Ubiquitous and Robust UxV Networks: Overviews, Solutions, Challenges, and Opportunities

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***Abstract*—Empowered by their exceptional versatility and autonomy, unmanned vehicles (UxVs), including ground, aerial, surface and underwater vehicles, are emerging as promising tools to execute tasks ubiquitously. Due to the increasing complexity of the environment and tasks, cooperation among multiple UxVs of different types is often required, which significantly relies on high-performance networking among them. However, the mobility, autonomy and heterogeneity of UxVs pose enormous challenges for UxV network management. This article summarises the promising perspectives and difficulties of the current and future UxV networks and proposes a software-defined management architecture for UxV networks to achieve wider coverage, reduced latency, and higher delivery ratio. The feasibility and advantages of this innovative architecture are further discussed, with preliminary experiment results confirming its superiority and potentials. Finally, future challenges and opportunities of networking and deployment are summarised.**

***Index Terms*—UxV, Software-defined Network, Network Management, Resource Optimisation, Heterogeneous Network.**

I. INTRODUCTION

THE future will witness a world ubiquitously networked with unmanned vehicles (UxVs), encompassing unmanned ground vehicles (UGV), unmanned aerial vehicles (UAV), unmanned surface vehicles (USV), and unmanned underwater vehicles (UUV), to perform a wide range of challenging tasks, such as surveillance, patrolling, and photography in any corner of the earth. The rapid development in technologies, materials, and manufacturing is equipping UxVs with exceptional autonomy, mobility and carrying capabilities, enabling them to function ubiquitously without the necessity for onboard manual control [1]. These features enhance the popularity of UxVs in the applications that are difficult, dangerous or tedious to human beings, where UxV networks become the crucial factor in enabling high-performance autonomous control and data communication.

For all tasks mentioned above, robust data communication and optimised resource allocation are common requirements for networked UxVs. Generally, there are two types of data transmitted within the UxV networks, including task-oriented data transmission in traffic channel (TCH), and the vehicle's and environment's state information sharing among multiple vehicles in control channel (CCH) to ensure efficient cooperation with minimal human intervention. TCH and CCH data communications have diverse and often stringent requirements on network latency, stability, and bandwidth. Meanwhile, the challenges for different types of UxV networks also vary, such as the high mobility, 3D scenario and energy constraints of aerial vehicles, and different wireless medium of aquatic vehicles. The adaptive adjustment of the network management strategy to accommodate the varied characteristics of different UxV networks is also a vital issue.

Network architecture and corresponding protocol research for distinct types of vehicles have been carried out for years [2]. However, due to the unbalanced distribution of infrastructures and huge management overhead, the existing distributed network architectures are still inadequate to meet the transmission requirements for fully autonomous UxVs in many challenging scenarios, such as post-disaster, remote areas, and wilderness [3]. Massive information exchange through CCH will be required in such unknown environment, resulting in substantial overhead that renders traditional distributed solutions less effective in real-time perception of the dynamic network state. Consequently, it becomes challenging to optimise each vehicle's networking configurations instantaneously. Meanwhile, the research on heterogeneous networks composed of different UxVs is still in the early stages. The heterogeneity of transmission technologies and communication capabilities of different UxVs have not been thoroughly explored [4].

The success of Software-Defined Network (SDN) technologies in routing, load balancing, and network function virtualisation has proven to effectively alleviate network management overhead and improve network performance [5], [6]. The separation of the data plane and control plane in SDN enables applications to optimise network management policies according to the real-time network conditions and corresponding task requirements, thereby improving the scalability and flexibility by reducing network reconfiguration overhead. For SDN, control traffic can be offloaded to the control plane in order to reduce network overhead while maintaining a dynamic global view of the network. However, the limited onboard resources and communication capacity of UxVs coupled with challenging deployment scenarios pose huge challenges to deploying SDN in the UxV network.

Thus, this article firstly reviews the characteristics of different types of UxV networks, along with the advantages and constraints of the existing methods for future UxV networks. We then propose a novel **S**oftware-**D**efined **UxV** **N**etwork (SDUxVN) to support integrated design of perception, com-

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munication and control (IPCC) for future ubiquitous UxVs. The key components and advantages of this architecture in different scenarios will be detailed through discussion and simulation experiments. We further discuss the network and deployment management challenges of SDUxVN and its components.

II. OVERVIEW OF UXV NETWORKS

A. *Terrestrial Network*

The number of autonomous vehicles will reach 54 millions in 2024 [7]. With an increasing number of UGVs being developed and connected to the existing terrestrial networks, devising an efficient management strategy for these networks to support their autonomy and cooperation has emerged as a huge challenge, consequently attracting substantial research interest. The mobility of the vehicles leads to a constantly changing network topology, rendering static management strategies ineffective. Coupled with more vehicles' state data to be collected to support autonomy and task execution, some of which have a stringent delay or bandwidth requirement - such as collision avoidance or driving assistance - these emerging requirements introduces new challenges.

Two notable architectures exist in the UGV network: the Vehicular Ad-Hoc Network (VANET) based on IEEE 802.11p and the cellular network based on C-V2X. C-V2X offers broader coverage and superior spectral efficiency, but it is prone to congestion and heavily depends on infrastructure [8]. As UGVs ubiquitously access the network, optimal resource deployment and allocation become crucial on both temporal and spatial scales. On the other hand, VANET, with minimal infrastructure needs and stable transmission, faces challenges like limited transmission range and reduced spectral efficiency [9]. Yet, VANET is ideal for specific small-scale scenarios, such as intersection coordination and post-disaster monitoring, where vehicles demand high Quality-of-Service (QoS).

Traditional ad-hoc network routing methods, when applied to UGV networks, often fall short due to high control overhead and a restricted view in distributed architectures. While innovative methods using additional metrics (position, velocity, and digital map) have emerged to assist the routing process, they come at the cost of increased communication, storage, and computation. Balancing routing performance and these costs is essential. The distributed routing process inherently restricts each vehicle's view. Even with additional information, achieving global solutions in evolving, dynamic networks remains a challenge for distributed architectures.

B. *Aerial Network*

The rapid development of low-cost, flexible UAVs has promoted the emergence of novel aerial networks wherein UAVs serve as either access points or connected terminals. With sufficient power supply, UAVs are able to reach any location on the planet, facilitating the deployment of aerial networks in remote and challenging areas inaccessible to terrestrial networks. Moreover, the communication link with UAVs has typically high probabilities of Line-of-Sight (LoS) channels, which can significantly mitigate signal blockage and shadowing. These characteristics designate UAVs as critical components of future heterogeneous UxV networks.

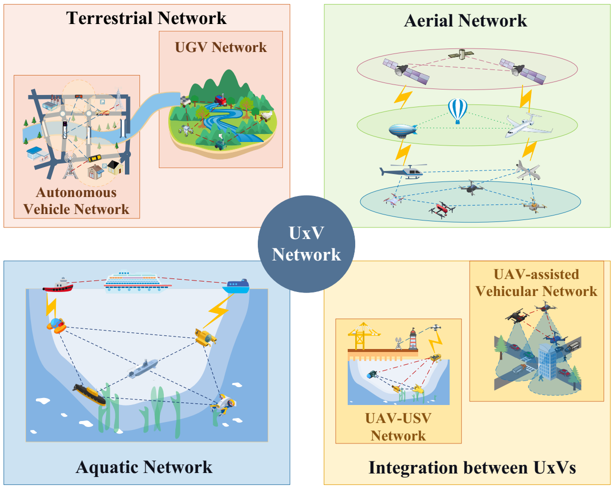

Fig. 1. Various types of UxV networks

UAVs have been explored for cooperative task execution aimed at improving work efficiency and task completion rate. Flying Ad-Hoc Network (FANET) emerges as a promising architecture for such cooperation. It offers a readily deployable and self-configuring solution to connect with terrestrial users. Furthermore, the information sharing enabled by FANET contributes to ensuring the safe operation of UAV swarms.

3D high-speed movements of UAVs empower FANET easy to deploy, but the dynamic network topology will also results in connectivity issues. Researchers utilised different metrics (location, speed, and energy consumption) as well as additional information (predefined trajectory, prediction model, and assistance from high-altitude platforms) to assist the routing process. However, in the high-density high-mobility scenarios, the huge network overhead and energy consumption caused by the transmission in CCH to exchange necessary neighbouring information are still inevitable.

The limitations on flight duration and transmission power, due to size, weight, pose challenges to the deployment of UAVs. Meanwhile, the complex LoS and non-line-of-sight (NLoS) condition can greatly impact the QoS of UAV communications, which depends directly on the positions of UAVs and terrestrial users. Fortunately, The high manoeuvrability of UAVs enables adjusting their 3D locations to achieve better network performance. UAVs' locations also need to be modified according to ongoing tasks like monitoring, covering and offloading. The design of a co-optimised network and deployment management strategy, which can efficiently complete the assigned tasks under the premise of ensuring high transmission quality will be a complex challenge.

C. *Aquatic Network*

Water bodies, covering about 71% of Earth, make aquatic networks vital in the UxV network. In these scenarios, UxVs are categorized into USVs and UUVs, as depicted in Fig. 1.

UUVs, operating autonomously, are more efficient in challenging underwater tasks than remotely controlled vehicles

[10]. The attainment of collaborative objectives necessitates coordination among multiple UUVs via the network, while architectures and routing protocols like AODV and GPSR are common for UUVs in 3D spaces [11], communication technology remains a bottleneck. Acoustic communication, favored due to radio frequency limitations underwater, faces challenges like high delay and error rates [11]. Enhancements in acoustic communication, such as multi-carrier modulation, are crucial [12].

USVs, on the water surface, benefit from better communication conditions due to fewer obstacles. Popular communication technologies for USVs include IEEE 802.11b and 802.15.4 [11]. USVs can bridge surface and underwater networks and act as reference points for UUVs, given the difficulty UUVs face in accurately sensing their positions underwater.

Coordinating UUV and USV communication and movement is challenging due to varied capabilities and energy constraints, especially in infrastructure-limited aquatic settings. Aquatic network management strategies should focus on minimizing redundant transmissions and optimizing resource allocation.

D. Integration between different UxVs

As depicted in the lower-right segment of Fig. 1, each type of UxV naturally has its limitations concerning flexibility, capacity, or energy. However, these drawbacks can be mitigated through the cooperation of different UxVs, provided they are supported by appropriate networking technologies and management strategies. For instance, leveraging the flexibility of UAVs, combined with superior LoS channel conditions, positions them as a powerful supplement to terrestrial networks. In infrastructure-sparse scenarios, they can serve as mobile relay nodes, and in areas with massive communication demands, they can act as temporary base stations. The abundant energy resources of terrestrial networks can also be harnessed to charge these UAVs. In aquatic scenarios, the USV, with its mobility and capability to interface with both surface and underwater networks, can relay communications for UUV networks. In collaboration with UAVs, they can effectively transmit data collected underwater to remote base stations. Energy-constrained underwater networks can also benefit from high-performance USVs.

However, the integration between different vehicles can introduce network and deployment management issues due to the heterogeneity. The diversity in vehicle types and communication technologies can lead to management difficulties due to varying transmission capacities. Vehicles with less capabilities can erroneously be chosen for data transmission based on the unrealistic premise of uniform transmission capability, while more capable vehicles will be overlooked due to mismatched resource allocation strategies. Therefore, it is necessary to jointly consider control and network management strategies across different layers—including power control, routing decision, and deployment strategy—to achieve optimal QoS in this heterogeneous UxV network [4].

III. SOFTWARE-DEFINED UXV NETWORK

A. Motivations

UxV networks have the potential to ubiquitously offer network services for different autonomous vehicles, emerging as a crucial component in the future worldwide network system. However, the realisation of efficient UxV network management necessitates the consideration of the following challenges:

Low scalability: Current network management strategies often rely on additional information (GPS service, digital map) and resources (computation, cache, energy) and have not fully considered the stringent environment condition of autonomous UxVs. The deployment environment and missions will challenge the resource-constrained vehicles or require solid infrastructure support. While an explosively increased number of UxVs are being deployed, it becomes crucial to consider the scalability of the future UxV network management strategies, which should be highly adaptive to diverse environments, boosting vehicle number, heterogeneous vehicle types, and networking technologies.

High overhead: Highly dynamic vehicular networks characterised by frequent location and topology changes exponentially increase network status changes and control traffic. This further challenge the limited communication and energy resources. Such traffic drastically increase in UxV networks because the frequency of the control traffic transmission is proportional to the increased hops and vehicle number. Ideally, UxV networks need to obtain a real-time, global view to support network management with limited control overhead. This will ensure that adequate resources are utilised for data transmission rather than control traffic.

Limited and unbalanced resources: The demand for networking, computing and energy resources fluctuates on both temporal and spatial scales in different tasks. Even in the same task, data transmission in TCH and control traffic in CCH will have different bandwidth and reliability requirements. However, due to the limited payload and poor or non-existing infrastructure, the available resources for UxV networks are often unbalanced and insufficient spatiotemporally. This calls for an efficient resource placement and allocation strategy.

B. Architecture Design and Advantages

SDN separates the control and data plane to significantly reduce the overhead of configuring and optimising the networking resources. Given its ability to maintain a global view of the network, the control plane enables the dynamic configuration of the network according to the current state and the availability of resources. Meanwhile, SDN enables programmability from the application layer, allowing for the installation of specific resource allocation and routing strategies for diverse task requirements. The advantages SDN brings to current mobile networks, such as 5G and VANET, have been widely proven in research and real-world practice [6], [13]. The integration of SDN into mobile network architectures, such as UAV and vehicular networks, has attracted significant interest. However, current efforts often fall short in several areas:

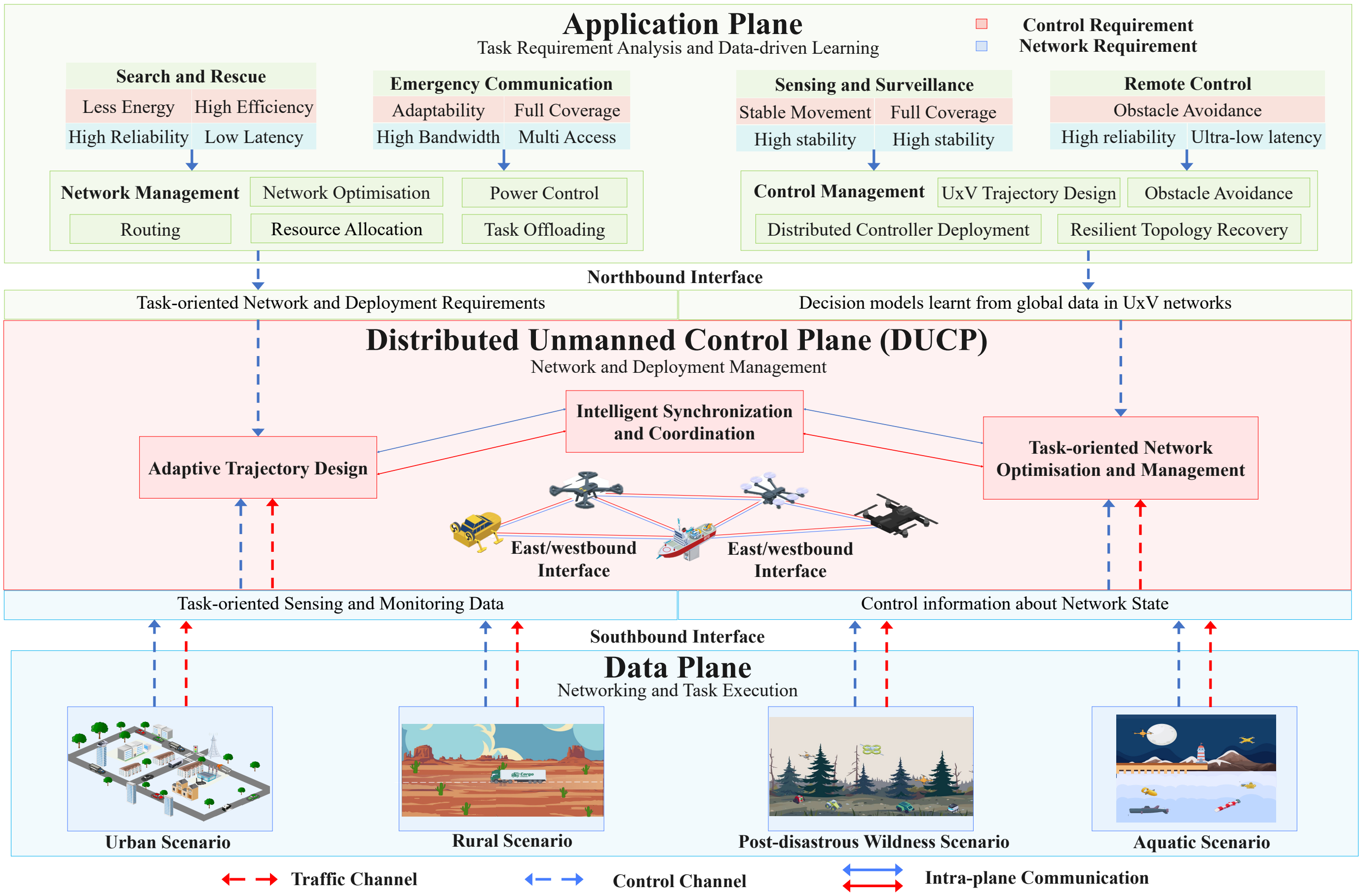

Fig. 2. Illustrations of SDUxVN and DUCP.

1) Most integrations focus on a single UxV type, either UAV or UGV networks, neglecting the need for a unified SDN architecture that considers the heterogeneity of UxVs [1], [5].
2) The control plane in these methods is typically deployed in solid terrestrial infrastructure like Road Side Units (RSUs) or Base Stations (BSs) [5]. These approaches demand extensive infrastructure support, which can be costly or impractical in challenging UxV environments. Furthermore, when the control plane is remotely situated, communication with the data plane becomes unstable due to traffic fluctuation, resource imbalance, and suboptimal wireless conditions. This instability can lead to errors in real-time network management and a chaotic global network view, compromising SDN performance.

To address these challenges, we introduce the SDUxVN architecture (refer to Fig. 2). This architecture consists of:

Application Plane: Located on a remote cloud server, it interfaces with users or applications. Its main roles are to convert task requirements into specific data transmission and UxV deployment requirements, and to use global data to train decision-making models. Given its non-stringent delay requirements for the requirement transmission, it can be situated at distant, resource-rich locations without compromising performance.

Distributed Unmanned Control Plane (DUCP): It is located in the centre to the proposed architecture. This innovative plane consists of high-capacity UxV controllers, functioning as a physically distributed but logically centralized control plane. For a UxV to be part of the DUCP, it must:

1) have surplus computational and communication resources beyond their primary tasks;
2) operate in environments with optimal channel conditions for quality data transmissions;
3) be agile in deployment and adaptable to the typical deployment scenarios.

In rural and urban areas, we deploy high-performance UAVs for the DUCP, leveraging their high mobility and NLoS communication advantages. Suitable fixed-wing UAVs will be selected due to their large payloads, further enhancing the UxV network's computational and communication capacities.

For aquatic settings, high-performance USVs are ideal. They communicate on the surface and use acoustic channels for underwater communication. Their significant payload capabilities are invaluable in resource-limited aquatic environments, and they offer more deployment flexibility than traditional buoys. They can also cooperate with UAVs to relay data to remote base stations. The high manoeuvrability of both makes their collaboration exceptionally adaptive and flexible.

Data plane: comprises UxVs with sensors and networking tools. They execute tasks, while playing a vital role in collecting and transmitting data throughout the entire architecture. Upon receiving actions from the DUCP, they act immediately, capturing videos, adjusting network variables, and sensing their surroundings. Meanwhile, these UxVs consistently update their status and forward the gathered data, ensuring real-time perception and allowing for optimal decision-making.

The DUCP, armed with task requirements, decision models, and controlling algorithms, offers real-time global network perception and joint optimization. Its agility allows high adaptability to changing network conditions. By leveraging decision models from the application plane, DUCP makes joint decisions for both network and task management, ensuring optimal performance and task quality.

DUCP's intelligent coordination ensures a consistent global network view across UxV controllers. This coordination adaptively refines the deployment strategy of DUCP while dynamically updating strategies to fit various environments and tasks with SDN's programmability.

As the core of our architecture, DUCP's unique control traffic offload mechanism and added computational resources guarantee optimal resource allocation. Control traffic can be offloaded to DUCP, preserving vital resources for task-specific data transmission. The architecture supports various tasks, from sensing to emergency communication, all autonomously. This autonomy distinguishes SDUxVN from other networks, like non-terrestrial networks and space-air-ground networks, which require expert intervention, particularly for emergency communications. In our design, the emphasis is on 'unmanned'. From control to networking, this architecture implements complete autonomy. Users only define the task, and the system operates independently, ensuring optimal UxV control and network management.

In challenging applications, DUCP mitigates the drawbacks of lacking infrastructure, allowing swift UxV deployment. The control plane's global view further refines deployment strategies for faster adaptation. In areas with adequate infrastructure where UxV traffic can vary dramatically, SDUxVN's DUCP responds swiftly with adaptive strategies. Unlike traditional controllers, our architecture's inter-plane communication benefits from UxVs' enhanced mobility and channel conditions. DUCP can adapt dynamically to existing infrastructures, optimizing network loads during peak times and enhancing network connectivity during off-peak hours.

IV. CASE STUDY

A. Simulation Setting

We conducted simulation experiments to validate the benefits of SDUxVN and DUCP in UxV network management across urban (Tiexi District, Shenyang City, China), rural post-disaster wilderness, and aquatic scenarios. The goal is to showcase the architecture's consistent robust performance and its ability to handle UxV network heterogeneity and dynamics.

Using our simulator [1], scenarios were created where controllers collect control information from the data plane for SDUxVN's real-time decisions. UxVs in the data plane move randomly, sending control packets to the control plane every second. If a UxV is out of a controller's range, it seeks a nearby vehicle for packet relay. In urban and rural scenarios, high-capacity UAVs serve as DUCP, with UAVs and UGVs in the data plane. UGVs move on the ground, adhering to streets in urban areas, while UAVs have unrestricted 3D movement. For aquatic settings, USVs act as DUCP, with USVs and UUVs in the data plane. USVs move on water surfaces, and UUVs navigate 3D underwater spaces. Given UxVs' varied capacities, their transmission power and speed differ, highlighting network heterogeneity. Air-to-ground and air-to-air links use a probabilistic path loss model [14], while underwater channels adopt an acoustic model [15]. The control plane has either four or nine controllers. Parameter settings are detailed in Table I.

TABLE I
SIMULATION PARAMETERS

Simulation parameter name	**Value**
Simulation Area	$5193m \times 5863m \times 300m$ $1500m \times 1500m \times 500m$ $(Aquatic)$
Number of vehicles	$200/400/600/800/1000$
UGV velocity	$0-60km/h$
UAV velocity	$0-30km/h$
USV and UUV velocity	$1-5knots$
Vehicle transmission range	$500m$
Data packet size	$1024Bytes$
Standards	IEEE 802.11p / Acoustic
SNR receiver threshold	$-10dB$
Bandwidth	$10MHz$ / $25KHz$(Acoustic)
Scenario	Urban / Rural / Aquatic
UGV maximum power	$300mW$
UAV maximum power	$150mW$
USV maximum power	$500mW$
UUV maximum power	$100mW$
Queuing Model	Jackson Network

In the first two scenarios, we evaluate three control plane placement strategies:

Distributed ground control plane (DGCP): Uses controllers on RSUs, evenly distributed and stationary.

Distributed unmanned control plane (DUCP): Employs UAV-mounted controllers with placements similar to DGCP.

Adaptive distributed unmanned control plane (ADUCP): Utilizes UAV-mounted controllers, with positions adjusted based on UxV data plane positions using the Kmeans++ algorithm.

For the aquatic scenario, we assess two strategies:

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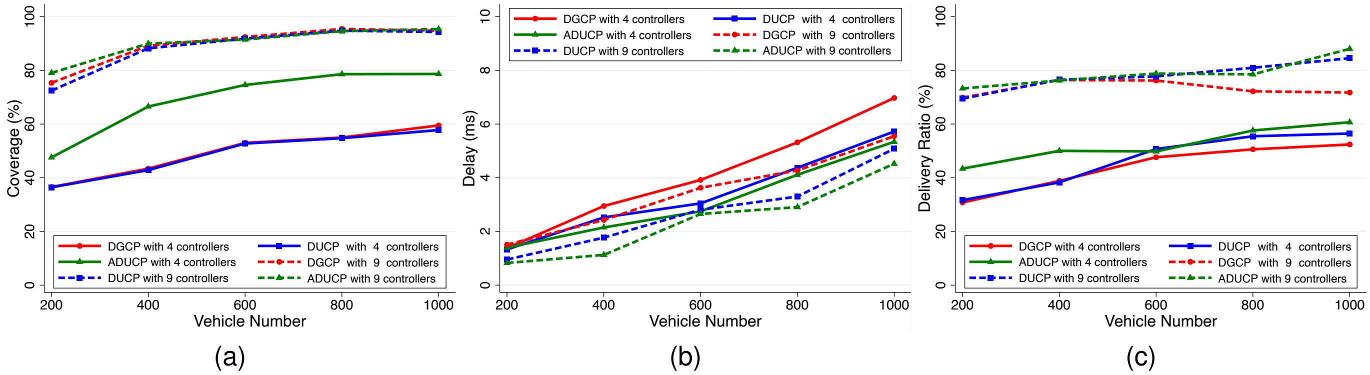
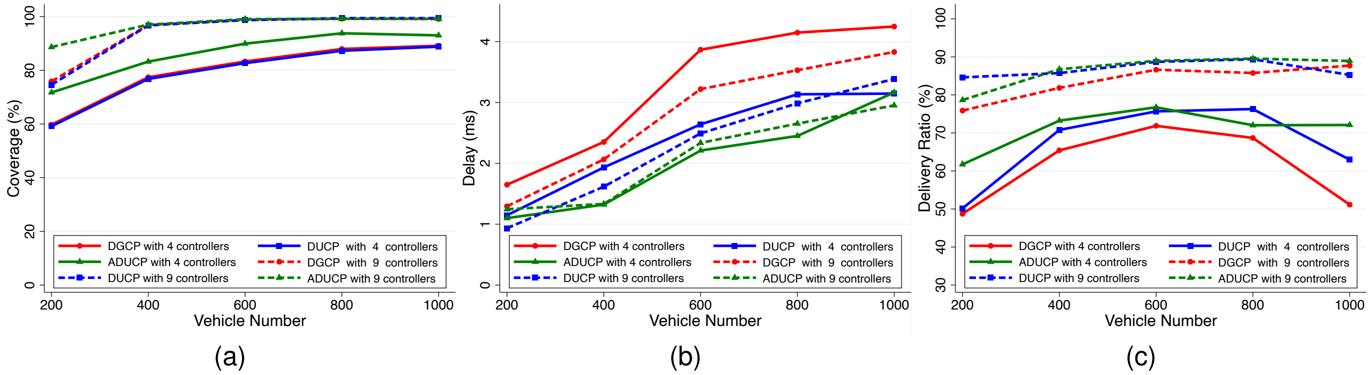
[1] https://github.com/a824899245/SDVN-platform



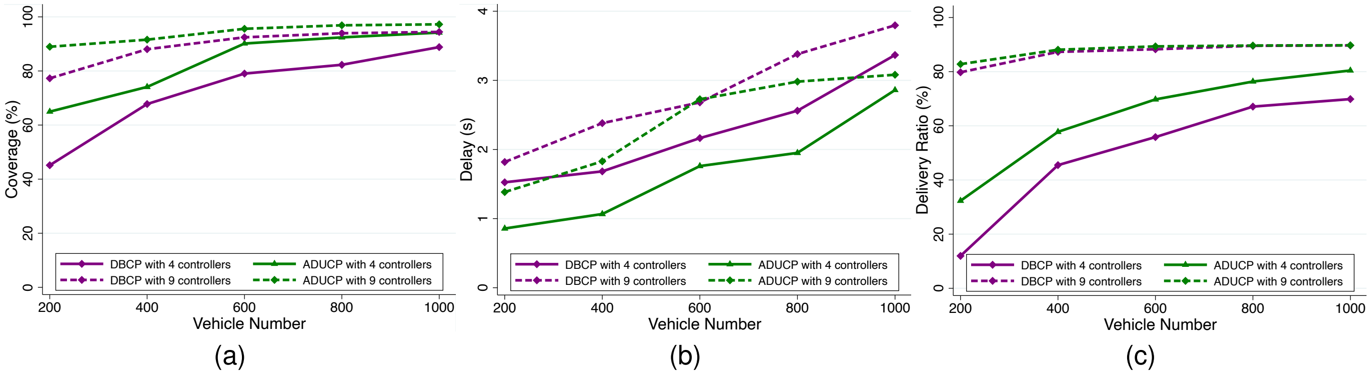
(a) (b) (c)

Fig. 3. Three metrics versus vehicle number in the urban scenario. (a) Coverage (%), (b) Delay (ms), (c) Delivery ratio (%).



(a) (b) (c)

Fig. 4. Three metrics versus vehicle number in the rural scenario. (a) Coverage (%), (b) Delay (ms), (c) Delivery ratio (%).



(a) (b) (c)

Fig. 5. Three metrics versus vehicle number in the aquaric scenario. (a) Coverage (%), (b) Delay (ms), (c) Delivery ratio (%).

Distributed Buoy control plane (DBCP): Uses controllers on fixed buoys, evenly distributed.

Adaptive distributed unmanned control plane (ADUCP): Employs USV-mounted controllers, with positions adjusted based on UUV positions using the Kmeans++ algorithm.

UxVs are associated to the closest controller based on the last beacon exchange. We use the Deep Deterministic Policy Gradient (DDPG), a deep reinforcement learning model, for transmission power control. In the DDPG setup, the state comprises the UxVs' current positions, UAV controllers, maximum UxV transmission power, and association. The action is the transmission power, with the average Signal-to-Interference-plus-Noise Ratio (SINR) serving as the reward. All placement policies utilise the specifically trained DDPG models to determine the transmission power.

In our design, the DUCP acts as the agent, with the other experiment conditions being the environment. During learning, the agent determines the next action based on the current state. These actions guide the data plane uplinking data to the DUCP. The agent then retrieves the SINR for each transmission, using it as the current learning reward.

After the training converges, the DUCP assesses the network state at each slot, deciding on network optimization actions and relaying them to corresponding UxVs. These UxVs then adjust data transmissions and deployment to optimise network performance.

The following three metrics are evaluated:

Coverage: This metric denotes the ratio of vehicles that are connected to the control plane either through direct or multi-hop connections.

Delivery delay: This refers to the average end-to-end delay from the moment a packet is created to the moment it is delivered to the destination.

Packet delivery ratio: This is calculated as the ratio of successfully delivered control packets to the total generated control packets.

B. Results and Analysis

In the first experiment of the urban scenario, depicted in Fig. 3(a), DGCP and DUCP exhibited suboptimal performance ($36.55\% - 59.50\%$ and $36.44\% - 57.78\%$ from 200 vehicles to 1000 vehicles) in coverage with four controllers. However, ADUCP, leveraging its mobility, achieved the best coverage ($47.58\% - 78.66\%$ with four controllers, $79.06\% - 95.39\%$ with nine controllers). This result underscores the necessity of an effective deployment strategy based on the current network status, even when employing DUCP.

The implementation of association and power control strategies, coupled with the advantageous aerial-terrestrial channel conditions offered by DUCP, substantively enhances QoS-related metrics. As we can see in Fig. 3(b) and 3(c), DUCP can bring improvement in communication quality in all scenarios: higher delivery ratios ($31.66\% - 56.48\%$ with four controllers, $69.46\% - 84.74\%$ with nine controllers), and lower delay ($1.33ms - 5.54ms$ with four controllers, $0.95ms - 5.08ms$ with nine controllers). With its better coverage, ADUCP achieves better and more stable delivery ratios ($43.39\% - 60.67\%$ with four controllers, $73.24\% - 88.01\%$ with nine controllers), and performs superiorly to DUCP in terms of delay ($1.39ms - 5.34ms$ with four controllers, $0.82ms - 4.52ms$ with nine controllers). These results convincingly demonstrate the improvements brought to UxV network communication by DUCP and the subsequent enhancements in transmission quality when suitable controller placement strategies are integrated.

In the second experiment, all control plane placement strategies demonstrated improved performance across all metrics compared to the urban scenario, attributing this to the better channel conditions in the rural scenario. ADUCP emerged as the most effective option for managing the UxV network under nearly all settings, recording less delay ($1.65ms - 3.35ms$ with four controllers, $1.43ms - 3.59ms$ with nine controllers) and better delivery ratio ($61.74\% - 72.08\%$ with four controllers, $78.41\% - 88.92\%$ with nine controllers), as depicted in Fig. 4(b) and 4(c). When the number of vehicles reaches 1000, both DGCP and DUCP experience a decline in the delivery ratio metrics with four controllers (51.14% and 62.97%), while ADUCP offering stable network services to a majority of UxVs in the data plane (72.32%). This further establishes that ADUCP, along with its suitable placement strategies, enhances scalability and adaptability to network heterogeneity.

In the experiments involving aquatic scenarios, the performance of all control plane placement strategies under the coverage metric was similar to other scenarios ($64.95\% - 94.18\%$ with four controllers, $88.95\% - 97.23\%$ with nine controllers) due to the reduced simulation area. However, due to its unique channel model, performance on all QoS-related metrics (delay, delivery ratio) shows a decline. Nevertheless, the advantages of ADUCP for aquatic networks were still evident. Compared with the commonly used fixed buoy control plane, the mobile USV evidently offers superior performance in terms of delivery ratio and delay ($32.31\% - 80.43\%$, $0.86s - 2.86s$ with four controllers, $82.78\% - 89.75\%$, $1.38s - 3.08s$ with nine controllers). When contrasted with the first two scenarios, there remains a significant gap in the delay metric. The bottleneck for such big gaps is not in the network architecture but is constrained by physical layer technologies. This will be a crucial direction for our future research.

As validated by our experiments, DUCP and ADUCP offer substantial benefits for managing UxV networks in all scenarios, whether in infrastructure-dense or sparse situations. ADUCP has better coverage of the data plane with fewer controllers and lower deployment costs. Furthermore, when combined with an effective power control and user association strategy, ADUCP can be further enhanced to provide superior network services, ensuring wider coverage, reduced latency, and higher delivery ratio.

V. CHALLENGES AND OPPORTUNITIES

SDUxVN, as a high-performance autonomous network architecture, holds the potential to enhance the network and task execution performance of UxVs. Unlike traditional SDN, it presents unique challenges and complexities arising from UxVs' mobility, heterogeneity, and autonomy, necessitating timely and thorough research for practical applications.

A. Open Issues in SDUxVN

1) Multi-objective Optimisation on Network performance and Task Completion: The deployment scenarios for UxV networks are typically task-driven. This means that UxVs need to execute a series of actions to achieve different task objectives, such as monitoring, data collection, remote control, These actions encompass deployments, landings, hovering, data transmission, etc. Consequently, changes in the UxV's position and the network topology occur, significantly influencing network performance, as transmission distance plays a crucial role in communication quality. SDUxVN, through its management strategies on UxV trajectories, DUCP deployment, and network optimisation, must adjust related strategies jointly, considering both task completion quality and network performance as objectives.

SDN introduces flexibility and programmability to UxV control and network management. Furthermore, it can access sufficient computational resources from the application plane and real-time global network status from the data plane. Given these prerequisites, a robust multi-objective optimization algorithm capable of managing high-dimensional coupled variables emerges as the core solution to this problem.

2) Cross-layer Resource Optimisation for the Heterogeneous Network: The SDUxVN architecture introduces innovations across layers for optimal resource allocation in UxV networks, including autonomous multi-access, resilient routing, and real-time resource adjustments. In this architecture, different layers exhibit a high degree of interdependency. The modification on one single layer necessitate coordination across multiple layers. For example, relocating the DUCP can influence metrics like throughput and delay. Thus, achieving optimal resource allocation demands cross-layer coordination.

Heterogeneity, including different physical layer technologies and transmission capacities, should also be considered jointly. Many management strategies assume uniform capacities for all vehicles, which can lead to selecting less capable vehicles, potentially reducing communication quality. Harmonising the two aspects of heterogeneity is crucial for the UxV network management.

B. Open Issues in DUCP

1) Ubiquitous and Adaptive DUCP Deployment: The deployment strategy of DUCP will have a great impact on the working efficiency and network performance. Inappropriate deployment of DUCP will induce control traffic loss and deteriorated network performance. Given varying tasks, involved vehicles, available resources, and environments, designing adaptive deployment strategies for DUCP is the fundamental issue for a high-performance network. UxVs in the data plane follow specific movement trajectories when performing tasks such as search and rescue. DUCP must dynamically adjust its position, altitude, and topology according to the deployment of the data plane. Concurrently, DUCP deployment must also maintain the stability of control information transmission on CCH to ensure the QoS across the entire UxV network.

2) Intelligent Synchronisation and Coordination among Multi-UAV Controllers: The information synchronisation and coordination among distributed control planes is vital for SDN to guarantee consistency of network view and operation. It is bounded to be a nontrivial task since all controllers must make the same decision independently based on limited communication resource on CCH. The straightforward approach would be direct exchange of synchronisation messages among controllers, which is difficult due to the dynamic nature of the UxV network and high transmission load. Distributed learning, as a trending learning architecture, can provide invaluable assistance in this context. With a robust distributed transfer learning model, controllers can autonomously extract reusable knowledge to synchronise and decide when and how resources should be used in synchronisation.

VI. CONCLUSIONS

This paper outlines the potential trends and challenges that arise from the rapid development of the UxV network. To design a ubiquitous and autonomous UxV network architecture for stable cooperation in multi-UxV systems, we propose the SDUxVN architecture and corresponding DUCP. Further, we present a detailed discussion supported by corresponding simulation experiments, as a starting point to demonstrate the advantages of this architecture. We also explore the challenges and corresponding opportunities in our envision of SDUxVN and DUCP. In summary, SDUxVN and DUCP will offer exciting new opportunities for UxV network management, facilitating the ubiquitous deployment of UxV systems and efficient cooperation among a massive number of UxVs.

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