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A Survey on High-Altitude Balloon UAVs for Vertical Heterogeneous Networks

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요 약

본 논문은 차세대 6G 통신의 수직 이종 네트워크(VHetNet)의 중요한 구성 요소가 될 것으로 기대되는 성층권역 풍선 무인항공기인 Stratolite를 소개한다. 부력을 동력으로 사용하는 Stratolite의 주요 하드웨어 구성 요소를 소개하고 성층권의 대기 흐름을 따라 이동하면서 발생하는 역학적 특성을 조사한다. 저고도 무인항공기 기지국 및 저궤도 위성 기지국과 Stratolite를 무선 통신 관점에서 비교하여 Stratolite가 두 기지국의 장점을 융합하여 지속 가능한 공중망을 구성할 수 있음을 보인다. 또한, VHetNet에서의 Stratolite의 주요 활용 시나리오를 소개한다. Stratolite의 특성을 고려하여 콘스텔레이션, 무선 자원 관리 기술, 빔포밍 등의 물리 계층 기술이 Stratolite의 주요 활용 시나리오를 실현하기 위해 어떤 방식으로 적용되어야 하는지 조사하여, Stratolite의 물리 계층 설계가 지상망-항공망-위성망의 오케스트레이션을 핵심적으로 고려해야 하는 것을 설명한다. Stratolite는 장시간 지속 가능한 항공 네트워크를 실현하여, 차세대 통신 네트워크인 VHetNet의 핵심 구성 요소로 활용될 것으로 기대된다.

키워드 : Stratolite, 수직 이종 네트워크, 고고도 풍선 항공기, 무인항공기, 저궤도 위성
Key Words : Stratolite, vertical heterogeneous network, high-altitude balloon UAV, unmanned aerial vehicle, lowearth orbit

ABSTRACT

This paper presents Stratolite, a stratosphere-operated balloon-shaped aerial vehicle, as an essential element within vertical heterogeneous networks (VHetNets) for 6G communications. We elucidate the pivotal hardware components of Stratolites that primarily leverage balloon buoyancy, and then subsequently expound upon the aerodynamic attributes derived from the Stratolites floating within air currents. From a wireless communication perspective, Stratolites are compared with UAVs and LEO base stations as sustainable alternatives that cherry-pick the advantages of the two base stations. Then, the promising usage scenarios of Stratolites in the VHetNet are proposed, in which Stratolites play a key role as intermediaries between terrestrial and space networks. We investigate physical-layer methodologies encompassing constellations, radio resource management, and beamforming to actualize the proposed usage scenarios, emphasizing the orchestration of ground-air-space networks. We anticipate that Stratolites will pave the way for attainable and sustainable aerial networks for next-generation wireless communications.

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Ⅰ. Introduction

Vertical heterogeneous networks (VHetNets) that integrate space-aerial-terrestrial networks have been actively discussed in pursuit of the realization of SixthGeneration (6G) wireless communication technologies. In June 2023, the Vision Recommendations document titled "IMT towards 2030 and beyond" by the International Telecommunication Union Radiocommunication Sector (ITU-R) incorporated massive communication and ubiquitous connectivity as envisioned usage scenarios for 6G[1]. VHetNet is foreseen as a crucial facilitator of these 6G scenarios, offering adaptable network capacity and worldwide coverage on a grand scale.

This vision closely aligns with the Third Generation Partnership Project's (3GPP's) recent concentration on the non-terrestrial network (NTN), as documented in the technical reports 38.821[2] and 38.331[3]. As a major component of VHetNet, we introduce Stratolite, a high-altitude balloon base station, to establish a resilient aerial network.

Balloon-type high-altitude unmanned aerial vehicles (UAVs) are recently under discussion to overcome the energy limitations of the UAV network[4]. Prior to the consideration of balloon UAVs, various approaches to address the energy limitation have been put forth in the literature. From the radio resource management perspective, [5] proposed a network management framework to minimize energy consumption. Another research focus has been directed towards minimizing mission time or flight distance within ad-hoc networks[6]. [7] also suggested coverage maximization schemes to reduce the number of deployed UAV base stations.

Research from a hardware-centric perspective has also been prevalent. The majority of the research has focused on multi-rotor UAVs, utilizing the precise controllability of multi-rotor UAVs. However, multi-rotor UAVs have to spend substation energy to sustain their operational altitude. Consequently, discussions have arisen regarding aerial networks employing fixed-wing UAVs because fixed-wing UAVs utilize lift power, and thus have higher energy efficiency than multi-rotor UAVs. However, fixed-wing UAVs have a minimum velocity to generate lift power and research works focus on the property. For example, [8] suggested a circular trajectory to provide continuous coverage. [9] proposed an air-to-ground channel model, considering the Doppler shift from the fast-moving fixed-wing UAVs. On the other way, [10] suggests tethered UAVs that provide energy from the connected power line. These software and hardware methods have successfully increased the network lifetime, but none of these address the essential problem: *energy for control significantly exceeds energy for communication.* For example, small cell base stations consume hundreds of watts[11], while 30kg multi-rotors consume 6 to 9 kW for operation.

We introduce an innovative solution called Stratolite that compromises the drawbacks of UAV and lowearth orbit (LEO) base stations by cherry-picking their advantages. We first describe the hardware configurations and characteristics of Stratolite. Then, we discuss new research topics and open challenges to realize a practical Stratolite network.

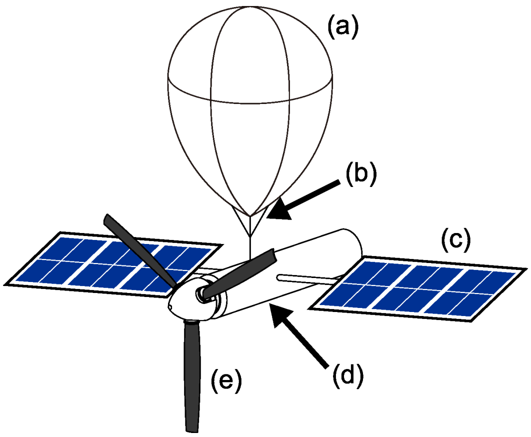

Fig. 1. Conceptional architecture of a Stratolite. Stratolite consists of (a) a superpressure balloon, (b) a lift gas chamber, (c) solar panels, (d) a vehicle body with peripherals (batteries, RF antennas, and computing devices), and (e) a lateral propeller.

Ⅱ. What is Stratolite?

2.1 Hardware Architecture

Stratolite is a type of UAV that consists of a superpressure balloon, a chamber with lifting gas, solar panels, batteries, and radio transmission devices, as illustrated in Fig. 1. The volume and density of superpressure balloons are relatively stationary regardless of the external temperature and atmospheric pressure. Then, the balloon floats along with the level pressure surface. The altitude of the balloon can be controlled by pumping and releasing lift gas in the balloon. Stratolites can horizontally move with the help of lateral propulsion and external air flows. Stratolites replace energy consumption for hovering with the buoyancy of the balloon, taking advantage of high energy efficiency. Moreover, the operating time could be additionally prolonged by the energy sourced from solar panels.

Stratolites operate at the bottom of the stratosphere (18-25km above sea level). The temperature in the stratosphere increases along with the altitude, so Stratolites can be stably controlled without unexpected convection and turbulence. Google's Loon project[12] has confirmed the controllability of the superpressure balloon via simulation based on the real stratospheric wind dataset provided by the Copernicus Climate Change Service[13].

2.2 Comparison with UAV and LEO Base Stations

We compare Stratolites with other types of aerial base stations (ABSs) to justify the feasibility of Stratolites. The physical properties are summarized in Table 1. Stratolites exhibit attributes reminiscent of an intermediary between UAVs and LEO base stations. With these features, the potential advantages of Stratolites are expected to surpass the benefits of UAV and LEO base stations.

ABSs, specifically those using UAVs and LEO satellites, have recently gathered increasing research and industrial interest as they can provide ubiquitous connectivity by moving toward on-demand users[14]. Such high valuation is mainly derived from the mutual properties of ABSs, across UAV and LEO base stations, which can be listed as i) large coverage, ii) flexible network configurations, and iii) service capability in mountainous and maritime areas. ABSs can easily secure line-of-sight (LoS) access links to users by taking advantage of high altitude and mobility[15], whereas the conventional base stations suffer from link blockage due to buildings, trees, and landforms. However, the drawbacks of ABSs seem to be obscured by the huge interest and expectations on ABSs.

Table 1. Comparison with UAV and LEO base stations

Parameters	UAV	Stratolite	LEO
Altitude (km)	≤ 1	18-25	500-2000
Comm. Delay (ms)	$\leq 10^{-2}$	0.1-0.16	3.3-13.3
Path loss (dB)	101-113	147-155	175-187
Velocity (km/h)	≤ 100	0-130	340-1150
Network lifetime (day)	≤ 1	200-300	1000-2000
Coverage	Small	Large	Very large
Base station cost	Very low	low	High
Energy source	Battery	Solar Panel	Fuel
Maneuver DoF	High	Median	Low

2.3 Drawbacks of UAV base stations

Consuming large energy to maintain the altitude becomes especially problematic for the UAV base stations[10]. Then, the network lifetime with UAV base stations is relatively short compared with the other types of base stations, as UAV base stations are equipped with limited energy sources. If small-sized copters with less than 10 kg are utilized as a femtocell base station, the energy consumption from the maneuvering (200W-2000W[16]) outstrips the femtocell operating power (6W[17]). This energy inefficiency inevitably leads to the emission of volumetric greenhouse gases, which is directly contrary to the global trend toward green communications. The flight altitude of UAV base stations is typically lower than a couple of kilometers. Then, UAV base stations are not free from privacy and security problems in living areas, and regulations of the airports and military. In addition, securing public safety from UAV crashes still needs to be addressed before building aerial networks[18], because there are not enough failsafe policies and regulations for UAVs, to the best of the authors' knowledge.

2.4 Drawbacks of LEO base stations

Major research interest in space communications with LEO base stations lies in finding optimal constellations of thousands of LEO base stations across the Earth[19], as the LEO base stations cannot sustain their latitude and longitude due to the high velocity. Then, the other thousands of LEO base stations should be additionally deployed to increase the network capacity in the specific area. Most of the Earth's area is sparsely populated hinterlands such as oceans, deserts, and forests. However, there is no way to use the surplus capacity for hotspots in populated areas, resulting in inefficiency. Numerous LEO satellites share the same operating altitude with the LEO base stations, so largescale deployment is also problematic in terms of collision avoidance and processing space debris. In addition, several observatories reported that LEO base stations occlude space observations and generate massive light pollution.

Ⅲ. Prospective Usage Scenarios

Stratolite networks are expected to provide communication services as a middle layer of VHetNet, as illustrated in Fig. 2. Aligned with the 6G recommendations from ITU-R, Stratolites can be utilized in the following usage scenarios. The usage scenarios are summarized in the Table 2.

3.1 Providing services to IoT devices

Stratolites are expected to significantly contribute to supporting internet-of-things (IoT) networks. The number of IoT devices has been exponentially increasing, becoming more and more burdening the current communication systems. Accordingly, research challenges for satisfying the latency, data rate, and connectivity of massive IoT devices have been raised. The *massive communication* in the usage scenario of the 6G recommendation by ITU-R well represents this vision[1].

We expect that a large-scale constellation of Stratolites can provide immense coverage, providing data links to massive IoT devices. IoT devices can be ubiquitously located, including remote mountainous and maritime areas. Then, current terrestrial networks might not be enough to support IoT networks. Moreover, current space networks are

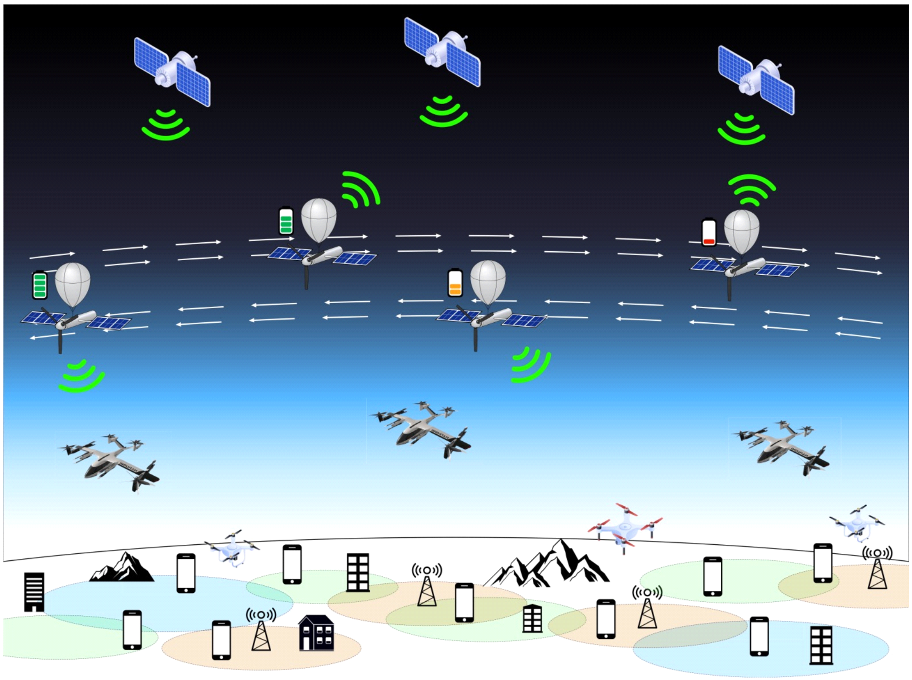

Fig. 2. Conceptional illustration of Stratolites in the VHetNet. Blue, green, and red colors in the coverage are associated with satellite, Stratolite, and ground base stations, respectively.

Table 2. Summary of promising usage scenarios of Stratolites

Scenario	Description
Offering services to IoT devices	Stratolites' constellations can provide large coverage and lower the high pathloss and propagation delays of IoT devices.
Edge and cloud servers	Locating in the middle of VHetNet, Stratolites can properly store and provide data required for ground users and LEO base stations.
Backhauling and relaying	Stratolites can provide backhaul links to LEO base stations or amplify radio signals from ground terminals, having highly likely LoS links.
Control center for CAVs	Stratolites can establish reliable VHetNet to support fast-moving aerial vehicles by providing large coverage.

also inappropriate for serving IoT devices due to the high path loss and propagation delays. The uplink transmission power from the IoT device should be greatly enlarged to satisfy the quality-of-service (QoS)[20], and this might shorten the IoT device's lifetime. Meanwhile, Stratolite can provide direct links to IoT devices with radio attenuation lower than the terrestrial and LEO base stations, providing seamless and ubiquitous connection.

3.2 Edge server and data cloud with VHetNet

Stratolites are located in the middle of the VHetNet, so can mediate terrestrial and space networks. Especially, there is no need to experience a long propagation delay when the Stratolite can provide the restored data that a ground user requires to space networks. Moreover, Stratolite can simultaneously collect data from IoT devices, and support edge functionality to provide the collected data.

It is challenging to determine which data will be stored because the user distributions and request patterns change along with the drifts of Stratolites. Therefore, trajectory, data request prediction, and cache contents routing should be considered for Stratolite to be utilized as an edge server.

3.3 Providing backhaul and relaying links

Stratolite can be a cost-effective way to provide wireless backhaul links to satellites, aerial base stations, and isolated base stations. The backhaul link from Stratolites has a similar property as the LEO base stations' backhaul link that is rarely affected by shadowing, multipath, and scattering, being highly likely to be LoS[21]. These properties facilitate the use of mmWave and free-space optical communications that can significantly enhance the signal power gain in the communication link. Adaptive beamforming and beam tracking with massive multi-input multi-output (MIMO) systems are necessary for Stratolites to provide backhaul links to wide-spreading small cells regardless of weather and the movement of Stratolites.

Stratolite can be a promising solution for relaying the terrestrial user with space base stations. The uplink signal from the ground user goes through severe attenuation due to the far distance to the satellite. Then, ground users are often required to equip high-gain antennas to communicate with the LEO base station. Meanwhile, the communication links between the ground user and Stratolite are within tens of kilometers, most of which are LoS links. Then, Stratolite can enlarge the uplink coverage without the help of additional antennas.

3.4 Control and support aerial/space vehicles

There has been a huge paradigm shift in aerial mobility since the concepts of urban air mobility (UAM) and a connective autonomous vehicle (CAV) were actively discussed[22]. The rapid growth of UAM and CAV raises challenges for supporting numerous aerial vehicles. The challenges include a lack of control centers and data hubs, dealing with congestion and frequent hand-overs, and covering existing gaps in terrestrial networks. Such requirements exceed the capability of current terrestrial networks since the requirements come from fast-moving aerial vehicles, whereas the ground base stations mainly focus on providing services to ground users. Stratolites can support aerial vehicles located on the coverage gap of the terrestrial network, guaranteeing reliable connections with a high QoS level.

Ⅳ. Technologies Enabling VHetNets

Comprehensive network management and control are required to realize the VHetNet usage scenarios, including Stratolites' positional constellation, radio resource management, inter-base station interference control, user association, and admission controls, which mainly determine network throughput, transmission delay, and outage probability. This section introduces the essential management and deployment factors of Stratolites in the VHetNet. These factors are summarized in the Table 3.

4.1 Stochastic deployment of Stratolites

The locomotion of Stratolites is mainly made by airstreams in the stratosphere, which is inherently stochastic. Then, the maneuver of Stratolite becomes probabilistic, resulting in stochastic system designs for network management. [12] showed some possibility that balloon-type base stations in the stratosphere can be imperfectly controlled by just adjusting their altitude. Therefore, as the large-scale atmospheric flows are predictable[13], the optimal control strategy could be computed according to the network's utility.

Once Stratolites are controllable, the service provider might establish a massive Stratolites constellation to provide wireless services to the cell area. Early research works such as [23] and [24] proposed a constellation of high-altitude platforms (HAPs) to improve the large-scale network utility. Nonetheless, a fine-tuned control strategy according to the aerodynamics of Stratolites still needs to be addressed.

4.2 Radio resource management

Frequency resource allocation, power control, and admission control should be adaptively considered in accordance with the environmental dynamics. The coverage of ground, aerial, and space base stations is frequently overlapped as the base stations are vertically deployed in the given cell area. Then, cross-layer network orchestration matters to resolve emergent problems such as controlling inter-layer interference, satisfying end-to-end QoS requirements, and minimizing the base station energy consumption. Such cooperative schemes include not only the base station deployments but also the channel allocation, power control, and user access choices. For example, [25] suggested radio resource management for HAPs that multicast OFDMA signal to meet the ground users' capacity requirements. The authors designed a Lagrangian relaxation-based optimization scheme to determine the optimal radio power, sub-channel, and time slot allocation.

4.3 MIMO, antenna, and beamforming

The key enablers of the Stratolites are MIMO, NOMA, antenna design, and beamforming. Stratolites necessitate high transmission and receiving gain, intra-/inter-layer interference management, and highgain beamforming to reimburse the high path loss and overlapped radio spectrum. Especially, the beam steering is crucial to stably provide communication links that are randomly perturbed along with the movement of Stratolites. The CAPANINA, a HAP

Table 3. Summary of key enabling technologies for Stratolites in the VHetNet.

Main design factor	Description
Non-deterministic control	The movements of Stratolites are probabilistic due to their dependency on the external winds. A robust control algorithm needs to be developed to establish VHetNets with Stratolites.
Radio resource management	Adaptive radio resource management and cross-layer orchestration are vital for optimizing Stratolites' deployments, minimizing interference, and meeting QoS requirements from ground terminals.
MIMO, antenna, and beamforming	Antennas and propagation enable Stratolites to acquire high-gain backhauls and links with low intraand inter-cell interferences.

project in Europe, adopted multi-antenna beamforming to avoid interference from other adjacent HAPs. Angular antennas with a high directive gain and massive antenna arrays to generate narrow beams and reshape cells can be applied to accomplish the Stratolites' requirements. [26] suggested multi-user MIMO precoding to minimize the energy consumption in the two-layer HetNet which consists of HAPs and LEO base stations. [27] proposed a MIMO non-orthogonal multiple access (NOMA) scheme in the HAPs network to maximize the total throughput of ground users, considering the spatial correlation between the channel gain of adjacent LoS users.

Ⅴ. Conclusion

Stratolites would become a crucial component of VHetNet which realizes integrated ground-air-space network for 6G communications. The hardware architecture, characteristics, and maneuver mechanism have been introduced, compared with the characteristics of small UAV and LEO base stations. Then, we describe promising future use cases of Stratolites in the VHetNet. Diverse physical-layer factors are investigated for Stratolites to support the above usage cases, including mobility control, resource management, and propagation design, considering the Stratolites' operational properties. With the vision of a future connected world, Stratolites will be the promising enabler of a sustainable aerial network.

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