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Review

Unmanned Autonomous Intelligent System in 6G Non-Terrestrial Network

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Abstract: Non-terrestrial network (NTN) is a trending topic in the field of communication, as it shows promise for scenarios in which terrestrial infrastructure is unavailable. Unmanned autonomous intelligent systems (UAISs), as a physical form of artificial intelligence (AI), have gained significant attention from academia and industry. These systems have various applications in autonomous driving, logistics, area surveillance, and medical services. With the rapid evolution of information and communication technology (ICT), 5G and beyond-5G communication have enabled numerous intelligent applications through the comprehensive utilization of advanced NTN communication technology and artificial intelligence. To meet the demands of complex tasks in remote or communication-challenged areas, there is an urgent need for reliable, ultra-low latency communication networks to enable unmanned autonomous intelligent systems for applications such as localization, navigation, perception, decision-making, and motion planning. However, in remote areas, reliable communication coverage is not available, which poses a significant challenge for intelligent systems applications. The rapid development of non-terrestrial networks (NTNs) communication has shed new light on intelligent applications that require ubiquitous network connections in space, air, ground, and sea. However, challenges arise when using NTN technology in unmanned autonomous intelligent systems. Our research examines the advancements and obstacles in academic research and industry applications of NTN technology concerning UAIS, which is supported by unmanned aerial vehicles (UAV) and other low-altitude platforms. Nevertheless, edge computing and cloud computing are crucial for unmanned autonomous intelligent systems, which also necessitate distributed computation architectures for computationally intensive tasks and massive data offloading. This paper presents a comprehensive analysis of the opportunities and challenges of unmanned autonomous intelligent systems in UAV NTN, along with NTN-based unmanned autonomous intelligent systems and their applications. A field trial case study is presented to demonstrate the application of NTN in UAIS.

Keywords: non-terrestrial network; unmanned autonomous intelligent systems; 5G/6G network; unmanned aerial vehicle (UAV); mobile edge computing (MEC); cloud computing; distributed computing; artificial intelligent (AI)

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1. Introduction

The concept of non-terrestrial networks (NTNs) that are capable of providing wireless communication coverage in complex and non-ideal environments is a popular topic, especially for conditions where a reliable means of wireless connections for time-critical tasks is urgently needed. Previously, wireless cellular communication services were designed to offer coverage to human users with smart phones or other portable devices; however, recently, machine-type communication is also in significant demand, such as with internet of things (IoT) devices and machine-type communication (MTC) devices. The demand for communication services further drives network evolution and expansion into non-traditional areas such as industry applications, remote surgery, AR/VR and so on [1–6]. Unmanned autonomous Intelligent system (UAISs), such as self-driving vehicles, multi-robot systems, unmanned aerial vehicles, and unmanned ground vehicles have experienced increasing demand in terms of ubiquitous wireless connection requirements to fulfill tasks such as perception, localization, navigation, collaboration with nearby agents in a multi-agent system, and the offload of computation-intensive tasks to back-end or resource-abundant facilities [7].

In recent years, the development of unmanned aerial vehicles (UAVs) and satellites has brought about extensive opportunities for NTN applications with low cost and deployment flexibillity. Furthermore, 4G/5G infrastructural deployments on the ground have steadily increased across the globe, with numerous cellular base stations around cites and along highways. However, in remote or unreachable regions, such as deserts and mountainous areas, ground cellular network coverage is not available due to high cost or environment limitations [8–12]. In addition, the use of NTNs is beneficial when ground networks are overloaded during special events like sports games or due to the sudden failure of base station infrastructure due to natural disasters in specific areas. Therefore, in the scenarios mentioned above, non-terrestrial networks (NTNs) are a promising solution for providing communication coverage in areas that are unable to be covered via traditional ground infrastructure. In some cases, especially in conditions such as power failures caused by disasters or a sudden increase in the number of users, the need for ubiquitous network access can only be met using non-terrestrial communication methods such as unmanned aerial vehicles (UAVs) or satellites [13–18].

Owing to the extensive applications of UAIS in conjunction with 6G NTN communications, ranging from autonomous self-driving vehicles, unmanned aerial vehicles to multi-purpose robots for precise agriculture and disaster rescue scenarios. Efforts have been made in research toward 6G and beyond NTN technology to provide connectivity and intelligence. Therefore, a comprehensive and in-depth review of 6G NTN technology from the perspective of unmanned autonomous intelligent systems is crucial for undertaking further research in this domain. Numerous publications concerning the challenges and opportunities of UAIS in NTNs have been presented. However, the present work mostly emphasizes NTN communication itself or applications in a particular domain, such as intelligent transportation systems, autonomous vehicles and unmanned aerial vehicles. A systematic review of the existing work related to various UAIS in 6G NTN is required. The purpose of the paper is to provide a systematic review of the current trends and state of the art of UAIS in the context of 5G/6G NTN communication. We will discuss the role of UAVs in NTN communications and provide a comprehensive summary of various UAIS applications in UAV NTN, including unmanned ground vehicles (UGVs), unmanned aerial vehicles (UAVs), and connected and automated vehicles (CAVs).

The rest of the paper is organized as follows. Firstly, in Section 2, the current status and development of NTN are analyzed. In Section 3, a comprehensive analysis of the role of UAVs in NTNs is illustrated. In addition, the challenges and research opportunities of UAVs in NTNs are thoroughly analyzed. In Section 4, we discuss UAV NTN-enabled application of UAIS in UGVs, CAVs and unmanned maritime applications. Open research topics in this particular domain that need further discussion are proposed. In Section 5, a field trial case study is presented to demonstrate the application of UAIS in NTN communications. Section 6 is the conclusion of this paper.

2. Non-Terrestrial Networks in 5G/6G

In this section, we review the general characteristics and evolution process of 5G and beyond-5G non-terrestrial networks.

2.1. The Evolution of Non-Terrestrial Networks

Non-terrestrial networks (NTNs) were first mentioned in the use case of fifth-generation (5G) communication standards, and the concept has drawn extensive attention from research scientists for the grand vision of space–air–ground–sea integrated networks (SAGSINs). The 5G ecosystems have included satellite communications as an important means of producing NTNs. The initial research of NTNs started right after the Third-Generation Partnership Project (3GPP) organization announced its first release of the 5G communication standards containing the NTN concept. Since then, a variety of research papers have been published concerning NTN technology. The evolution of 3GPP NTN standards of 5G communication is illustrated in Figure 1. In release 15 of 3GPP 5G standards, TR 38.811 was introduced as "NR Research Supporting Non-Ground Networks", which illustrated the application scenarios of NTN communications and pointed out the unresolved problems that may have a great influence on the application of NTNs. The next evolutionary step of 5G NTN was finished with release-16 of 3GPP, which put forward solutions for supporting NTNs, in which satellite communications were listed as a priority for NTN applications. In release 17 of the 3GPP 5G standards, LEO (low Earth orbit) and GEO (geostationary transfer orbit) satellite applications were emphasized, while high-altitude platform station (HAPS) applications were also taken into account. Finally, 3GPP froze the release 17 standards at its 96th plenary session. A practical architecture of a NTN communication network is shown in Figure 2, which can be divided into space, air, and ground layers. The top part of the NTN network architecture is the space network, which is usually made up of a number of inter-connected satellites, while the middle part of the network is composed of HAPS (high-altitude platform stations), LAPS (low-altitude platform stations), and air-to-ground networks utilizing UAVs and airships. The ground part is the conventional terrestrial network [18–23].

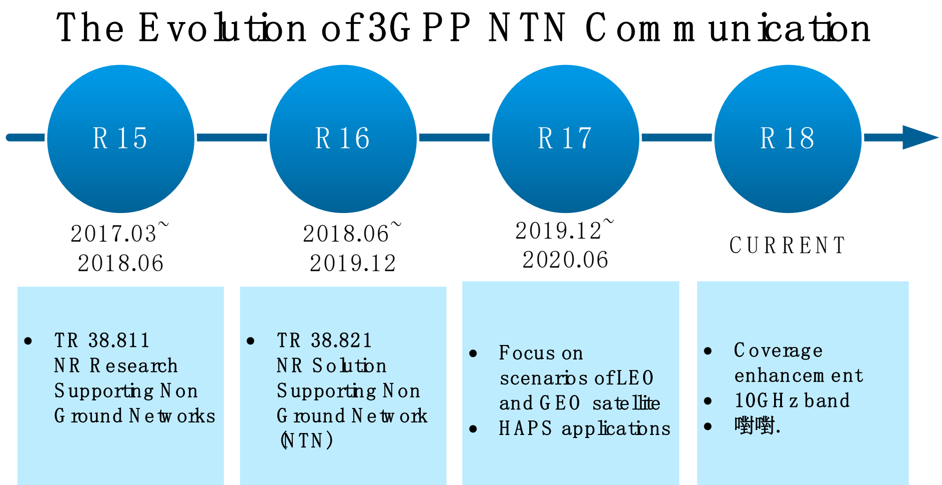

Figure 1. The evolution of 3GPP NTN standards.

NTN technology represents new prospects in wireless communication applications such as satellite communications and low-altitude communication utilizing unmanned aerial vehicles and airships for internet of things devices or autonomous systems. UAVs and airships acting as radio access network infrastructure are capable of providing lower-latency services than satellites, which is crucial for time-critical applications. NTN communication expands the application of 5G communication from terrestrial communication to space/air communication. The transformative advancement in communication technology promoted the shift from fifth-generation communication to sixth-generation, which highlights the vision of ubiquitous networks and space–air–ground coverage [24–27].

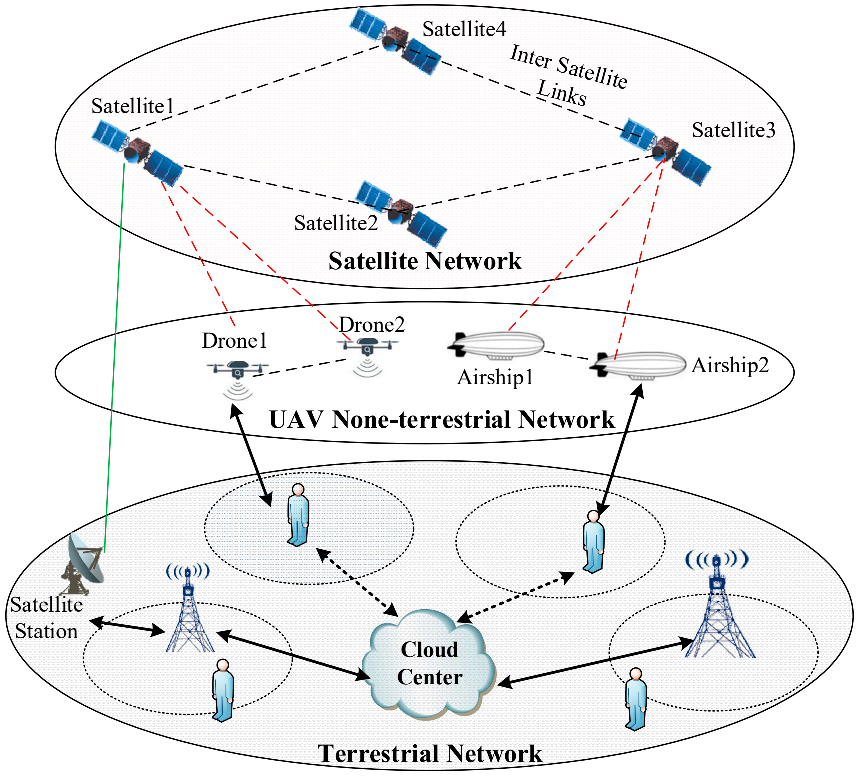

Figure 2. The illustration of 3GPP NTN network architecture [22].

2.2. The Role of UAVs in NTNs

In sixth-generation (6G) communication networks, space–air–ground–sea integrated networks will satisfy communication demands around the globe, whether in deserts, mountains, or islands. In contrast to common network users like cell phones and other portable devices, UAIS have faced great challenges in terms of network connectivity, throughput, and reliability since platforms such as robots, self-driving cars, or unmanned boats might be unevenly distributed in remote areas and in high-speed maneuvers, which demand flexible and ubiquitous network coverage. In this case, few existing ground network infrastructure is available for the urgent demand for a task-critical and time-sensitive network using conventional terrestrial methods. Considering this challenge, it is beneficial to employ non-terrestrial infrastructures, including satellites and unmanned aerial vehicles (UAVs), HAPS, and LAPS, for wide-area communication coverage for UAIS.

In particular, NTN is a flexible means to provide on-demand coverage for machines and adapt to the nature of the uneven distribution of UAIS in practical fields; thus, the architecture of the NTN should be designed within a cell-free architecture [24]. In addition, driven by the requirements of time-sensitive missions of UAIS, massive data generated from UAIS must be processed as quickly as possible. Therefore, non-terrestrial communications-based multi-access edge computing is essential and requires the help of UAVs to build high-speed links between UAIS users and UAVs [25–27]. Depending on the role of UAIS platforms in NTNs, the architecture of NTNs can be defined as follows:

(1) UAV platform as an NTN user: In this use case, UAV platforms are utilized as network users in an NTN architecture, which is a primary form of UAIS in NTNs. For instance, UAVs and satellites can be considered as NTN users serviced by other platforms.
(2) UAV platform as an NTN relay: In this use case, UAVs are considered mobile relays for scenarios in which direct links cannot be achieved due to geographic obstacles or extended communication ranges.
(3) UAV platform as an NTN base station: In this case, UAVs are equipped with base stations for connectivity coverage. Sometimes, UAV platforms with abundant payload capabilities are further utilized for multi-edge computing.

Unmanned aerial vehicles (UAVs) are ideal operation platforms for flying base stations, relays, access points and other non-terrestrial communication infrastructure, which fully leverage the advantages of the high maneuverability and flexibility of the platform. Therefore, UAVs are preferred when performing network coverage missions in dangerous or communication-congested areas where reliable communication does not exist or has been corrupted. In the past, UAV-based systems have been designed and used for military operations and disaster rescue applications. Such applications include surveillance, inspection, personnel searches, and dangerous situation alerts. Nowadays, UAVs have evolved into platforms for non-terrestrial network coverage for ubiquitous network applications supporting the communication demand of users in various applications. With the constant innovations in the domain of mobile communications, UAV NTN communication coverage for UAIS on the ground, in the air or in the ocean is drawing much attention. Advancements in NTN communications hold potential driving factors for supporting UAIS with low-latency, high-bandwidth and multi-access edge computing in complex environments [28,29].

3. UAV-Assisted Non-Terrestrial Networks

Unmanned aerial vehicles (UAV) have been widely utilized in military operations, disaster relief tasks, and wild-area monitoring for perception, surveillance, material delivery and communication purposes due to their high mobility, flexibility, and relatively low-cost characteristics. In 6G scenarios, the role of UAVs is irreplaceable, serving as aerial network nodes providing ubiquitous network connections in the lower-altitude airspace between terrestrial networks and satellite networks. For the future vision of 6G networks that have extended coverage on the ground, in the air, and in space, realizing a space–air–ground integrated communication network by means of utilizing UAVs and other low-altitude aerial platforms is of the utmost significance.

In 6G NTN scenarios, UAVs are capable of performing various communication tasks, which include serving as base stations, communication relays, and user equipment (Figure 3. When mounted with communication equipment, UAVs can be employed as flying base stations or communication relays to maintain communication services to ground users in case of crippled or congested ground base stations. In contrast, from the recent literature, UAVs can also be considered as aerial nodes, connecting to ground and non-terrestrial networks, referred to as cellular-connected UAVs, which have drawn more and more attention from research scientists. Cellular-connected UAVs are promising in a number of applications such as surveillance, autonomous driving, parcel delivery, post-disaster rescue, and communication enhancement. Previous works have placed great emphasis on UAV-assisted cellular communications. However, in recent studies, UAVs connected to communication infrastructure serving as cellular-connected platforms are also drawing attention.

In addition, in scenarios that require wide-area communication coverage, a swarm of interconnected UAVs through Flying Ad Hoc Networks (FANETs) are utilized to integrate with terrestrial infrastructure to extend network coverage, as has been studied by a variety of researchers. UAV communications have a variety of advantages, ranging from line-of-sight links to dynamic deployment, which is promising in terms of enabling space–air–ground–sea connections. However, a variety of common problems still need in-depth investigation to support all kinds of UAV applications concerning NTN communications. In UAV NTN communication, place deployment, flight trajectory optimization, and resource allocation in mobile edge computing are hot topics under profound discussion.

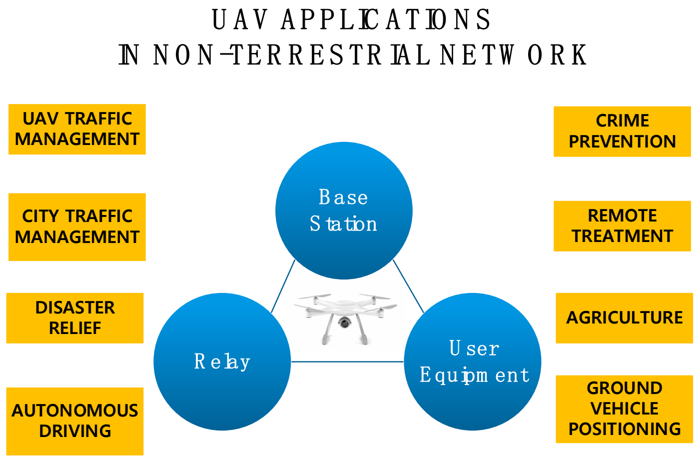

Figure 3. Illustration of UAV applications in NTNs.

3.1. UAV Path Planning and Control in NTN Communications

Integrating unmanned aerial vehicles (UAVs) as flying base stations, relays or user equipment is expected to be an important topic in the context of beyond-5G/6G non-terrestrial networks. Multiple operational aspects of UAV-assisted 5G/6G networks have been investigated in various studies, which include UAV place of deployment, ground interference cancellation, antenna orientation optimization and cell partition [30,31].

From the perspective of unmanned autonomous intelligent systems, the motion control of UAV platforms in communication scenarios is a multi-disciplinary problem that requires knowledge relating to autonomous control, wireless spectrum environment perception, cellular user communication quality awareness, and so on. Thus, trajectory optimization in NTNs has been widely studied. In recent years, UAV trajectory optimization and path planning have drawn extensive attention from research scientists due to the inter-discipline knowledge and sophisticated models involved in the trajectory planning of UAV communication. Efficient trajectory optimization or path planning is conducive to maneuvering according to UAV communication performance and ground user requirements. Although path planning is a basic problem in UAV control, the synergy between UAV path planning and the performance of the wireless communication systems poses new challenges that are not covered by traditional UAV navigation and trajectory optimization paradigms. Deep reinforcement learning (DRL)-based algorithms and other non-convex optimization methods are utilized to solve dynamic path planning and control problems [32–46].

(1) **UAV Path Planning for Flying Base Stations Scenario**

The deployment position and motion trajectory of UAVs have an impact on the ground communication coverage and capacity when UAVs are used as flying base stations. In general, UAV deployment and trajectory optimization are challenging problems due to the extensive number of parameters involved, such as UAV air-to-ground channel model, inter-UAV interference avoidance, UAV power consumption, motion constraints, and so on.

To address the challenges caused by joint optimization for UAV motion control and wireless communication in NTN communications [32], investigated a distributed framework based on DRL to control and optimize UAV base stations when considering ground users' fairness. This work considered flight time as the main constraint to optimize overall throughput during a fixed flight time. In order to deal with real-time path planning problems for UAV base stations, a variety of research works have been published [33–35]. In traditional UAV control schemes, ground operating stations have limited knowledge of ground users' status, and thus real-time online trajectory planning is challenging to perform. Moreover [32], considered UAV maneuver curvature for received signal strength optimization in a multi-base station scenario. This problem is challenging since the UAVs are maneuvering at high speed, making it impossible to optimize the coverage of SNR in advance when using terrestrial base stations. The authors of this work emphasized the fairness of service of users since the numbers and coverage of the UAV base station are quite limited in practical applications. By constructing it as described, the user fairness using received signal strength, a multi-agent-based control scheme was implemented for distributed path optimization. Moreover [33], proposed a flow level model for a UAV base station network and a DRL-optimizing method for network traffic balancing based on a realistic UAV radio model. The contribution of the study is the first introduction of a traffic flow model to describe UAV base station communication performance, which was later used as input for DRL-based trajectory control.

Furthermore [34], demonstrated a circle trajectory setup for multiple-ground-user coverage. The trajectory problem was converted to a Euclidean k supplier location problem that minimizes the maximum distance of any ground users to the nearby UAV base station facility. Moreover [35], designed a deep Q learning network and greedy algorithm-based UAV trajectory optimization paradigm for unevenly distributed ground users. In [36], the authors emphasized a multi-target coverage dynamic trajectory optimization scheme utilizing a knowledge-incorporated approach considering inter-UAV connectivity maintenance. The study showed promising applications in both UAV base station communication coverage and monitoring coverage tasks.

(2) **UAV Path Planning for Aerial Mobile Relay**

Recently, UAVs have been considered popular platforms for communication relay purposes due to their deployment flexibility and maneuverability. In contrast to satellite communications, UAV relay systems hold the potential advantages of high-volume and low-latency communication through line-of-sight links. A UAV-aided mobile relay is utilized to transmit information from ground users to terrestrial or non-terrestrial base stations, which is of great importance in scenarios such as disaster management for extending communication ranges over mountainous terrain. The placement and trajectory of UAV mobile relays have a significant influence on communication distance and the quality of service for wireless users.

Typical application scenarios involving UAV relays include movable robotic platforms, wireless sensor nodes and internet of things devices. In such cases, the transiting power of the ground nodes is relatively low compared to UAV relays, indicating that deployment location and flight trajectory have a major impact on the relay link, thus requiring the careful optimization of the motion parameters. From the literature [37–43], investigated trajectory optimization methods concerning the condition of the ground user.

Furthermore [37], proposed an iterative solution for joint optimization of UAV trajectory, power consumption, and time-slot assignment, which is modeled as a non-convex problem. The joint optimization of trajectory and power is the foundation of communication resource allocation. Therefore [38], considered a path planning and power consumption optimization paradigm for a space–air–ground integrated relay network in a non-orthogonal multiple access scheme. The results of the proposed paradigm outperformed that of a fixed circle trajectory. Moreover [39], investigated a novel solution for trajectory design and transmitting power minimization for a UAV-assisted relay system. The study considered a cognitive relay scenario in which the trajectory was designed according to the speed and altitude constraints of the relay system.

In [40], an efficient algorithm was designed for a UAV relay's three-dimensional trajectory optimization in order to achieve a higher-throughput network in the case of the interference of ground users of the same frequency band. The trajectory optimization was conducted considering the influence of intentional jamming. Similarly [41], studied a multi-UAV trajectory optimization framework in which UAVs acted as both aerial base stations and wireless relays. The study is of great significance for large-scale communication coverage scenarios in which UAV base stations and UAV relays collaborate to complete the network coverage task.

(3) **UAV Path Planning for Cellular-Connected UAV User Equipment**

Except for the fact that UAVs have been successfully utilized as flying base stations and relay nodes, recently, UAVs performing practical tasks tend to be connected to ground cellular base stations as user equipment, which brings about the issue of optimal path finding considering connectivity constraints and ground interference [42,43].

A study [44] proposed an analytical model to demonstrate the influence of trajectory and altitude on the quality of service in relation to UAV cellular users. From the study, we can see that with the UAV moving from the center to the edge area of the base station coverage, the minimum constrained altitude decreases. The study indicated that the motion parameters should be well considered for better UAV user equipment quality of service. Moreover [45], investigated an iterative method for trajectory planning to minimize the time required to fulfill the task and overall power consumption for UAV aerial users. The proposed method considered a minimum task fulfillment time under the signal-to-noise ratio requirements. Furthermore [46], proposed an online trajectory-optimizing scheme for minimal power consumption based on an outage probability map reconstructed from sparse sampling. The contribution of this work was the introduction of an outage probability map through which a trajectory planning method considering power consumption dramatically reduced the outage of connection between the UAV user and the base stations. However, the reconstruction of the outage probability map database cannot be constructed in advance and are energy-consuming, which are major drawbacks of the method. However, in [47], a DRL-based UAV user optimization method was utilized considering the impact factors of UAV power, flight trajectory, antenna pattern, interference from other ground base stations, and other environmental factors. The optimization scheme was converted to a Markov decision process, which can be solved via the deep Q-learning method. Researchers [48] considered a cellular-connected UAV for synthetic aperture radar sensing tasks using the successive convex approximation method. Integrating communication and sensing is a major aspect of future 6G technology, while the proposed trajectory optimization method considered the sensing resolution requirements and converted the non-convex problem to a convex one using the successive convex approximation (SCA) method. Researchers [49] proposed a dynamic programming algorithm to optimize trajectories of cellular-connected UAVs for communication enhancement with considerations in terms of flight altitude. The trajectory planning process considers flight path and altitude at the same time since the altitude of the UAV affects the backhaul performance of the cellular-connected UAV to a great extent.

The authors in [50] reported a path-planning method for task-critical missions in which connectivity maintenance is of utmost importance. The signal map of the ground base station was constructed in advance to support the DRL-based algorithm for the optimal UAV path. Similarly [51], reported a UAV curvature design for UAV users with a fixed start and final locations. This work was designated to minimize the flight duration time of the cellular-connected UAV, which has a constrained outage duration upper bound during flight. Researchers [52] emphasized the role of path planning in the effort of interference cancellation. The joint optimization method applying trajectory adjustment and interference cancellation distinguished the UAV users from the ground users to achieve better performance.

The existing works on UAV trajectory/path planning in NTN communication is summarized in Table 1. Apart from DRL-based UAV joint trajectory and communication optimization methods, other non-convex optimization paradigms have been utilized to solve the problem. Researchers in [53] investigated a coordinate multi-point transmission method-based mobility control method considering both the displacement and vertical movement of cellular-connected UAVs. In addition, multi-UAV path planning is also considered a major issue in UAV NTN communication. A study in [54] considered a mixed-integer linear program scheme for multi-UAV base station motion optimization. Furthermore, reference [55] proposed an iterative single-head attention approach for path planning and communication optimization for a group of UAVs through distributed control.

Moreover, reference [56] introduced a method for maintaining the freshness of information received by base stations while optimizing the UAV trajectory at the same time in a wireless sensor information collection scenario.

Table 1. Summary of existing work on UAV trajectory/path planning in NTN communication.

Literature	Topics	Contributions	Year
[32]	UAV Base Staion	Investigated a distributed framework based on DRL to control and optimize UAV base stations considering ground users' fairness	2021
[33]	UAV Base Staion	Proposed a flow-level model for UAV base station network and a DRL-optimizing method for network traffic balancing based on the realistic UAV radio model.	2019
[34]	UAV Base Staion	Demonstrated a circle trajectory setup for multiple ground uses coverage.	2020
[35]	UAV Base Staion	Designed a deep Q learning network and greedy algorithm-based UAV trajectory optimization paradigm for unevenly distributed ground users.	2021
[36]	UAV Base Staion	Emphasized a multi-target coverage dynamic trajectory optimization scheme utilizing knowledge-incorporated approach	2021
[37]	UAV Relay	Proposed an iterative solution for joint optimization of UAV trajectory, power consumption and time-slot assignment.	2019
[38]	UAV Relay	Considered a path planning and power consumption optimization paradigm for a space-air-ground integrated relay network in a non-orthogonal multiple access scheme	2018
[39]	UAV Relay	Investigated a novel solution for trajectory design and transmitting power minimization for a UAV-assisted relay	2021
[40]	UAV Relay	The paper proposed an efficient algorithm designed for UAV relay's three-dimensional trajectory optimization in order to achieve higher throughput.	2021
[41]	UAV Relay	The paper studied a multi-UAV trajectory optimization framework in which UAVs acted as both aerial base stations and wireless relays.	2022
[44]	UAV User Equipment	The paper proposed an analytical model to demonstrate the influence of trajectory and altitude on the quality of service in UAV aerial cellular users	2020
[45]	UAV User Equipment	The paper investigated an iterative method for trajectory planning to minimize the time to fulfill the task and overall power consumption for UAV aerial users	2021
[46]	UAV User Equipment	The paper proposed an online trajectory optimizing scheme for minimal power consumption based on outage probability map reconstructed from sparse sampling.	2023

Table 1. *Cont.*

Literature	Topics	Contributions	Year
[47]	UAV User Equipment	The paper considered a DRL-based UAV user optimization method considering impact factors of UAV power, flight trajectory, and antenna pattern.	2022
[48]	UAV User Equipment	The paper considered a cellular-connected UAV for synthetic aperture radar sensing tasks using successive convex approximation.	2022
[49]	UAV User Equipment	The paper proposed a dynamic programming algorithm to optimize trajectories of cellular-connected UAVs for communication enhancement	2020
[50]	UAV User Equipment	The paper reported a path-planning method for task-critical missions in which connectivity maintenance is of utmost importance.	2022
[51]	UAV User Equipment	This work reported a UAV curvature design for UAV users with fixed start and final locations.	2019
[52]	UAV User Equipment	This study emphasized the role of path planning in the effort of interference cancellation.	2022

Recently, reconfigurable intelligent reflection surfaces (IRSs) and UAVs have been combined together to achieve communication coverage enhancement in challenging environments [57]. In [58], the trajectory planning of the UAV with IRS onboard is addressed using the DRL method. Ref. [59] proposed UAV optimal path planning for maximizing the reflecting rate considering the UAV motion limit by means of a heuristic method.

3.2. UAV Mobile Edge Computing in NTN Communications

In real-world applications, users such as IoT devices have limited batteries and relatively low computation resources, posing challenges for IoT devices in terms of executing computation-intensive applications. UAVs with onboard computation capabilities are promising in terms of supporting mobile edge computing (MEC) to solve the problem. In UAV-aided non-terrestrial networks, IoT devices with limited commutation resources can offload their computation-intensive tasks to a UAV with abundant computation resources at the edge of the network, resulting in reduced energy consumption and communication overhead to back-end cloud servers. Compared to terrestrial stationary base stations acting as MEC infrastructure, UAV-aided MEC has the potential to serve the users on demand, which also poses challenges to these systems. However, owing to the limited payload capacity and energy, UAVs have limited capabilities when serving as MEC servers. Therefore, MEC systems supported by UAVs have urgent requirements in terms of motion control and energy consumption optimization.

Many existing studies utilized a centralized strategy to optimize the offloading process, which is inefficient in multi-UAV/user scenarios. To resolve the computing resource allocation problem in UAV-aided MEC, the authors of [60] proposed a decentralized multi-agent reinforcement learning-based method to minimize computation latency for a number of users. To minimize power consumption in a multi-UAV MEC scenario [61], proposed a multi-layer strategy utilizing UAV deployment location optimization and offloading task prediction based on a long short-term memory mechanism.

Considering the complicated UAV-aided MEC system, the optimization of UAV motion control, energy consumption, and computation resources cannot be fulfilled using conventional convex methods, which is challenging. For trajectory design of UAV MEC systems [62], proposed a DRL paradigm to control UAV trajectory and maximize the system's stability at the same time. In a multiple-input single-output (MISO) UAV MEC scenario, the authors of [63] studied the energy-saving strategy considering beam-forming and UAV trajectory.

Owing to the line-of-sight connections between UAV MEC platforms and ground users, the data offloading task can be achieved at high speed. However, this also brings about security issues since the line-of-sight links are prone to attacks by other platforms. Nevertheless, the data links usually work in a broadcast manner, which might be used by eavesdroppers to intercept the data.

For secure MEC processes [64], considered UAV placement and RF power to comprehensively solve the maximum security capacity problem. Non-orthogonal multiple access (NOMA)-based UAV MEC have advantages in channel efficiency, thus enabling more users in scenarios of limited resources. To resolve the secure communication of the NOMA-based UAV MEC problem [65] proposed an optimizing paradigm for maximizing secure capacity through jointly optimizing UAV trajectory and resource allocation. Furthermore, the authors of [66] proposed a security enhancement method emphasizing an airborne eavesdropper scenario in NOMA UAV MEC systems.

3.3. Unmanned Aerial Vehicles Application in NTNs

With the assistance of NTN communication, UAVs are capable of supporting a variety of tasks, including material delivery, air traffic control, and disaster relief operations.

(1) **Delivery**

Reference [67] proposed a vaccine delivery scheme called SanJeeVni, which utilized blockchain and 6G communication in vaccine delivery to ensure trusted logistics within strict delivery time constraints. The scheme proposes a UAV swarm network in which the delivery trajectory design and motion control of a UAV swarm are achieved through intelligent edge computing. With 6G-empowered eRLLC (Extremely Reliable and Low-Latency Communications) technology, the flight time of UAVs was strictly limited, ensuring timely delivery of vaccines to users in need. Furthermore [68], introduced a blockchain-based secure drone delivery system for medical equipment logistic missions using ground-based station networks.

(2) **UAV traffic management**

With the development of 5G/B5G communication technology, UAV traffic management (UTM) has recently garnered significant attention from research scientists [69–71]. This is due to the dramatic evolution of UAV applications such as parcel delivery, precise agriculture, and survey mapping, which usually operate beyond the visual line of sight mode. As a result, efficient and secure traffic management is urgently required. In the future, UAV traffic will become even denser and busier, making UTM essential for coordinating multiple autonomous UAVs beyond the visual line of sight (BVLoS) in complex UAV traffic environments. The UTM requires an efficient communication backup to handle complex airborne communication in environments with heavy air traffic, as opposed to relying on existing cellular networks for terrestrial communication. Researchers in [70] introduced a 6G-enabled UTM paradigm in a highly dense and urban air traffic scenario emphasizing non-terrestrial communications, including aerial and satellite communication.

(3) **Disaster Relief and Management:**

Communication reconstruction is crucial in disaster relief scenarios because road destruction, power interruptions, and the paralysis of terrestrial base stations will isolate the affected area, leading to an "information island" phenomenon. Unmanned aerial vehicles are extensively utilized in disaster scenarios to offer communication coverage for ground user equipment (UE), including affected residents and first responder rescue teams, when ground network infrastructure is disconnected from the power supply or destroyed by sudden disaster events [72–75]. UAVs employed as aerial communication nodes are essential for disaster management, facilitating communication recovery and information exchange. In reference [72], a proposal for stochastic geometry-based UAV-assisted wireless communication in disaster scenarios was presented, considering partial ground failure. Furthermore [73], investigated an aerial communication scheme utilizing multi-UAVs for multi-purpose disaster relief operations, with a focus on device-to-device communication and energy efficiency. Moreover [74], examined the fairness of service provision in a post-disaster millimeter-wave communication system. Researchers [75] highlighted the topological challenges in UAV-assisted communication during post-disaster rescue operations.

Figure 4 illustrates a real-world senario of wildfire detection and early warning in mountainous regoins. A group of unmanned helicopters equipped with 5G base stations and mesh communication payloads is deployed to provide network coverage for firefighters in mountainous areas. Images containing fire point information, collected via optical and thermal sensors on board the UAVs, are then transmitted to the ground command truck via a UAV 5G network. After image processing and recognition, fire point locations are distributed to individual firefighters via the non-terrestrial 5G network and displayed on their helmet-mounted AR devices or cellphones. UAV-assisted networks have facilitated a variety of applications, such as post-disaster area assessment, personnel search, and information collection [76–78].

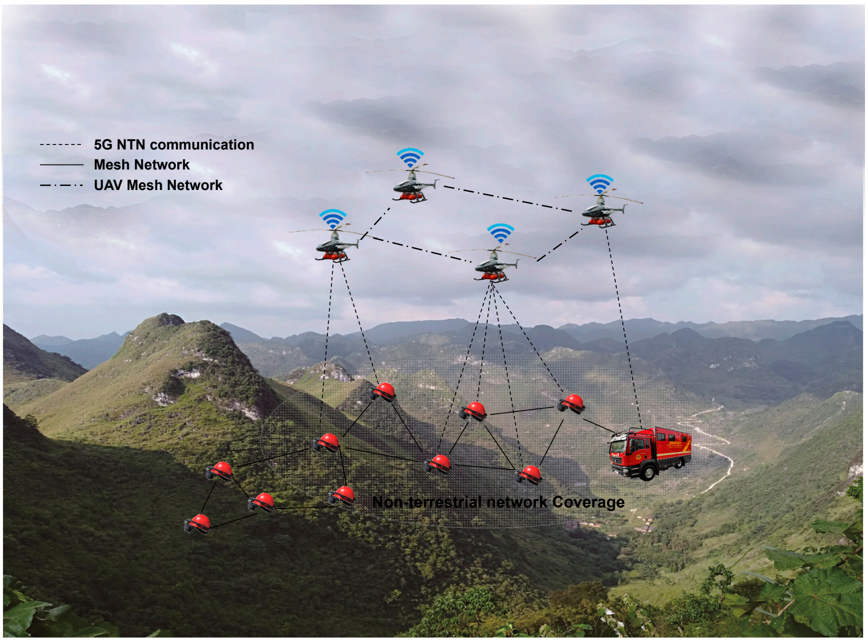

Figure 4. Illustration of UAV fire detection architecture.

With the emergence of new technologies in the domain of UAVs, UAV-assisted non-terrestrial networks demonstrate significant flexibility and mobility. However, there is still a need for further study on issues such as UAV-to-UAV or UAV-to-satellite collaboration communication, device-to-device communication, and UAV optical communication [79].

4. Application of UAV-Aided Non-Terrestrial Networks in UAIS

An unmanned autonomous intelligent system (UAIS) [80–88] is defined as a mechatronic system capable of fulfilling universal tasks without or with limited human involvement. Typical UAIS include connected autonomous vehicles [89], swarm robot systems [90], unmanned aerial vehicles [91], unmanned ground vehicles, unmanned maritime vehicles [92], smart manufacturering systems [93–96], agricultural robots [97–101], service robots, and medical robots [102–104]. These systems are increasingly dependent on the comprehensive application of artificial intelligence, data science, ubiquitous networks, and distributed computing to fulfill complex tasks and adapt to ever-changing environments. Compared to traditional rule-based automation systems, UAIS offers advanced capabilities such as autonomy, intelligence, and collaboration. It supports general-purpose tasks such as perception, autonomous decision making, reasoning, and collaboration [105,106].

One of the key factors that facilitate the UAIS ecosystem is the development of low-latency, ultra-reliable, and high-volume wireless communication, supporting a growing range of unmanned ground vehicles, self-driving cars, maritime unmanned vehicles, mobile robotics, and more. UAIS has demonstrated a growing need for ubiquitous network connectivity to facilitate the exchange of information and the offloading of computational tasks to edge computing devices or cloud servers. In some instances, network connections may be unavailable due to inadequate communication infrastructure or communication congestion. The emergence of the NTN communication concept sheds new light on UAIS by providing ubiquitous network connection and mobile edge computing. On the other hand, UAIS can also be utilized to support NTN communication in a variety of ways. UAVs are typical UAIS platforms used to support NTN communication, while UGVs, USVs, and CAVs are all promising in performing communication coverage tasks in 6G NTN.

The rise of artificial intelligence (AI) has played an important role in providing UAIS with advanced autonomy and decision-making capabilities. AI is utilized to enable systems that can learn from experience and adapt to diverse and complex environments, which is vital to applications of UAIS. With the rapid advancement of software and hardware, various deep learning/reinforcement learning algorithms along with computing platforms offer sufficient computation resources to UAIS applications. In addition, the emergence of multi-access edge computing and distributed computation offloading has greatly boosted the development of AI-based applications, especially UAIS, which can fulfill specific tasks, such as object detection/reorganization, decision-making, and autonomous navigation. While in practical applications of UAIS, massive computation resources and low latency connections are not always available and have many limitations in real-world scenarios [107–110]. Typical communication requirements of the UAIS in NTN is illustrated in Table 1, which pose significant challenges for NTN communication.

With the assistance of artificial intelligence, UAIS can become an organic part of the future intelligent NTN communication. Advancements in UAIS are increasingly emphasizing decentralization, ubiquitous connectivity, and collective intelligence, which are vital for supporting an elastic and self-adaptive network architecture. The new trend of UAIS development has put forward higher requirements for autonomous capabilities, as illustrated in the Table 2, which will support the ubiquitous coverage of wide areas.

Table 2. Typical communication requirement of UAIS in NTN.

Unmanned Autonomous Intelligent System	Application	Communication Requirements
UGV	Command and Control	Ultra-low latency
	Perception	High data rate
	Data Offloading	High data rate Low latency
UAV	Flight Control	Ultra-low latency
	UAV Traffic Management	Low latency
	Object Delivery	Low latency
	Mobile Edge Computing	Low latency High data rate
others	Monitor and Survey	High data rate
	Reconnaissance	High data rate
	Swarm Coordination	Low latency
	Formation Control	Low latency

The various applications of UAIS in NTN communication scenarios will be discussed in detail in the following part of the paper. From the perspective of 6G communication, network coverage will extend beyond current boundaries and cover multi-dimensions: on the ground, in the air, space, underwater, and underground. Thus, an integrated communication coverage method utilizing both terrestrial and non-terrestrial infrastructure will be beneficial for UAIS in terms of quality of service (QoS), resilience, and sustainability of the networks. Unmanned aerial vehicles (UAVs) and satellites will play vital roles in enabling UAIS applications.

4.1. Unmanned Ground Vehicle in UAV-Aided NTN Communication

Unmanned ground vehicles (UGVs) are popular in the research of unmanned autonomous intelligent systems and have a variety of applications, including military operations, anti-terrorism, smart agriculture, logistics, delivery, and mining. UGVs are capable of fulfilling complex tasks such as environment perception, data collection, data transmission, decision making, motion control. However, UGVs are usually compact and have limited computation resources which can restrict their ability to fulfill massive computation tasks due to the size and energy limit of the platform. Therefore, the support of extensive computation resources is crucial for the application of UGVs. Sometimes, UGVs are designed for applications away from cities where there is no network infrastructure. In case of power interruptions caused by natural disasters, UGV communications supported by terrestrial network infrastructures may break down or result in a loss of control, leading to the failure of time-sensitive tasks. To address these challenges and equip UGVs with sufficient communication capabilities for control instructions, real-time data exchange, and computation tasks offloading. Non-terrestrial network platforms, such as airships and unmanned aerial vehicles, can complement the blind sectors of terrestrial base stations to extend network coverage in remote areas.

4.1.1. Communication Requirements of Unmanned Ground Vehicle in NTN Communication

Currently, there are three primary modes of operating the UGVs: remote-controlled, semi-autonomous, and fully autonomous. The first mode is further divided into visual line of sight (VLOS) and beyond visual-line-of-sight (BVLOS) control, respectively. Although UGVs in the VLOS mode can be controlled using direct wireless links, and semi-autonomous UGVs require higher bandwidth to transmit real-time images and perceptual information. For semi-autonomous UGVs capable of situation awareness, object detection, and navigation, the communication requirements include the following [111]:

- Communication for uploading work scenarios and updating the knowledge base;
- Remote communication for offloading the local processing tasks of the UGV to the edge server or cloud server;
- Command and control (C2) of UGV, including the transmission of first-person view (FPV) video information and real-time control instructions to the UGV operator or supervisor.

The communication peak service requirement of UGV above is further calculated using methods derived from the 3GPP standardization documents [112], as illustrated in Table 3 below.

As shown in Table 3 above, command and control, offloading processing tasks, and video streaming of the FPV use case require a network with very low delay and high reliability, which is challenging to achieve using conventional communication methods. In satellite communication, propagation delay is relatively high due to the communication distance between the satellite and the ground user, which poses signifiant challenges to UGV application in NTN scenarios. In the meantime, UAV and LAPS platforms tend to be much more flexible when deployed in challenging terrains, adapting to ground users to provide ultra-reliable and low-latency communication links for time-sensitive UGV tasks.

Table 3. Peak service requirements for UGV use cases in NTN communication.

Use Case	Parameters				
	Exchange Intensity	Exchange Type	Data Rate	Max. Delay	Reliability
Command and control	high	stream	28 kbps	20 ms	99.9%
Video streaming of FPV	high	stream	120 Mbps	40 ms	99.99%
Offloading processing tasks	high	burst	1.1 Gbps	2 ms	99.9%

4.1.2. NTN Communication in Unmanned Ground Vehicle Control

In the future, 6G network ultra-reliable and low-latency communication (URLLC) will be essential for UGVs, which are indispensable for real-time applications such as smart agriculture [113–115], intelligent industry, and various other applications. To accurately control the UGV, tactile feedback and interactive virtual reality (VR) can stimulate the human brain, aiding users in adjusting operation time, pressure, and gestures. These factors are crucial for remote operations. The tactile feedback and interactivity of VR applications require low-latency and broadband networks. URLLC is necessary to deliver extremely low latency for real-time feedback for operators, based on short-length packets. To address this challenge, ref. [113] proposed an approach that utilized UAVs as forward relays to transmit short URLLC control packets between a control station and multiple ground mobile vehicles in smart agriculture scenarios. Researchers [116] proposed a radar-aided millimeter-wave communication method for UAV-UGV cooperation in a disaster scenario where ground network infrastructure is available. In addition, the UAV–UGV cooperation networks were further investigated in terms of bandwidth allocation [117], data collection [118], navigation [118–120], and other related aspectes.

When UGVs are utilized for surveillance or disaster relief missions in less populated areas lacking terrestrial infrastructure, UAV-aided networks are valuable for controlling UGVs and directing them to the target area. For high-speed maneuvering platforms, achiveing high-speed communication presents a challenging problem. Researchers in [116] proposed a mm-wave radar-aided communication scheme for UAV-UGV cooperation. The worst-case QoS maintain method for UGVs was developed using QoS-awareness power distribution. However, in reference [121], a software-defined radio method was utilized to extend the communication range between UAV and UGV using OFDM. The study enhanced UAV UGV communication by introducing a new waveform based on OFDM to increase the likelihood of line-of-sight links.

Researchers of [122] considered the target perception and tracking problem utilizing a UAV-UGV group. The study involved a heterogeneous communication scenario in which consensus control was achieved in the case of changing topology. Furthermore, the authors of [123] introduced a novel communication protocol for the collaboration of air–ground platforms. The cooperative communication scheme allowed inter-communication between UAVs and UGVs through a client–server architecture. In [124], a joint path optimization scheme was proposed to enable the optimal recharging location of the UAVs for wireless communication. Ref. [125] considered a path optimal problem of one UAV and multiple UGVs wherein the UAVs provide communication coverage and share information with the UGVs. A sequence strategy was utilized to determine the access sequence of the UGVs.

UGVs are also promising platforms for extending network coverage to expand service availability and provide network connectivity for other ground users. In reference [126], a graph-based optimization method for virtual resource allocation of slices was proposed in ground vehicle-assisted networks. A system modeling procedure inspired by graph theory was used to model networks and the energy cost of vehicle-assisted B5G networks. The rapid advancements in autonomous technologies have also promoted the development of vehicular networks. Vehicular Ad hoc Network (VANET) shows promise for future intelligent transportation systems. Vehicle-to-vehicle communication is utilized to collect and share information. For UGV applications supported by NTN, a variety of security issues remain challenging [127–129].

4.2. Connected and Automated Vehicles in UAV-Aided NTNs

Connected and automated vehicles (CAVs) and autonomous driving are popular subject in the realm of smart cities, where there have been significant advancements in both academic and industrial settings in the past few years. CAVs are systems that are equipped with advanced perception, cognition, planning, and control capabilities, allowing them to operate autonomously by sensing traffic via onboard sensors and exchanging information with roadside unit devices. Autonomous driving is a popular field of research that builds the foundation of intelligent transportation system (ITS). In complex road traffic and challenging weather conditions, the collection of multiple pieces of information from various sensors may be ambiguous, resulting in a failure to accurately acquire environmental information. Therefore, it is increasingly important for CAVs to communicate with other vehicles, pedestrians, and roadside facilities in order to establish a more intelligent and safe transportation system [130,131].

4.2.1. Vehicle-to-Everything Communication via NTN

The autonomous driving capabilities of CAVs rely on information from both onboard sensors and external connections. Cameras, Global Positioning Systems (GPS), and Light Detection and Ranging (LIDAR) are typical sensors onboard CAVs. The external connections of vehicles include Vehicle-to-Infrastructure (V2I), Vehicle-to-Vehicle (V2V), Vehicle-to-Cloud (V2C), and finally Vehicle-to-Everything (V2X), which are established via communication methods like cellular or direct communication [130–133]. The future development of 6G technology holds promise for enabling the V2X prospects through an advanced communication network that is flexible, high-speed, ultra-reliable, and has low-latency for information interactions between CAVs and other infrastructure. This will be achieved through the comprehensive integration of terrestrial and non-terrestrial networks. It is believed that 6G communication technology will better satisfy the requirements of the next-generation V2X in remote and uncovered areas via satellite and UAV communication. Furthermore, in the case of cloud/edge-based real-time tasks for CAVs, a reliable and low-latency connection is of extreme importance. With NTN communication technology, the data transmitting and offloading between CAVs and external devices can achieve an ultra-low latency of less than 1 ms [134–136].

To enable autonomous driving in intelligent transportation systems, CAVs must maintain connections with various vehicles and roadside units (RSUs) in a real-time manner. This connection is vital for accurate traffic perception, automatic navigation, and collision avoidance of CAVs. With the advancement of cellular-vehicle-to-everything (C-V2X) technology, the utilization of V2X present high demands for extensive network coverage, offloading computation-intensive task, low latency, and stringent reliability. This presents new challenges for communication systems. Due to the high deployment cost and strict location selection requirements, conventional terrestrial base stations cannot guarantee wide area coverage of V2X applications. Therefore, UAV-assisted V2X was introduced as a non-terrestrial means with flexibility and ease of deployment to support CAV wireless communication.

Non-terrestrial networks tend to be an effective means for V2X communications. UAV non-terrestrial networks show promise for estabilishing V2X connections scenarios where signal blockage occurs due to buildings and challenging terrains. However, UAV-based V2X communication still faces underlying challenges, including ultra-low latency communication, limited battery life, high volume communication, and low access efficiency. A variety of studies have been published on non-terrestrial UAV V2X communication for CAVs, addressing issues such as low-latency vehicle-to-vehicle communication, energy consumption optimization, and channel prediction. Researchers [137] analyzed rotary-wing and fixed-wing unmanned aerial vehicles as CAV network access points, using millimeter-wave technology for high-speed connectivity to CAVs (Figure 5). Based on the study results, UAV HAPS systems outperformed low Earth orbit satellites (LEOs) in terms of lower latency. To address the latency issues of CAV V2X communication [138], explored a scheme involving UAV-assisted deployment of roadside units, with a focus on minimizing CAV latency while also optimizing CAV energy consumption. To address the requirements of vehicular platooning or formation control issues, a study in [139] evaluated a UAV-V2X network in the context of UAV unstable motion. The evaluation involved the use of association probability for a vehicular-to-UAV link, while vehicular-to-vehicular links were modeled using the Poisson point process. In V2X connections, data dissemination is essential for sharing information between CAVs. In reference [140], a novel dynamic path-planning method for a UAV base station was employed to optimize the data dissemination process by minimizing communication overhead. This method aimed to enable efficient data caching in V2X networks.

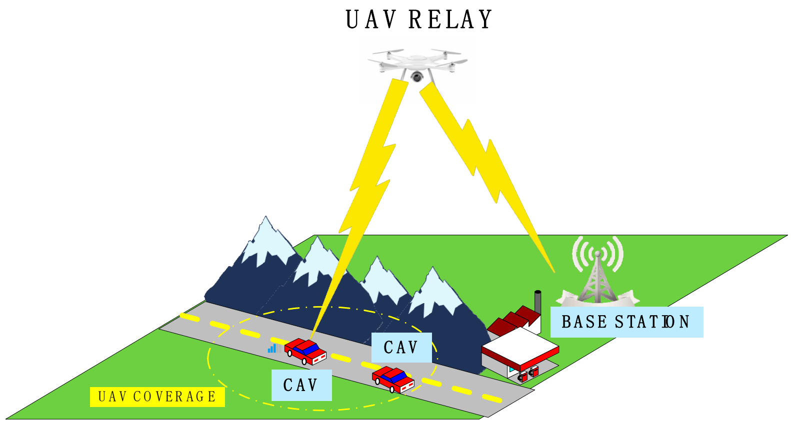

Figure 5. The illustration of UAV-assisted V2X scenario.

4.2.2. 6G NTN-Enabled CAV Capabilities

The autonomous driving of CAVs is a major application of 6G NTN communication and will facilitate fully automated CAV applications in a variety of ways. In the future, with ubiquitous 6G communication coverage, CAVs will be capable of interconnecting with nearby vehicles, RSUs, pedestrians, and other elements. This capability is essential for achiveing fully automated self-driving and enhancing the safety of intelligent transportation systems. NTN-enabled V2X communication holds potential in various scenarios for fully automated CAVs, including vehicle localization, navigation, environment perception, platoon formation, and real-time control. For example, UAVs can function as flying base stations or RSUs, capable of sending accident broadcasts and early warnings to vehicles on highways through reliable line-of-sight links, thereby enhancing road safety.

From the perspective of upcoming 6G technology, edge computing plays an increasingly important role in the context of CAVs. Due to limited computing and storage resources, external resources are necessary to provide data storage and computing offloading services [141]. In dynamic road intersections, vehicular edge computing systems need to be much more flexible, intelligent, and adaptive than stationary systems [142]. To tackle this problem, in [141], the potential for implementing vehicular edge computing using NTN was explored. This approach would allow connected autonomous vehicles to transfer large computing tasks to UAVs or HAPS. In the past few years, UAV and HAPS platforms have been widely used to enhance the communication and computation capabilities of ground vehicles in applications such as traffic monitoring in complex environments. The authors in [143] proposed a dynamic topology optimization method for transmitting traffic monitoring information using UAVs. In [144], a systematic approach was implemented to optimize the computation offloading for traffic data collected by UAVs. The aforementioned approach dealt with the the issues of UAV computation task offloading utilizing a game-based model.

The autonomous navigation of CAVs is based on precise position and orientation information relative to high-definition maps, which is crucial to autonomous driving. The emergence of NTN V2X communication technology presents new opportunities for improved vehicular localization and navigation. In remote areas such as mountains and deserts, terrestrial cellular networks are not always available. Therefore non-terrestrial networks, such as UAVs and satellites, can be utilized to achieve the localization of CAVs [145–147]. Researchers in [145] proposed a relative localization method for CAVs using UAVs. This method involves making time delay measurements with multiple nodes to determine the relative position of CAVs. Furthermore [146], addressed the optimal UAV swarm configuration problem in vehicle localization They utilized reinforcement deep Q-learning was utilized to optimize localization based on signal strength.

Platoon formation coordination is widely discussed in applications of CAVs to improve control robustness and reduce fuel consumption. In a UAV V2X scenario, the dynamic motion of vehicles and changing road situation brings about great challenges for continuous vehicle-to-vehicle communication. In [148], UAV platforms were utilized as mobile communication relays to assist with inter-vehicle communication. To avoid the failure of multi-user detection caused by obstacles, the power allocation in non-orthogonal multiple access (NOMA) system was optimized with a low signal overhead strategy. Taking into account the maneuverability of CAVs [149,150], used comprehensive joint methods considering mobility, communication, and energy consumption problems to establish V2X connections for vehicle platoon tasks.

Table 4. Summary of previous work concerning CAVs in 6G NTN communication.

Literature	Topics	Contributions	Limitations
[143]	Traffic monitoring in complex environments	Utilizing blockchain-based UAV/HAPS communication to assist traffic perception data transmission	The architecture of internet of drones need further study.
[144]	Traffic monitoring in complex environments	Offloading/sharing decision making using a sequential game method	The edge computing architecture was not mentioned in detail
[145]	Localization	Utilizing UAV-based method to assist localization	The moving vehicles and terrain blockage severely impact UAV–vehicle communication
[146]	Localization	Achieve vehicle localization with signal strength with a swarm of UAVs	The interference and uncertainty of wireless channel hindered the reliability of communication.
[147]	Vehicle platoon control	A sliding mode controller was proposed based on the observed vehicle states for longitudinal cooperation of CAVs	Inter vehicle information was not discussed.
[148]	Vehicle platoon	Power allocation of uplink NOMA in vehicle platoon	The platoon method needs in-depth discussion
[149]	Vehicle platoon	Joint resource optimization and mobility control of UAV-aided vehicles platoon	The role of vehicle platoon in MEC require in-depth study
[150]	Vehicle platoon	Joint Communication and Computation Resource Scheduling of a UAV-Assisted Mobile Edge Computing System for Platooning Vehicles	The wireless power transmission mechanism of vehicles require investigation.
[151]	Vehicle platoon	An energy consumption minimization-based resource management paradigm was proposed	The platoon method of the ground vehicle was not covered

The existing literature on NTN V2X applications is summarized in Table 4, along with the challenges and unresolved issues of the mentioned works. As shown in Table 4, the use of NTN-based V2X technology can enhance tasks such as localization, perception and object detection through NTN communication. CAVs can maintain reliable and high-throughput connections through NTN V2X communications in areas with insufficient terrestrial infrastructure for real-time traffic information interactions. This significantly enhances the safety and reliability of fully automated transportation systems. Based on data from V2X communications, CAVs are capable of controlling themselves in a safer manner, thereby avoiding accidents and road damage that occur beyond the line of sight of onboard sensors. However, the growing complexity of V2X communication systems also raise concers about security problems, particularly in UAV air-to-ground channels. With the advancement of CAVs and NTN communication technologies, the realization of an autonomous transportation system will be established in both cities and remote areas. With the support of UAVs, the overall safety of intelligent transportation systems will be enhaced through early warning and air-to-ground cooperation [152–156].

Intelligent Reflection Surfaces (IRS) are an emerging field that has drawn much attention from researchers in the 6G mobile communications field. In addition to the successful implementation of UAVs in V2X connections, IRS shows promise as a communication relay in V2X scenarios. It can be deployed as an aerial IRS with UAVs or other aerial vehicles serving as payload platforms. Researchers [153] proposed a case study of a UAV-assisted network for CAVs V2X network utilizing random scattering by an IRS. Researchers [157] proposed a 5G-based IRS communication for secure V2X to enable applications such as advanced self-driving and extended sensing in the case of a UAV–V2X scenario. Open issues, such as the placement of UAV–IRS platforms, optimization of beamforming and IRS supported edge computing, are promising directions for further investigation [156,157].

4.3. Unmanned Maritime Vehicles in UAV-Aided NTN Communication

Maritime network traffic has grown rapidly in the past few years due to the significant expansion development of manned and unmanned platforms utilized for national defense, scientific research, oceanic surveys, and international shipments [158]. In the new era of 6G communications, the vision of ubiquitous wireless coverage has brought new insight into the full-dimensional network architecture that integrates space, air, ground, and sea networks. Compared to terrestrial networks, maritime communication is far from satisfactory and requires thorough investigation.

Non-terrestrial networks have created new opportunities for maritime applications, particularly unmanned maritime vehicles, which have critical communication needs due to the challenges of deploying terrestrial communication infrastructure in ocean areas. Unmanned Maritime Vehicles enconpass unmanned surface vehicles (USVs) and unmanned underwater vehicles (UUVs) [158–161]. An unmanned surface vessel is a promising platform capable of performing hazardous and labor-intensive tasks typically carried out by manned vessels. With advanced control, perception, and communication systems, Unmanned Maritime Vehicles (UMVs) are capable of performing various military and civil tasks, such as search and rescue, reconnaissance, transportation, waste clearance, and resource survey. With the advancements in integrating high-capacity and ultra-reliable non-terrestrial network technologies, ubiquitous maritime connectivity can be achieved to support UMV applications.

4.3.1. Unmanned Surface Vessels in NTN Communication

Currently, maritime communication heavily relies on satellite and radio communications which are unable to meet the growing demand for broadband communication in maritime unmanned autonomous intelligent systems. However, satellite communication cannot support real-time maritime applications because of high propagation delays. On the other hand, radio communications, such as very high-frequency (VHF) communication, typically only support voice services, with limited bandwidth for high data rate communication.

(1) **UAV-Aided Maritime Communication for USVs**

Thanks to the successful application of UAV air-to-ground non terrestrial network, the maritime communication have seen possibilities of adopting UAVs for oceanic communication. The ultra-low latency feature of UAV-assisted networks will shed new light on the maritime UAIS applications such as control and coordination of multiple USVs. However, there is a long way to go for applying UAVs to maritime communication since the limitation of endurance, power consumption and all weather capabilities of UAVs. The UAVs usually are not designed for the salty and misty environments and long time of operation over the sea may cause mechanical and electrical failures. Secondly, the energy of UAVs is quite limited which prevent it from operating for long time network coverage for typical long endurance maritime applications. In addition, in extreme weather conditions, such as tornadoes and storms, very few kinds of UAVs are capable of normal operation. Thus, various obstacles appear in the path of UAV maritime communication applications. However, maritime radio channels are complicated and are seriously affected by adverse weather conditions, tide movements, ocean current activity and other factors, causing problems in air-to-sea channel modeling in oceanic communication [162].

Topology optimization: Due to the continuous maneuvering of oceanic nodes such as USVs, the design and maintenance of their topology is also challenging. Topology design is a fundamental issue that needs to be addressed, given the constantly changing nature of the maritime environment. In [163], an integrated communication framework for terrestrial, sea and HAP is proposed for multi-USV control. The authors of the paper considered the inter-USV distance and channel interference to maintain the stable handover of the network while USVs are maneuvering at high speed. The authors of [163] proposed an integrated network architecture for terresstrial, maritime, and high altitude platform for UAV and USV cooperative communication. The proposed architecture considered the switching cost caused by node mavuering and link interference using a reinforcement-learning-based whale optimization method. Furthermore [164], proposed a multi-USV group communication scheme in which the total communication cost was minimized using a nested-ring algorithm for topology optimization that considered the factor of occlusion, weather, and inter USV distance.

Formation control: Formation control is a critical issue because multi-USV systems can accomplish complex tasks that a single USV cannot achieve. The main challenge of formation control is the need for dependable and low-latency communication for collaboration between USVs. In the USV group network, the interval distance between USVs and interference from nearby nodes tend to increase time delays and decrease network throughput. Therefore, unmanned aerial vehicles (UAVs) are introduced as effective means to support cooperative communication with USVs, building a combined network of air and sea using UAVs [165].

To create a secure and efficient network for UAV-USV formation, cooperative communication was employed, taking into account the time-varying topology and node locations [166]. The efficiency of formation tasks was severely affected by the communication between UAV and USV. Therefore, a communication scheme based on ad-hoc network architecture with node position information for UAV-USV communication was investigated. Researchers of [167] proposed a self-adapted synchronized event-triggered formation control strategy aimed at decreasing communication burden. A formation control method for under-actuated USVs was studied using dynamic surface control. Inspired by the event-triggered mechanism, the authors of [168] also proposed a formation control scheme utilizing sliding mode control protocols within a fixed time. By employing the dynamic event-triggered approach, the system updated the controller status less frequently, thereby reducing the consumption of communication resources

Cooperative task coordination: In cooperative tasks such as maritime rescue, surveillance, and harbor security, the UAV-USV cooperative mechanism heavily relies on reliable communications between them. A variety of studies have focused on the challenges of communication during UAV-USV cooperative operation since the oceanic environments have major impact on the communication system due to adverse weather and challenging channel conditions.

The end-to-end delay, network throughput, and packet loss probability should be carefully optimized [169,170]. The authors of reference [169] introduced a communication framework between UAVs and USVs for time-critical applications. According to previous research [171,172], the communication range of UAV significantly affects the cooperation efficiency of the UAV–USV system. The authors of reference [173] proposed a UAV–USV cooperative perception scheme for coastal monitoring utilizing UAV–UGV cooperative platforms as communication relays. Additionally, a joint object detection algorithm was proposed using an enhanced CenterNet model. For UAV–USV cooperation, mobile edge computing schemes have also been applied to the maritime Internet of Things (MIoT) [174].

(2) **USV-assisted maritime communications**

The limited flight duration time and inability to operate in adverse weather conditions severely impacted the usability of UAVs in maritime communication. With its long endurance and all-weather operation capability, USV is a promising solution for providing three-dimensional and ubiquitous network coverage for oceanic operations in maritime NTNs. The use of USVs for maritime communication is a promising research area that can be integrated with UAV non-terrestrial networks to expand communication coverage for unmanned maritime platforms. In contrast to ground or air communications, maritime communications advancements are far from satisfactory in achieving ubiquitous wireless connectivity. USV with autonomous maneuverability and self-determination abilities offer a promising solution for extending oceanic network connectivity and improving quality of service.

In [175], a novel method is introduced for mobile relaying assisted by USVs to demonstrate the application of utilizing USVs in maritime non-terrestrial wireless communications. On the other hand, USVs can be utilized for data collection purposes to collect seabed-based data, in support of the underwater internet of things (UIoT) [176,177]. Ref. [178] utilized MIoT for maritime transportation systems. However, in [179], by combining the satellite network and USV-assisted wireless communication, a hybrid communication scheme was proposed to maximize the communication throughput and coverage.

The recent advancement of NTN in maritime are sumarized in Table 5. However, maritime NTN communications are still in the early stages of research, and several problems still need further investigation in the field of maritime communication applications, which include maritime channel conditions, maritime mobile edge computing, data security, and UAV–USV–satellite communication coordination [179]. For instance, MIoT is a vital issue in maritime information exchange and is worth in-depth investigation.

Table 5. Summary of previous work concerning USV in NTN communication.

Literature	Topics	Contributions	NTN Communication Type
[162]	Multi-USV Control	An integrated communication framework for terrestrial, sea and HAP for multi-USV control.	HAP–USV
[164]	Multi-USV Communication	Multi-USV group communication scheme with nested topology	USV–USV
[166]	USV Formation Control	Cooperative communication framework design considering varying topology	UAV–USV
[167]	USV Formation Control	Event-triggered formation controller for lower communication power consumption	UAV–USV
[168]	USV Formation Control	Dynamic event-triggered control scheme for fixed time formation consensus.	UAV–USV

Table 5. *Cont.*

Literature	Topics	Contributions	NTN Communication Type
[169]	UAV-USV Cooperation	Performance and reliability evaluation of communications for USV–UAV cooperation tasks	UAV–USV
[170]	UAV-USV Cooperation	UAV–USV cooperative tracking and landing scheme using model-based control.	UAV–USV
[171]	UAV-USV Cooperation	Collaborative surface coverage of oceanic area utilizing UAV and USV	UAV–USV
[172]	UAV-USV Cooperation	USV–UAV marine cooperative search and control by means of visual information	UAV–USV

4.3.2. Unmanned Underwater Vehicles in Underwater Communications

Unmanned underwater vehicles have much potential in fulfilling sophisticated missions that are dangerous or impossible for humans to accomplish. For applications of unmanned underwater vehicles (UUVs) or autonomous underwater vehicles (AUVs), communication is even more sophisticated, as underwater communication channels have been barely investigated by research scientists. The rapid development of wireless communications has extended from terrestrial to aerial spaces to enhance user connectivity in NTN. However, the underwater wireless communications are rarely discussed, despite being an essential component of 6G NTN networks.

Underwater communication is achieved via multiple means including radio signals, acoustic communication, lasers, and cabled communication. However, due to physical constrains, underwater communication cannot be achieved using a straightforward means, since radio communication is nearly impossible in the underwater scenario. Underwater communication is typically achieved using USV and buoys, which serve as gateway for radio communication and various underwater communication methods. Ref. [180] proposed a hybrid underwater communication scheme integrating acoustic, optical, and fiber optic communications to support underwater applications. Cabled communication is a traditional method because conventional radio transmission is nearly impossible in underwater environments. An applicable network architecture was investigated by [181] utilizing a hybrid network between cable-assisted communications and wireless underwater communications in which cable-based sink nodes and tethered cable UUVs were utilized to provide short-distance communication for autonomous underwater vehicles.

Formation Control: With the advancement of underwater communication in the 6G era, AUVs are widely utilized as nodes in underwater communication network, posing challenges related to formation control and collision avoidance of AUVs in complex underwater scenarios. The stable formation and safe operation of AUVs in underwater environments is beneficial for network topology management and network robustness. Ref. [182] investigated a formation control paradigm with a heterogeneous underwater communication method for AUVs under communication constraints. Ref. [183] proposed a framework utilizing a fusion control method with a distributed mechanism to accomplish real-time formations in underwater wireless communication environments. The authors of [184] considered the formation control and collision avoidance problem in a multi-agent system involving UAVs, USVs, and UUVs. In this work, to fulfill the formation control task, the communication between USVs and UUVs were achieved using moving buoys to maintain the cross-media communication topology.

Localization and Navigation: Localization is a critical issue for AUVs in underwater NTN networks. However, the conventional satellite positioning method might be unsuitable for deep-water applications. The localization method can be divided into stand-alone and cooperative positioning methods. For the stand-alone localization method, AUVs estimate their position based on globally collected information. A simple cost-efficient method is proposed to globally estimate the AUV position in [185]. In [186], the authors emphasized on the angle of arrival model for cooperatively extracting positions of multiple targets. The proposed scheme evaluated three-dimensional position information through D-optimality criterion. The authors of [187] examined the impact of changes in propagation speed relative to water depth and clock synchronization on achieving improved accuracy of position estimation. In [188], the proposed approach combined maximum likelihood estimation and the Gaussian belief method to mitigate the effects of noise and non-linearity in the formula.

USV-AUV Cooperation: Form recent literature, AUVs are typically utilized in coordination with USVs or other platforms to collectively fulfill tasks as USVs have stronger communication and perception capabilities compared to AUVs. Furthermore, USVs are also considered as communication hubs for accessing maritime radio networks and underwater communication simultaneously, performing the role of air-to-underwater gateway. Researchers [189] emphasized the influence of the random wave fluctuation in underwater acoustic communication for USVs in underwater node communication. Ref. [190] proposed an AUV–USV system for search tasks in which acoustic communication is used for the USVs to transmit perception information to AUVs, while wireless radio was utilized among a group of USVs. In this application, satellite communication was also introduced to assist USV localization, thereby forming a space-sea-underwater network architecture. In reference [191], a communication scheme for UAVs and underwater drones was introduced, and the pros and cons of multiple underwater communication methods were summarized.

Open issues still exist in the domain of underwater unmanned autonomous system communication, such as cross-medium communication, visible light communication (VLC) [192], software-defined underwater networks [193], and information security. Cross-medium communication is derived from the challenge of directly merging underwater access networks with contemporary terrestrial networks with water–air signal conversion. Acoustic millimeter-wave communication is realized as the water–air interface [194]. Ref. [195] proposed a blockchain-enabled secure underwater communication system for unmanned underwater drones in oceanic special classification. Nevertheless, the aforementioned issues require further discussion.

5. A Case Study of UAV NTN Airborne Network in Mountainous Area

Unmanned aerial vehicles are ideal platforms for carrying network equipment, such as cellular base stations, to provide communication network coverage to ground users. They serve as flying base station platforms in an NTN use case. Cellular networks utilizing UAVs as airborne base stations have shown great potential to expand the service area for users as needed.. For multiple UAV base stations, it is worth noting that an effective and efficient handover scheme is crucial for ensuring the quality of service (QoS).

In rural or mountainous areas, wireless communication coverage is not always accessible due to cost-inefficiency or the impossibility of building the terrestrial infrastructure required. Due to environmental factors such as inclement weather, rugged terrain and diverse vegetation, communication coverage is unstable. The unreliable information transmission network coverage result in service interruptions, signifcantly impacting the daily lives of the residents living in those areas and hindering tasks such as disaster management.

To tackle this issue, utilizaing UAV airborne NTNs is a feasible approach for providing wireless communication services in this particular scenario. The UAV planning of UAV in NTN communication service and data transmission optimization architecture is a crucial issue that necessitates the use of technologies such as network coding, multi-path transmission, and real-time task offloading to greatly enhance the real-time operation and reliability of communication networks [196–198].

5.1. Design of Field Trial of UAV NTN Network System

To assess the practicality of a UAV NTN airborne network in mountainous regoins for disaster relief operations and natural resource exploration, a thorough field trial is planned and executed. Here, we introduce the experimental system component and conduct a more in-depth study of the proposed case.

In this case, a group of UAVs are utilized to provide airborne network coverage for mountainous regoins (Figure 6). To provide emergency coverage and service using NTN communication, UAVs are considered flexible and easy-to-deploy platforms for carrying base stations. In Figure 6, we illustrate the setup of multiple UAVs achieving NTN emergency communication coverage. As for the platform, we select the rainbow CH-4 fixed-wing UAV as the carrier platform for NTN communication, which is developed and manufactured by the China Academy of Aerospace Aerodynamics, an entity under the China Aerospace Science and Technology Corporation (CASC). The take-off weight of CH-4 UAV is 1330 kg with a payload up to 345 kg and the flight endurance is over 40 h. The CH-4 platform is utilized to install 5G base stations and other equipment. In our solution, to support the wireless link from UAVs to the control center/nearby UAV, a satellite transceiver is also installed at the back of the UAV with a transmitting speed of 2 Mbps.

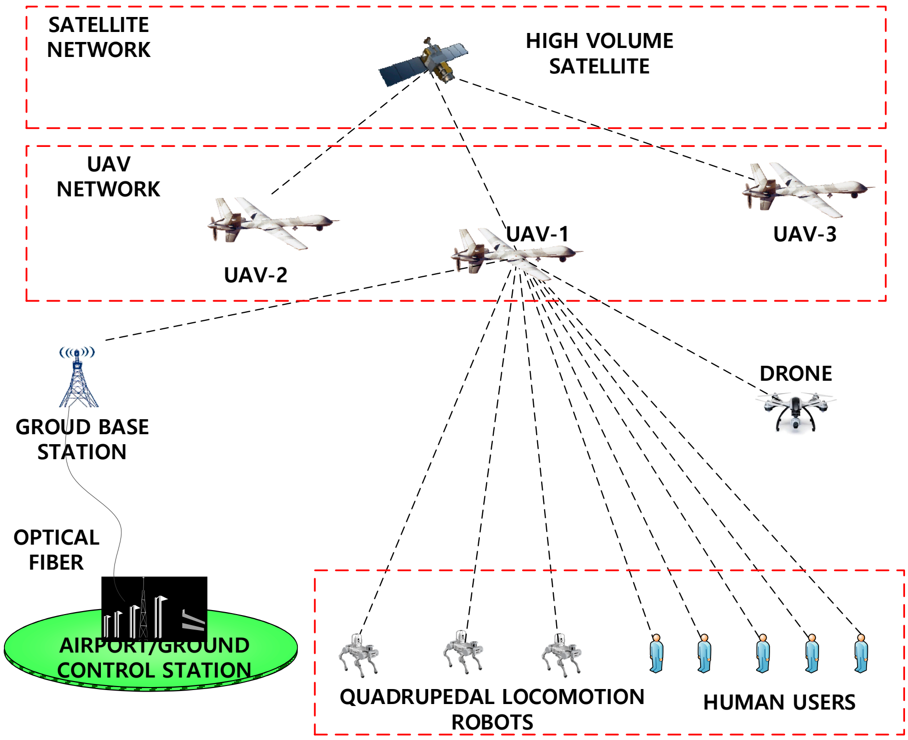

Figure 6. Overview of UAV airborne network in the case study.

Non-terrestrial networks have gained significant attention due to the expansion of large-scale wireless communication networks coverage facilitated by the use of airborne platforms like satellites and UAVs. The network architecture of our field trial is divided into three layers. The top layer consists of a high-capacity communication satellite, which is used to transmit status information from UAVs to the remote control center and to send control instructions to the UAVs. In addition, satellite links are also utilized to maintain communications between UAVs. The middle layer of the network is composed of three interconnected fixed-wing CH-4 UAVs with 5G base stations onboard. The base stations onboard the UAVs are commercial base stations that operate at a frequency of 2.6 GHz, creating a multi-UAV coverage network. This setup is useful for verifying the performance of multi-UAV coverage in different applications and validating the multi-platform use case scenario, as interference may occur at certain radio frequencies in practical applications. The three fixed-wing UAVs are interconnected to each other via satellite networks. The ground layer of the network is utilized for the backhaul of UAV base stations. The UAV equipped with a the base station operating at the frequency of 2.6 GHz, is connected to a ground base station connecting to the UAV ground control center in the airport by means of a fiber optic transmission cable. Furthermore, MEC servers can also be integrated into the UAVs and robots offering low latency task offloading for end users.

The purpose of the field trial was to validate the usability of NTN communications for robotics and other applications in mountainous areas for post-disaster relief and rescue scenarios. The UAV NTN network is designed to provide ground communication coverage when ground communication infrastructure is crippled or unavailable. Various kinds of ground user equipment is needed to access the UAV network in disaster relief operations. In the field trials, the selected ground user equipment (UE) of the air-to-ground network include quadruped locomotion robots, rotary wing UAVs and cell phones. Robots are widely used in scientific studies and industry for surveillance, area perception, and other autonomous tasks, while in disaster management scenarios, multi-spectral cameras are mounted on the robot to spot the locations of wildfire points or people trapped after earthquakes. Multi-spectral images collected by cameras of relatively high-resolution require high data rates to be transmitted to cloud servers or disaster headquarters in order to post early warnings and identify victims. In mountainous disaster rescue scenarios, it is impossible for wheeled or tracked vehicles to move freely, and quadrupedal locomotion robots are utilized for rescue operations. Customer Premise Equipment (CPE) is mounted on the robot to provide access capabilities to the UAV 5G network. Cell phones are connected to a UAV base station with a frequency of 2.6 GHz, which is supported by most commercial operators.

5.2. Field Trial Results

5.2.1. Parameters

The field experiments were conducted on 11 January 2023 with several measurement points in the coverage area of the UAV on the ground. We managed to conduct the field trial with one rainbow CH-4 fixed-wing UAV to provide ground communication coverage. In the field trial test, a commercial 5G base station is mounted on the CH-4 fixed-wing UAV with a frequency of 2.6 GHz. The transmission power of the base station is 260 W with a 64 TR massive MIMO antenna. The trajectory of the UAV is designed as a circle with a radius of 3 km with a ground speed of 180 km/h and the flight height is set to 2 km above the ground (Figure 7). The map of field trial is shown in Figure 7 above with three test points marked red on the map. The trajectory of the UAV is shown in a black circle.

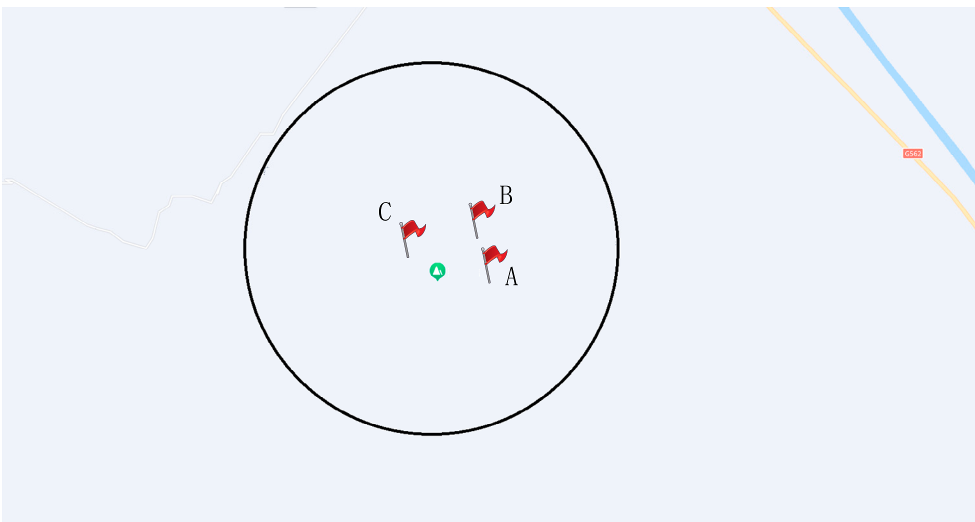

Figure 7. Field Trial Map of UAV: The cirlce trajectory on the map indicate the flight path of the UAV; A, B, and C denote the three measurement point under the coverage of UAV base station.

5.2.2. Results and Analysis

The images in Figure 8 show the scenes of field trials in mountainous and desert areas in the western part of China. To test the quality of service (QoS) of the communication network for the ground UEs, we establish three different measurement points near the center of the flight trajectory of UAVs. The experiments have successfully verified the ability of various kinds of UEs to access the network, edge computing resources, and intelligent services without the support of ground network infrastructure. The test results of the field trial are shown in Table 6 below. At measure point A, the user equipment is in a stationary setup, 3400 m away from the UAV. The downlink is stable with RSRP above −90 dBm with a maximum downlink speed of 17 Mbps and a maximum uplink of 756 Mbps. Additionally, the time delay is about 30 ms without offline phenomenon.

(a) (b)

Figure 8. Field trial scene of UAV airborne NTN: (**a**) quadrupedal locomotion robot with Customer Premise Equipment (CPE) on board; (**b**) CH-4 UAV equipped with 5G base station and satellite antenna preparing to take off.

Table 6. Ground UE test results of UAV NTN network field trial.

MeasurementPoint	Type	Distance to UAV (M)	Throughput (Mbps)	Downlink RSRP (dBm)	Downlink SINR (dB)	Time Delay (ms)
A	Uplink	3490.17	26.99	−88.13	28.81	/
	Ping	3707.13	/	−97.63	22.31	323
	Uplink	3705.50	10.82	−101.81	14.81	/
	Downlink	3654.38	697.34	−83.13	33.69	/
	Ping	3473.81	/	−94.50	24.69	23
	Uplink	3418.66	17.23	−91.50	25.19	/
	Ping	3500.57	/	−85.38	26.31	31
	Downlink	3418.87	756.49	−84.06	35.81	/
B	Ping	3815.15	/	−82.23	34.37	27
	Downlink	3600.85	707.65	−85.73	28.99	/
	Uplink	3570.03	40.60	−76.89	39.07	/
C	Uplink	3415.97	22.02	−78.29	39.34	/
	Downlink	3744.77	362.91	−99.41	24.50	/
	Ping	4049.63	/	−98.69	25.06	16

In terms of UAV communication coverage applications, this field trial has successfully validated the UAV NTN networks for mountainous area coverage with a network edge rate of 17 Mbps, a peak rate of 756 Mbps, an average delay of 21 ms, and a total system bandwidth of 240 MHz. In order to verify network flexibility, this field trial achieved on-demand coverage of 36 square kilometers and a peak coverage of approximately 180.3 square kilometers along a mountainous area. The collaborative networking provided by three UAVs in the airspace supported broadband transmissions for 41 users, with a system outage probability of less than 0.04% (Table 7).

Table 7. UAV airborne network coverage field trial results.

Application	Item	Results
Multi frequency integration	Network edge rate	14 Mbps
	Peak rate	744 Mbps
	Average delay	21 ms
	Total system bandwidth	240 MHz
UE coverage	Coverage	36 km^2 (on demand)
	Number of UEs	41 (>10 Mbps)
	System outage probability	Less than 0.04%

Various application is verified through the UAV NTN communication, including text messages, video streams, robot operation system (ROS), and so on. With the support of NTN communication, a multi-robot collaboration experiment is also conducted with quadrupedal locomotion robots. Quadrupedal locomotion robot is a novel platform that is able to move in challenging terrain from the inspiration of locomotion of legged animals, which is effective in mountainous disaster rescue scenarios. Quadrupedal locomotion robot is a useful tool for disaster relief and area surveillance in complex environments such as mountainous or remote areas. In the field trial, a group of four robots equipped with multi-spectrum image sensors and customer premise equipment (CPE) is utilized to test coordination capabilities with collective behaviour under the support of the UAV NTN airborne network. During the field trial, the robots were connected to the UAV base station to maintain data links to the operator and nearby robots. The operator-to-robot control instruction delay is less than 20 ms, which is sufficient to support inter-robot collaboration tasks such as joint environmental perception, formation control, and collision avoidance. The above-mentioned capabilities are crucial in successful emergency management scenarios ranging from earthquake victims searching to dangerous item detection. During the field trial, a group of four quadrupedal locomotion robots formed a team to perform joint environmental perception tasks while maintaining fixed formation and collision avoidance via the UAV network. (Figure 9)

(**a**) (**b**)

Figure 9. Field trial of quadrupedal locomotion robot formation: (**a**) quadrupedal locomotion robot formation control; (**b**) perspective of the robot in the group.

On the other hand, a long-range teleoperation experiment was also conducted during the test. The robot and the control terminal are all connected to the UAV base station, and the operator controls the robot via 5G UAV communication using the terminal equipment. It has been proven in the experiment that the robot can be teleoperated through a UAV network from a distance of up to 50 km. The result is show in Table 8.

Table 8. Robot application of UAV airborne network coverage field trial results.

Application	Item	Results
Multi robot control	Robot control instruction delay	less than 20 ms
	Robot control range	50 km
High-definition video streaming	Channels supported of 4k video stream	16
	Video stream delay	less than 70 ms

5.3. Discussion

The field trial successfully demonstrated the feasibility of NTN in support of UAIS in a mountainous area with no preexisting communication network infrastructure. However, there are still technological challenges with the UAV NTN network for providing coverage in remote mountainous areas, which will be discussed below from different perspectives.

Firstly, intelligent service switching and network transmission coding optimization are required to address the issue of service interruption caused by dynamic changes in the UAV posture in complex on-site network environments. When multiple UAVs carrying 5G base stations transverse various terrains, user terminals will frequently switch between UAV 5G base stations, resulting in service interruptions and poor quality of service (QoS) in this scenario. The handover paradigm between base stations is of great importance, and further effort is required to investigate this issue.

The application of edge computing server onboard the UAV enables the perception of connection status, facilitating intelligent prediction and active planning of the base station handover paradigm. This ensures the continuity of the command and dispatching service during the base station handover. A network acceleration device utilizing forward error correction coding has been designed and implemented in a 5G multi-access environment. This device can simultaneously utilize multiple available communication links in a complex network environments to achieve efficient data transmission. In weak network environments with fluctuating wireless links, reducing the end-to-end packet loss rate and increasing the rate of multi-link aggregation transmission can address the challenges of poor reliability and the difficulty in ensuring stable services in mountainous communication environments.

Secondly, real-time computation offloading technology based on optimal transmission theory is urgently needed to solve the real-time response problem of unmanned aerial vehicles. Using the new technology of edge computing, different services with different requirements for computing resources and time limitations can be satisfied. In addition, global situation awareness needs to rely on the high-performance computing power of the rear cloud computing center, integrate image data, weather, and other multi-modal data for centralized computing, while control and dispatching applications with high real-time requirements such as trajectory planning need to be accomplished with low latency is processed on edge computing nodes. An intelligent task offloading algorithm that integrates optimal transmission theory and unmanned aerial vehicle control needs in-depth investigation. Considering the capabilities of the front and rear computing nodes and network bandwidth, the strategy can perform intelligent allocation and dynamic scheduling of computing tasks, maximizing the utilization of on-site computing and communication resources, improving data processing efficiency, and reducing the communication service response latency.

Finally, the field trial has revealed the problem of a lack of UAV online trajectory adjustment capabilities according to user QoS. In the field trial test, the trajectory of the UAV is controlled manually by human operators in the control center. The operator has no idea of user-end QoS status; therefore, they are unable to adjust the trajectory to enhance the performance of the user equipment. To handle this issue, an intelligent UAV trajectory control scheme considering user equipment QoS and channel status would benefit overall system performance, which is vital for improving users' experience, especially at the cell edge. A heat map of user QoS might be a useful input for the online trajectory adjustment algorithm. In the next stage of research, we will consider the UAV trajectory adjustment method based on a QoS heat map to improve the user communication quality in UAV NTN for better practical usability.

6. Conclusions

While there has been notable progress in the development of UAIS and wireless mobile communication technology in recent years, the current focus of UAIS is primarily on applications that depend on terrestrial network infrastructure. To resolve the challenge of ubiquitous network coverage for various UAIS applications, we proposed insights into 6G UAV NTN communication-enabled UAIS capabilities, which is a promising inter-discipline field for future research in distributed computation, human-machine interaction, and multi-agent cooperation. The 6G NTN concept along with edge/fog/cloud computing and artificial intelligence will be a major driving force for the evolution of unmanned autonomous intelligent systems. Integrating 6G NTN capabilities, UAIS is capable of enabling a variety of applications including intelligent transportation system in smart city, disaster relief and management, smart agriculture, oceanic surveys and other intelligent applications to come. In this paper, we proposed a comprehensive review of the challenges and opportunities that non-terrestrial networks may bring about in the field of unmanned autonomous intelligent systems. A case study of UAV NTN communication was presented to demonstrate the application of UAV NTN technology for UAIS in regions where terrestrial network infrastructure is unavailable. From the literature review and case study, we can conclude that UAIS in non-terrestrial network technology is an emerging field that holds great potential in enabling space–air–ground–sea integrated ubiquitous coverage, which holds various application prospects and research opportunities. Much research effort and industrial implementation work are urgently needed to promote the realization of more efficient, human-friendly, self-organized UAIS integrated with non-terrestrial network concepts and technologies.

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