Maneuver by Airstreams for Stratospheric Balloon Base Stations

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***Abstract*—Realizing sustainable aerial networks in current technologies has been considered infeasible due to physical limitations in unmanned aerial vehicles (UAVs). This paper introduces a brand-new aerial vehicle, stratospheric balloon base station (SBBS), which might be a breakthrough in aerial networks. SBBSs maneuver using buoyancy from the balloon, and equip solar panels to source the energy. Real implementation has shown that such configurations can prolong the flight time up to almost one year. However, the movements of SBBSs are stochastic as their maneuver solely relies on the airstreams. We adopt a deep Q-network (DQN) model to adaptively control the SBBSs for a given airstream pattern. The experiment reveals that sufficient controllability can be obtained when the air direction is diverse enough along the altitude. We also introduce challenges of SBBS networks that occur from the unique control characteristic of the SBBS. We believe that SBBSs can make our society connected more ubiquitously by realizing sustainable aerial networks.**

***Index Terms*—stratospheric balloon base station, deep Q-network, aerial network, low earth-orbit, unmanned aerial vehicle**

I. INTRODUCTION

Limitations in energy are the most formidable challenge in establishing reliable aerial networks by unmanned aerial vehicle (UAV) base stations (BSs). Enlarging the battery volume for increasing flight time directly causes escalated payload and power consumption, creating a tragic vicious cycle. Several approaches are suggested to increase energy efficiency or to detour energy limitations.

[1], [2] designed an energy consumption model that relies on the velocity of the UAV, then proposed the energy consumption minimization algorithm. [3] increases the energy efficiency by maximizing the coverage of UAV base stations. These research works suggest well-established efficient flight models, but the inherent inefficiency in energy consumption still exists.

One of the latest approaches to this energy problem is tethered UAV-BSs [4]–[6]. Tethered UAV-BSs utilize wired connections to source energy, which makes flight time unlimited. However, the wired connection may restrict the mobility of UAV BSs. Moreover, the power consumption for thrust still needs to be solved to avoid the inherent inefficiency from the flight energy consumption.

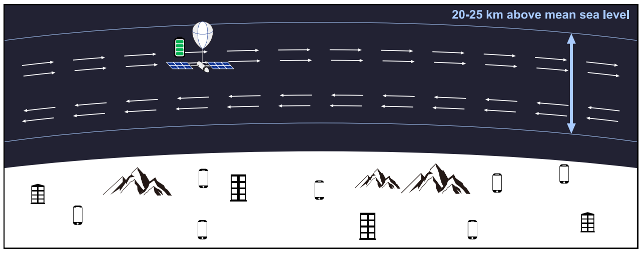

Figure 1. Conceptual wireless service scenario of a single SBBS.

Several research works adopt alternative UAVs such as fixed-wing [7] instead of multi-rotor UAV BSs. Fixed-wing UAVs additionally utilize lift power, so the energy efficiency is higher than that of multi-copters. However, the velocity of fixed-wing UAVs cannot be lower than their minimum control speed to avoid aircraft stalls. Such constraints obligate fixed-wing BSs to make frequent handovers, leading to large overheads in the network.

A novel balloon-type UAV has been reported in [8], which can resolve the above challenges of aerial networks. In this paper, we introduce the SBBS and and suggest a deep reinforcement learning (DRL) model to control the SBBS. Then, we summarize the challenges and open questions of SBBSs to establish reliable aerial networks.

II. STRATOSPHERIC BALLOON BASE STATIONS

We first introduce the concepts, peripherals, and controls of SBBSs, and compare SBBSs with other forms of aerial BSs. Then, we design a simple DRL model to move the SBBS to the designated position.

A. Comparison with LEO and UAV Base Stations

Fig. 1 illustrates the concepts of the SBBS. SBBSs regulate their altitude by controlling the air and lift gas ratio[1]. SBBSs passively control their position by floating along the airstreams at their altitude. The solar panels in SBBSs source the energy consumed by BS operations and maneuvers.

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[1] Counterintuitively, SBBSs use energy for descending because they need to pump the air inside of the balloon

Table I
CHRACTERISTICS OF THE THREE AERIAL BSS

Parameters	UAV BS	SBBS	LEO BS
Operating altitude	100-800 m	20-30 km	500-2000 km
Propagation delay	0.66-2.66 µs	0.13-0.33 ms	3.33-13.33 ms
Free-space path loss	101-113 dB	147-155 dB	175-187 dB
Network lifetime	Short	Long	Long
Coverage	Small	Large	Very large
Base station cost	Low	Medium	High
Energy source	Battery	Solar Panel	Fuel
Maneuver DoF	High	Low	Low

SBBSs have a variety of advantages over low-earth orbit (LEO) and UAV BSs. LEO BSs have the disadvantage of greater signal attenuation and propagation delay than SBBSs [9]. LEO BSs also have the potential to obscure star images observed by observatories [10] or produce large amounts of space debris, which could become an obstacle to space exploration [11], [12]. High launch costs and difficulty in correcting their orbits are other disadvantages of LEO BSs.

Meanwhile, UAV BSs have limited service time and may not be able to operate depending on the weather and terrain conditions [13], [14]. In addition, public safety and privacy protection should be addressed to introduce UAVs in our society [15].

SBBS can be a great alternative to LEO and UAV BSs. Table I lists the characteristics of the three types of BSs. SBBSs can operate stably for a long time and not be affected by weather. Moreover, SBBSs have a low launch cost because they only take off using buoyancy, and they are free from privacy and safety problems as they provide services at a high altitude.

B. Maneuver Design

Designing a robust control model is one of the most important problems in establishing reliable SBBS networks. Communication design to maximize network utility is highly related to the TP because the channel states between the SBBS and users rely on the position of the SBBS. Thus, the network utility may not be guaranteed unless the SBBS can follow the designed trajectories.

DRL models are considered to be more suitable for the TP of SBBS than analytical models. Building analytic control models might be infeasible as analytic models generally require large computing power, such as supercomputers for weather forecasting. Moreover, SBBSs cannot retrieve the entire information required to analyze the airstreams in real-time implementation. The dynamic change in the atmosphere also makes analytic navigation impractical. Meanwhile, the DRL model is designed to be adaptively updated with the change in the environment.

We design a simple deep-Q-network architecture (Fig. 2) to show the possibility of the movement by revisiting the DQN model in [8]. Whereas [8] shows that SBBSs can hold their position, we additionally simulate whether they can move to the specific position without a modification of the DQN network. We slightly change the reward function where the SBBS receives a reward of 1 when the SBBS gets close to less than 50 km from the target position.

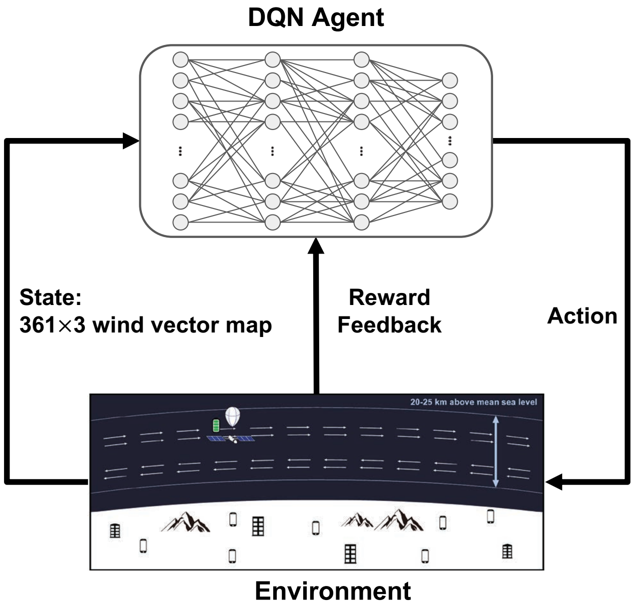

Figure 2. DQN architecture to decide whether the SBBS ascend, hold altitude, or descend. Accordingly, the SBBS can control its position.

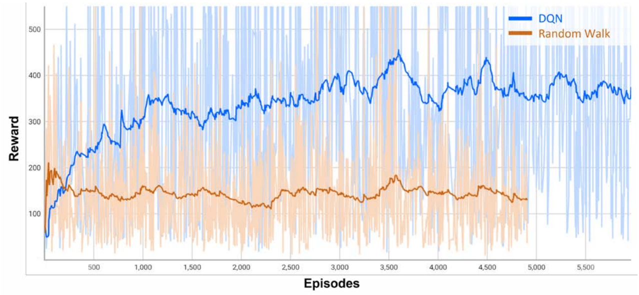

Figure 3. Numerical result for 5500 episodes.

C. Experimental Result

Fig. 3 shows the aggregated reward along the episodes for two schemes: one is DQN and the other is a random walk. Each episode consists of 960 steps, which implies that the maximum reward is 960. We additionally implement a random walk model which randomly decides three actions - ascending, staying, and descending.

The DQN model always outperforms the random walk model. When wind directions according to the altitude are diverse, the DQN model achieves almost the maximum reward. However, when the SBBS lies in harsh conditions (no diversity in wind direction), the SBBS must spend some time getting close to the target position. Interestingly, this implies that the DoF of SBBSs relies on the large-scale airstream pattern, unlike the other type of UAVs that utilize rotors.

III. FURTHER CHALLENGES

The experiment in the section II-C shows that the SBBS can control its position, but there still exist challenges to build reliable aerial networks.

When the SBBS enters an area that lacks diversity, the site could be covered by deploying multiple SBBSs. This deployment scheme is similar to the coverage provision policy of LEO BSs as the cell in the LEO network is covered by multiple LEO BSs that pass through the cell in series. However, the possibility of this deployment and consideration of network utility need to be studied.

The control DoF of the SBBS can be compensated by mounting additional propulsion systems. Then, the network should consider ground charging stations and energy consumption models. In addition to the mentioned scenarios, communication scenarios considering additional hardware variations may exist.

The reward of a DRL agent needs to be re-designed to consider the network utility. Communication resources should be optimized according to the utility function to provide a robust reward design. However, the control of SBBS is not deterministic, so optimizing the communication resource is probabilistic either. This stochastic network optimization is hardly studied and open question.

Developing an analytic model is also challenging due to the randomness in the control model. Providing a tight bound and optimal closed-form solution remains unsolved because the local airstream pattern is a stochastic process that changes over time,

IV. CONCLUSION

This paper introduces a brand-new stratospheric BS. SBBSs have the potential to be a breakthrough in aerial networks by only taking advantage of UAV and LEO BSs. Numerical simulation shows the controllability of the SBBS. However, the research on SBBS is in the early stage of development, so numerous research problems should be solved to bring SBBS into our society. Then, SBBSs will bring the era of ubiquitous connectivity via global aerial networks.

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