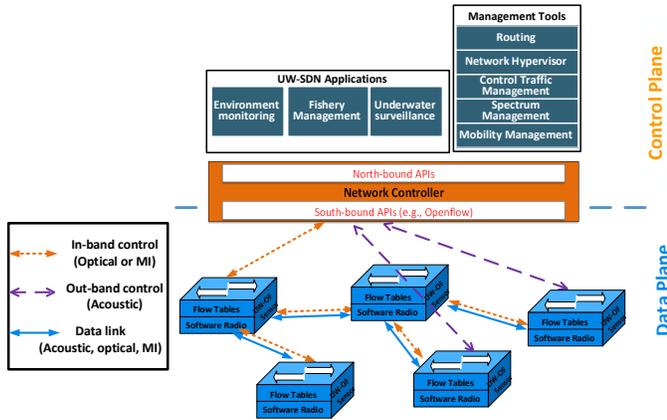


Fig. 4. Network Function Virtualization of SoftWater.

A. Scalable Network Function Virtualization

Network function virtualization (NFV) abstracts and decouples network functions from the underlying hardware, implements them in software, and places those softwarized network functions at the local general-purpose computers or at the remote centralized network servers [3]. There exist two major advantages of NFV. First, NFV makes the network architecture highly flexible because the softwarized network functions can be reconfigured quickly and adaptively. Second, NFV can greatly facilitate the globally-optimized network control and management by placing the softwarized network functions at the centralized network controllers or cloud servers. SoftWater maximizes the advantages of NFV by simultaneously implementing network-, MAC-, and Physical-layer function virtualization.

1) *Network-layer function virtualization*: Network-layer function virtualization decouples the routing function from the hardware routers and centralizes it at a network controller through an open network interface, namely OpenFlow. More specifically, the OpenFlow-enabled network-layer function virtualization basically abstracts the data plane by the sets of flow entries that are composed of a match and action pairs. Applications running on the controller use OpenFlow to implement any routing algorithm by configuring the flow table entries. Each flow entry constitutes a match policy where incoming packets are matched against any combination of the elements in the packet headers. These elements constitute source and destination MAC addresses, source and destination IP address, and source and destination TCP/UDP ports among others. The action constitutes forwarding the packet to a particular interface, dropping packets, sending the packets to controller, and forwarding to another flow table when where multiple/group flow tables are supported. The practicality and effectiveness of the network-layer function virtualization have been verified because of the successful field deployment of Openflow-enabled SDNs, e.g., B4 from Google [12], SWAN from Microsoft [11], and ADMCF from Huawei [1]. The recent deployments of software-defined WANs, e.g., B4 from Google [12], has successfully demonstrated the promising performance of SDNs by boosting the average link utilization

from 30% – 40% to over 70%.

In the SoftWater design, we implement the network-layer function virtualization by equipping the OpenFlow interface for each OF-sensor. Specifically, we install Open vSwitch (OVS) [18] for every underwater sensor, which is an OpenFlow-capable software switch that can easily be realized on a variety of hardware platforms ranging from high-performance servers to low-cost embedded devices. With OVS, each underwater sensor will be able to interpret, exchange, and respond to the OpenFlow protocol messages. Equipping sensors with OpenFlow capabilities (1) provides a unified interface to control and manage underwater sensors independent of the underlying underwater communication technologies based on acoustic, MI, or optical waves, (2) enables the fine-grained traffic engineering by defining customized control policies for any particular flow-space, which is a set of flows characterized by any combination of the header fields of the packet, and (3) allows to timely and simultaneously reconfigure the flow tables of any subset of underwater sensors, which enables the development of high throughput routing solutions, fast failure recovery schemes, and seamless underwater mobility management.

2) *MAC- and physical-layer function virtualization*: MAC- and physical-layer function virtualization exploits software-defined radio technologies to implement by means of software the resource (e.g., time, frequency, and code) sharing schemes at MAC layer and the baseband processing solutions (e.g., modulation, demodulation, channel coding, source coding, and MIMO precoding) at physical layer. More specifically, in SoftWater, each OF-sensor implements the MAC- and physical-layer functions on the local general-purpose single-board computers, e.g., beaglebone and raspberry pi, by exploiting the opensource GNU radio software packages. Such decoupling of PHY/MAC-layer functions from the radio hardware allows the independent evolution of radio technology and baseband processing/resource sharing solutions. In addition, the OF-sensor of SoftWater can be equipped with multiple hardware front-ends, e.g., LED photodiode, acoustic transponder, and coil-antenna, to simultaneously support different underwater communication technologies, e.g., underwater optical communications, acoustic communications, and MI communications. Such feature greatly facilitates the interoperability of underwater devices and enhances the networking performance by jointly exploiting the advantages of different underwater communication technologies. Moreover, the parameters of the MAC/PHY-layer functions, the communication technology selection, and the network-wide resource allocation policies can be reconfigured at the network controllers for realizing adaptive and optimized networking performance.

Despite its great advantages, implementing network function virtualization also imposes challenges into the network scalability because of the optimized but centralized control decisions from the network controllers.

To address such challenge, our proposed SoftWater adopts three integrated strategies including

- **High-performance network controllers located at sur-**

face buoys. With the current SDN technology, one single controller or server can achieve 12 million requests per second processing speed for the control messages between the switches and the controller. In SoftWater, we employ the high-performance embedded server, e.g., nvidia TK1, to implement the network controller. Such high processing capacity can be further enhanced by the adoption of controller clusters and advances in multi-threading technologies. Moreover, by equipping buoys with the energy-harvesting units, e.g., solar panels, the network controller can support long-term operations.

- **Logically centralized control plane.** We employ a logically centralized network controller by using multiple physically distributed controllers to address the performance limitation of single controller, while keeping the benefit of network control centralization. In particular, through the synchronization schemes, all the controllers placed at different buoys only share some necessary network-wide information and locally serve requests without actively contacting any remote controller, thus minimizing the flow setup times. What is more important, since all the controllers are placed on the surface buoys, they can utilize high-bandwidth through-the-air wireless links to share the necessary information.
- **Delay-minimum control traffic balancing.** In SoftWater system, when a new flow is initiated and no local forwarding policy is defined for such flow, the OF-sensor must forward the first packet of the flow to the controller for deciding an appropriate forwarding path. As a result, the timely and reliably delivery of control messages (e.g., the first packet of every new flow) for each OF-sensor largely impacts the efficiency and effectiveness of SoftWater. In particular, control traffic can be forwarded either by out-of-band control channel or in-band control channel as shown in Figure 1. The out-of-band solution relies on the dedicated and direct links, e.g., long-range acoustic links, between controller and OF-sensors. With in-band control solutions, both control traffic and data traffic have to share the same forwarding infrastructure, which means the control traffic may need to travel over multiple hops to reach the controller. In this case, we can adopt the delay-optimal control traffic balancing schemes [14] by finding the delay-minimum forwarding paths which can optimally distribute control traffic among all available underwater links in such a way that the control message forwarding delay between the sensors and network controllers is minimized.

B. Network Virtualization Capability

As shown in Fig. 5, the network virtualization enables multiple isolated virtual networks to share the same physical network infrastructure. This is achieved by abstracting and dividing network infrastructure resources (e.g., bandwidth, computing power, and topology) into multiple slices, which are disjoint or non-overlapped in both spatial and temporal domains. Each slice corresponds to one virtual network, which

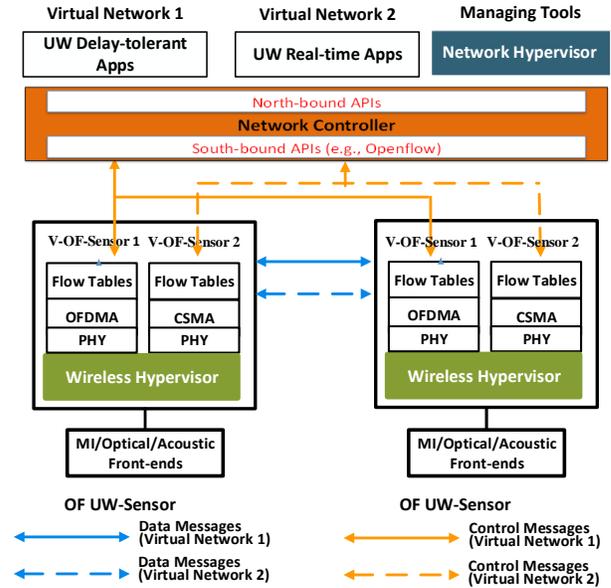


Fig. 5. Network Virtualization of SoftWater.

is assigned to one underwater application. By such way, SoftWater allows multiple underwater applications, e.g., underwater environment monitoring, fishery management, underwater surveillance, and tsunami detection, to dynamically share the same physical network infrastructure according to their respective demands and adopt its customized PHY/MAC/NET layer protocols, without owning the infrastructure and without interfering with the operations and performance of other applications. Moreover, by network virtualization, SoftWater can accelerate underwater technology innovation by allocating isolated network resources to deploy and test innovative technologies on the operational networks in large-scale real-life scenarios.

To realize network virtualization, SoftWater implements two functions: network hypervisor for high-level virtualization (Fig. 6) as well as wireless hypervisor for low-level virtualization (Fig. 7).

- The **network hypervisor** is a high-level resource management framework, which adaptively allocates non-conflicting multi-dimensional network resources to underwater applications or virtual network operators.
- The **wireless hypervisor** is a low-level resource scheduler that enforces or executes the resource management policies determined by network hypervisor by employing a variety of wireless resource dimensioning schemes, e.g., OFDMA, TDMA, or CDMA, so that the isolation among virtual networks is guaranteed.

C. SoftWater Management Tools

To enable the promising features and to maximize the overall performance of SoftWater, as shown in Figure 4, three essential management tools need to be developed: (1) reconfigurable multi-controller placement, (2) hybrid in-band and out-of-band control traffic balancing, and (3) utility-optimal network virtualization.

- **Underwater Openflow Protocol (i.e., Aqua-OpenFlow)** OpenFlow is a specific abstraction to provide control plane functionalities for switches in WAN, enterprise LAN, Internet, cellular core network, and data centers. Therefore, OpenFlow is designed to provide an abstraction for the routing functionality in wired networks. While OpenFlow can certainly be adapted for wireless environments, it is fundamentally an abstraction designed for one layer (routing) in a non-resource constrained environment. To maximize the network resource allocation in resource-constrained underwater networks, the new OpenFlow-type protocol, namely Aqua-OpenFlow, will be designed to provide abstractions to provide the control plane functionalities across different layers or planes. In particular, aqua-OpenFlow will extend the network function abstraction of OpenFlow by incorporating physical layer function abstraction (e.g., channel coding rates and modulation types), MAC layer function abstraction (e.g., backoff timer for contention-based MAC and time schedule/frequency/CDMA code for contention-free MAC), and energy plane (e.g., residue energy of the OF-sensors). In this way, the optimized cross-layer protocols can be easily designed and implemented on SoftWater.
- **Reconfigurable Multi-Controller Placement.** The traffic pattern of underwater communication networks can be spatially and temporally varying because new sensors are deployed, the sensors switch between sleep and active modes, or the AUVs are changing locations. As a consequence, the stationary and fixed controller placement may lead to the unbalanced processing load among the controllers and prolonged control message delay. To solve such problem, we utilize the potential mobility feature of surface buoys to adaptively change the placement of the controllers according to the current or predicted traffic patterns.
- **Hybrid In-band and Out-of-band Control Traffic Balancing:** The acoustic-based out-of-band control channel can establish one-hop direct connections between OF-sensor and controllers over long distance as shown in Fig. 1. Thus, the out-of-band control channel is suitable to manage the anchored OF-sensors or AUVs, which are sparsely deployed in the remote areas and are far away from other OF-sensors. However, due to the limited bandwidth of acoustic channel and high propagation delay, our-of-band control channel may lead to high control message delay. On the contrary, in-band control channel may rely on the short-range high-bandwidth optical or MI links, thus leading to the multi-hop forwarding paths for control traffic. Due to the reliable and high throughput of the optical and MI links, the control traffic may experience minimum delay over the in-band control channel. However, since in-band control channel has to share the bandwidth with data traffic, this may impact the throughput of data traffic. To solve this problem, SoftWater relies on the hybrid in-band and out-of-band control traffic balancing scheme, which optimally determines the modes of the control channel according to the network

topology, the network congestion condition, and the QoS requirements of control traffic.

- **Utility-optimal Network Virtualization:** Network virtualization is essential to support Infrastructure-as-a-Service, thus enabling a wide range of emerging underwater applications to simultaneously utilize the same physical network infrastructure. Since underwater network resources are limited, utility-optimal wireless network virtualization solutions are highly desirable (Section III-C). Specifically, the utility-optimal network hypervisor aims to maximize the global resource utilization, while guaranteeing the respective requirements, e.g., data rate and delay, demanded by each underwater application. Moreover, the throughput-efficient wireless hypervisor is demanding, which aims to achieve the isolation of multiple virtual networks at each OF-sensor, while ensuring the efficient resource utilization for enhanced throughput.

III. SOFTWATER MANAGEMENT TOOLS

A. Reconfigurable Multi-Controller Placement

It is very challenging to realize the scalable and efficient underwater SDN, e.g., SoftWater, by adopting a single and centralized controller as the whole network grows because of the increased number of network elements or traffic flows. To address such challenge, the placement of multiple controllers across the whole network can address the performance limitation of single controller. Moreover, the data traffic pattern of underwater communication networks can be changed as time proceeds because more sensors are deployed, sensors are re-positioned for different tasks, or AUVs are changing the roaming paths. Thus, the stationary and fixed controller placement can lead to reduced control plane performance.

To address the above challenges, we develop reconfigurable multi-controller placement strategies by exploiting the potential mobility capability of surface buoys, where network controllers are hosted. The proposed solution decides the optimal controller locations, i.e., buoy locations, according to the current traffic patterns in SoftWater system. First, the current network topology, AUV mobility pattern, and traffic models of the OF-sensors can be obtained by the network controller. Next, based on such information, the optimal controller placement problem can be formulated, which aims to minimize the required number of controllers and support all control traffic from OF-sensors at the same time. More specifically, the multi-controller placement should determine (i) the number of required controllers, (ii) their individual geo-locations, and (iii) the control domain assignments for each OF-sensor. Solving the above optimization problem is very challenging because it is NP-Complete. In other words, it is impossible to solve and obtain the optimal values in a time-efficient manner (i.e., even finding a feasible solution will require a certain amount of computing time). To counter this challenge, we leverage the fast approximation algorithm to timely yield a feasible near-optimal placement solution with guaranteed performance bounds.

B. Hybrid In-band and Out-of-band Control Traffic Balancing

In SoftWater, both in-band and out-of-band control channels are utilized. On the one hand, out-of-band control channel, relying on low-frequency long-range acoustic links, can provide one-hop connections between the controllers and the OF-sensors. Thus, this scheme is suitable for initial or network-wide system configurations, such as network topology discovery, optical links alignment, and node failure monitoring. On the other hand, the in-band control channel, relying on optical or MI links, can provide fast and reliable control traffic forwarding. Thus, this scheme is suitable for timely and fast configurations of flow tables for realizing dynamical and optimized routing. Moreover, for large-scale underwater communication networks, both in-band and out-of-band control channels have to be jointly exploited to maximize the control traffic throughput. However, such hybrid control traffic balancing scheme faces two challenges. First, fast balancing algorithm is demanding to find the forwarding paths for control traffic in a timely manner, while satisfying the QoS requirements of control traffic. Second, the unique mobile features of AUVs should be incorporated to provide ubiquitous and reliable connections between AUVs and network controllers.

To address these challenges, SoftWater adopts a novel hybrid in-band and out-of-band control traffic balancing scheme. The objective of scheme is to find the best control channel mode (i.e., in-band or out-of-band) along the optimal forwarding paths for the control flows in such way that the control traffic throughput is maximized and control message delay is minimized, while considering the mobility patterns of the AUVs. Inspired by our previous work [14], this optimization problem can be solved by several well-known fast-convergent algorithms, e.g. ADMM [6], which can provide the optimal solution within few milliseconds. Moreover, the obtained delay of such control balancing scheme is further feedback to the controller placement decision module, and trigger the adaptive control for better controller placement with the fulfillment of timely control message delivery in SoftWater.

C. Utility-optimal Network Virtualization

The network virtualization layer of SoftWater aims to create a set of virtual (or logic) networks on the shared network infrastructure. The virtual networks can be dedicated (i) to different underwater applications so that each service application can be treated with customized and independent resource provisioning algorithms, and (ii) to different network operators so that multiple operators can dynamically share the same underwater network infrastructure. To realize network virtualization, two functions are proposed as shown in Fig. 6 and 7: the network hypervisor for high-level virtualization, and the wireless hypervisor for low-level virtualization.

1) *Network Hypervisor*: Network hypervisor is responsible for high-level resource management as shown in Fig. 6, which determines how to allocate non-conflicting network resource blocks among virtual networks or network applications based on their demands. An utility-optimal network hypervisor is adopted to maximize the global resource utilization, while

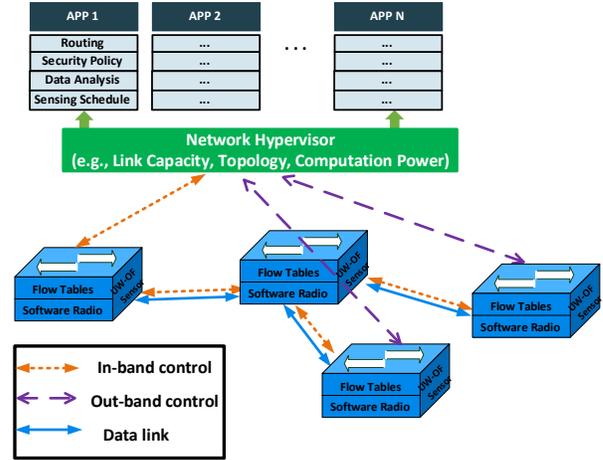


Fig. 6. Network Hypervisor of SoftWater.

guaranteeing the QoS requirements demanded by each virtual network or network application. In SoftWater, network resources include (1) underwater spectrum resources consisting of time slots and frequency channels, (2) underwater infrastructure resources, including OF-sensors, and (3) radio access technology options, such as acoustic, optical or MI communications. Considering a set of underwater applications, the QoS requirements can be defined in terms of data rate, delay, sensing coverage, and sensing frequency. Then, at each OF-sensor, the network controller can assign the wireless resource blocks (RBs) (e.g., underwater channels and channel usage time duration) to each underwater application. Moreover, the network hypervisor also determines the radio access technology of the OF-sensors for each application. The objective of utility-optimal network hypervisor is to optimally allocate resource blocks and radio access technology in such a way that the total energy consumption of all the OF-sensors is minimized, while satisfying the QoS requirements of all underwater applications.

2) *Wireless Hypervisor*: It is a low-level resource scheduler as shown in Fig. 7 that enforces or executes the resource management policies determined by the network hypervisor by employing a variety of wireless resource dimensioning schemes, e.g., OFDMA or wireless scheduling, so that 100% isolation among virtual networks is guaranteed. As a consequence, each virtual network can implement and adopt its own and customized NET/MAC/PHY layer protocols. Besides providing 100% isolation between the virtual networks, the wireless hypervisor has to ensure efficient utilization of the limited spectrum resources, which exhibit inherent channel and user diversity. For example, a well-known OpenFlow(-based) virtualization, called FlowVisor, is a layer responsible for the isolation among slices of the virtualized infrastructure and employs leaky-bucket scheme for bandwidth provisioning, which however, is not a work-conserving policy and thus cannot guarantee full bandwidth utilization. To solve this issue, we develop the queue-length based GPS (Q-GPS) scheme, which inspired by the throughput-optimal property of maximum weight scheduling, assigns weights proportional to

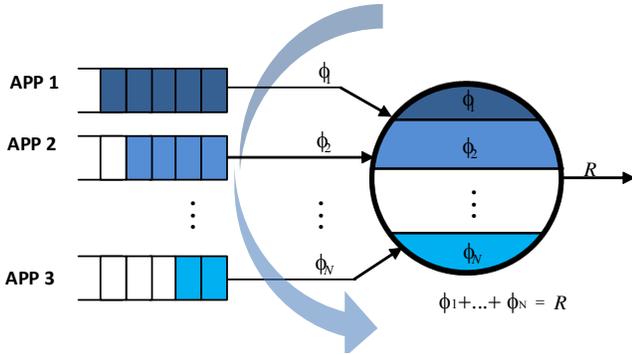


Fig. 7. Wireless Hypervisor of SoftWater.

the product of queue length and channel rate. The proposed Q-GPS can guarantee the isolation among virtual networks, while improving throughput and delay performance of each virtual network.

D. Research Challenges

- *3D Controller Placement:* The placement of network controllers on the surface buoys may induce high control message delay if the underwater communication networks are deployed in deep water scenarios. To address such challenge, the network controller can be hosted on certain powerful OF-sensors, which are deployed in underwater 3D spaces. In this case, the optimal 3D controller placement has to be developed to determine the optimal number and locations of the desired network controllers.
- *AUV-aware Control Traffic Balancing:* because of the inherently mobile features of AUVs, mobility-aware and proactive control traffic balancing schemes need to be developed, which minimizes the control message forwarding delay by taking into account the unique spatial and temporal mobility patterns of roaming AUVs. Accordingly, a hybrid solution should be adopted. On the one hand, the average control message forwarding delay will be minimized through semi-static control message forwarding rules by incorporating the historical mobility pattern of the AUVs. On the other hand, real-time control traffic forwarding rules, empowered by the fast-converging optimization solutions, will be enforced to address the dramatic control traffic changes caused by the unexpected movements of AUVs.
- *Computationally-efficient Network Hypervisor:* The utility-optimal network hypervisor is a nonseparable non-quadratic problem, which is NP hard. In addition, a huge parameter set brings a multidimensional data decision problem. Considering the precious resources of the network controllers located on the buoys, computationally-efficient algorithms need to be investigated, such as the dimensional reduction scheme [20] and large-scale convex optimization [7]. Moreover, the tradeoff between the performance and the complexity of the above algorithms will be compared to obtain the

optimal solving strategy.

- *Wireless Hypervisor for Underwater Acoustic Networks:* For terrestrial wireless networks, e.g., WiFi or Cellular networks, wireless hypervisor can be implemented by TDMA or OFDMA. However, both schemes are not suitable for underwater acoustic networks. On the one hand, TDMA requires the long time guards between consecutive time slots because of the unpredictable and long propagation delay of acoustic waves. On the other hand, FDMA is not suitable for acoustic links because of their very limited bandwidth and the vulnerability of limited band systems to fading and multipath. To address above challenges, CDMA can be exploited to realize efficient and effective underwater wireless hypervisor because CDMA is robust to frequency selective fading and compensates for the effect of multipath at the receiver in the challenging underwater environment [19]. Moreover, space division multiple access (SDMA) based on MIMO technology can be also exploited to realize wireless hypervisor.

IV. SOFTWARE-DEFINED UNDERWATER NETWORKING WITH SOFTWATER

In this section, we propose new software-defined underwater networking solutions, which leverage the full potential of the SoftWater architecture. Specifically, the throughput-optimal underwater routing is proposed to maximize the network throughput by utilizing all possible link capacities. SDN-enhanced fault recovery scheme is developed to timely restore the network operations with the minimum network performance degradation in the presence of node failures. Software-defined underwater mobility management is developed to To guarantee the seamless rerouting by minimizing the disconnection time of caused by AUVs, while ensuring that the rerouting paths can meet the QoS requirements of the traffic flows in terms of delay, jitter, and bandwidth.

A. Throughput-optimal Underwater Routing

Different from the terrestrial counterpart, underwater networks generally suffer from very limited bandwidth. Therefore, it is very demanding to develop throughput-optimal underwater routing algorithms, which can maximize the network throughput by fully utilizing all the possible underwater links for data packet forwarding. A well-known class of throughput-optimal routing solutions is backpressure policy [17]. This policy can stabilize the network under any traffic load that are supportable by any other routing algorithm, without requiring the explicit statistical information of arriving traffic flows and wireless channels. However, while the backpressure policy has been shown to achieve the maximum throughput performance, it suffers a substantial packet delay due to the waiting time of building up large "back-pressure" in queue backlogs. Moreover, relying on "back-pressure calculation", the backpressure policy requires continuous exchange of queue information among neighboring nodes, which imposes great burden into the already limited underwater communication links.

To counter such challenge, SoftWater adopts novel throughput-optimal delay-minimum routing algorithms by taking advantage of the global view of network controller and its superior computational power for realizing large-scale network-wide optimization. More specifically, when the new flows from OF-sensors are initiated, the first packet of these flows will be sent to the controllers via secure control channels. Such packet can contain the data traffic profiles of OF-sensors, e.g., the predefined or requested data rate of OF-sensors. Moreover, based on the existing underwater localization solutions, such as long baseline (LBL) and short baseline (SBL) systems, the network controller can obtain the global network topology. Consequently, the relative locations of the OF-sensors can be obtained. This information, combined with the deployed underwater environment parameters, e.g., conductivity, permeability, depth, and temperature, can be exploited to predict and estimate the link capacity between each pair of OF-sensors can be predicted. Then, based on the requested data rates of the traffic follows and the link capacity matrix of the network, we can formulate the throughput-optimal delay-minimum underwater routing as an large-scale convex optimization framework. Such framework aims to find the optimal multiple routing paths and the data rate allocated to each path for each traffic flow in such way that the average packet delay of whole network is minimized, while satisfying the flow conservation constraints, which guarantees that the maximum network capacity is exploited. Despite its high complexity, inspired by our recent work on large-scale optimization in SDN [14], such delay and throughput optimal routing algorithm can be efficiently solved at the network controller by exploiting its superior computation power along with the emerging fast-convergent optimization tools.

B. SDN-enhanced Fault Recovery Scheme

In the harsh underwater environment, sensor nodes are vulnerable to different types of failures [10], [9], which may affect the normal operation of the network. In particular, a single node failure may result in multiple invalid routing paths, which can cause the loss of the connectivity of lots of sensor nodes and thus disrupt the normal operation of the whole network. Thus, it is crucially important to timely recover the disrupted routing services in the event of node failures.

The controller need to define a strategy that would effectively respond to the detected failure to restore the services. There are two predominant approaches in failure recovery in the industry. These are protection and restoration. Protection is a proactive mechanism that aims to build an alternative secondary routing path to protect the primary path when failures are detected. Restoration on the other hand is a reactive mechanism where the control plane tries to restore the service upon detection of failure. SoftWater architecture could easily implement both protection and restoration schemes with low signaling cost, fast recovery speed, and optimized path planning.

- **For restoration scheme**, after the controller gets notification of a node failure, the network topology is

updated and then a restoration path is calculated using any particular routing algorithm on the new network topology. For affected OF-sensors which are on both the working and the restoration path, the flow entry is modified. For the other OF-sensors, there exist two conditions. If the OF-sensors are only on the failed path, the forwarding entries involving such failed path are deleted. If the OF-sensors are only on the restoration path, the new forwarding entries are added.

- **In the protection operation**, the protection (or secondary) path is pre-computed and it is installed together with the working (or primary) path into the flow entries at OF-sensors, such that each OF-sensor has two forwarding information, one for the protection path and the other for the original working path. Once the failure is detected in the working path, the OF-sensor will use the protection path for flow forwarding. More specifically, the fast switch-over between the working path and the restoration path can be realized by the group tables of OpenFlow [23] or flow entry priority [21].

While the restoration scheme can lead to the optimal restoration path, it induces longer failure recovery time than the protection scheme because of the required routing path setup time. For example, in conventional terrestrial networks, the existing research shows that using the SDN-enabled protection scheme, the maximum recovery time after failure detection is about 60 ms and all the flows are restored between 42 and 48 ms [22]. This meets the 50 ms failure recovery time required by carrier-grade network. However, using restoration schemes, the failure recovery time can be in the range of 200 - 300 ms [23]. To avoid above problem for SoftWater, we will adopt the hybrid fault tolerance algorithm, which augments the restoration technique by the protection scheme to improve failure recovery time, while guaranteeing that the optimal restoration path is utilized. More specifically, by this hybrid fault tolerance solution, the controller installs a primary path and a protection path for any given flow in OF-sensors. When the node failures are detected, the affected OF-sensors first switch from the primary path to the protection path, which will guarantee the minimum recovery time. Since the protection path may not be the optimal one under the newly updated network topology, our algorithm will also trigger the restoration procedure upon the failures are detected. In this case, the controller is informed of the presence of failures, recalculates the optimum path, and modifies the flow tables of OF-sensors via Openflow protocol if the newly calculated path provide a better metric over the protection path.

C. Software-Defined Underwater Mobility Management

Since AUVs are becoming the integrated parts for underwater communication networks, the effective mobility management is essential to establish rerouting paths that maintain the desirable connections for the AUVs when they are changing locations. Such connections can be between AUVs, between AUVs and surface buoys, or between AUVs and anchored sensors. To guarantee the seamless mobility management, the disconnection time caused by AUV mobility should be

minimum, while ensuring that the rerouting paths can meet the QoS requirements of the traffic flows in terms of delay, jitter, and bandwidth.

The control and data plane separation of SoftWater allows to simultaneously setup forwarding rules on all OF-sensors instead of hop-by-hop signaling, which greatly facilitates the seamless mobility. Moreover, the per-flow and network topology information at the network controller can be utilized to achieve per-flow QoS guarantees. More specifically, we adopt a mobility-aware re-routing approach where new routes are calculated before the AUVs move to new locations. This can be achieved by mobility prediction, which tells the highest possible location an AUV can move to based on its current location, its moving speed, its moving direction, and its historical mobility pattern. Based on the predicted results, the network controller determines which traffic flows need to be rerouted. Consequently, we propose a QoS-guaranteed rerouting algorithm to find the routes for those flows. More specifically, based on the residue capacity of each link in the SoftWater, QoS requirements of the flow, and the predicted locations of AUVs, the QoS-guaranteed rerouting scheme aims to find the optimal rerouting paths that satisfy the per-flow QoS requirements and provide the maximum network utility at the same time. In particular, the objective utility function can be formulated as the total network capacity. Moreover, the per-flow QoS requirements, e.g., delay, jitter, and bandwidth, should be satisfied. After the optimal rerouting paths are calculated, they are installed at the corresponding OF-sensors as the predictive routing paths, which will be activated if the AUVs move to the predicted locations.

D. Research Challenges

- *SDN-enhanced energy-efficient traffic engineering:* Because both anchored sensors and AUVs have limited energy resources, it is of significant importance to develop energy-efficient traffic engineering solutions. Under SoftWater, the network controller has the global view of the residue energy and the location of the OF-sensors along with the link capacity. Utilizing those information, the network controller can assign the most energy-efficient routing paths for each traffic flow in such a way that the network lifetime can be maximized, while ensuring that the satisfactory per-flow QoS performance is obtained. Moreover, if the OF-sensors are wirelessly rechargeable, the optimal roaming paths of AUVs can be determined by the controller to optimally charge the anchored underwater sensors in such a way that the balanced energy consumption and energy harvesting can be realized to enable the perpetual underwater operations.
- *Fault tolerance design for control plane:* Because SoftWater is a logically centralized architecture, which relies on the network controllers to update policies and take actions when new flows are introduced in the network, robustness of the control plane is of critical importance. The most fundamental mechanism to recover control plane failures in the centralized network is the "primary-backup replication" approach, where backup controllers

will resume the network control in the case of primary controllers failures. Specifically, (1) the impact of the controller number on reliability needs to be determined, and (2) the tradeoffs between reliability and latencies should be considered.

V. CONCLUSION

In this paper, we propose SoftWater as a new networking paradigm towards next-generation underwater communications systems. SoftWater provides high flexible architecture, which can accelerate the innovations for both hardware forwarding infrastructure and software networking algorithms through control and data plane separation, enable the differentiated and adaptive network control and management for diverse underwater applications through network virtualization, achieve maximum network throughput and robustness through optimized and centralized control, facilitate the joint exploitation of heterogeneous underwater communication technologies through network function virtualization, and enhance energy efficiency through the global view of the network energy status along with globally optimized energy-efficient routing and AUV-assisted recharging. To realize the promising properties of SoftWater, the essential management tools, including reconfigurable multi-controller placement, hybrid in-band and out-of-band control traffic balancing and utility-optimal network virtualization are introduced. Moreover, the novel software-defined underwater networking solutions, including throughput-optimal underwater routing, SDN-enhanced fault recovery schemes and software-defined underwater mobility management, are presented. In addition, the research challenges of realizing SoftWater are also summarized.

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