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FEATURES OF THE DEPLOYMENT OF MOBILE COMMUNICATION NETWORKS USING UAV

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The article considers the possibility of using 6G mobile communication technology for unmanned aerial vehicles, which is at the stage of active development. However, there is a problem of limited energy reserves in UAV batteries, which limits their effectiveness. This results in the need for regular charging stops, reducing the duration of their missions. The paper proposes a new approach to this problem using tethered unmanned aerial vehicles (UAVs). The basic idea is to create a network where tethered unmanned aerial vehicles (tUAVs) will maintain constant power and data transmission through a tether that connects them to a ground station (GN). This approach will avoid losing communication with the tUAV during recharging, ensuring continuous monitoring and control. The article examines in detail the concept of connecting a tUAV to the emergency department using a special cable that supplies electricity and transmits data at the same time. This approach makes it possible to constantly feed tUAVs and receive important information from them without the need for their severe limitation due to the need for recharging. A cable connection that supplies power and transmits data allows tethered unmanned aerial vehicles (UAVs) to leave the network coverage area only for short periods of time, such as during maintenance and repair. The article provides a comparative analysis between tUAVs and unmanned aerial vehicles (UAVs) that operate without tethering to a cable. The advantages and disadvantages of each approach are evaluated, taking into account their performance and the ability to maintain continuous communication in conditions of limited energy. Simulation results demonstrating the possibility of achieving up to a 30% increase in coverage probability using a tethered unmanned aerial vehicle (tUAV) with a cable length of 120 meters compared to an untethered unmanned aerial vehicle (UAV) demonstrate the potential effectiveness of this technology. The article also considers the challenges that may arise when implementing the proposed model in practice, and questions the tasks for further research that can contribute to the development of this innovative technology. Ways to further improve the technology may include improving cable length, optimizing energy efficiency and reducing maintenance costs. The research can contribute to the development of more advanced and productive unmanned aerial vehicle systems and open new opportunities for their application in various fields, from military applications to commercial and civilian purposes.

Key words: *unmanned untethered aerial vehicle, tethered unmanned aerial vehicle, unmanned aerial vehicle, base stations, macro base stations, ground station.*

Антоненко А. В., Буряк М. С., Цвик О. С., Бурачинський А. Ю., Балвак А. А., Занфіров Р. Р. Особливості розгортання мереж мобільного зв'язку за допомогою БПЛА

В статті розглядається можливість застосування технології мобільного зв'язку 6G для безпілотних літальних апаратів, яка знаходиться на стадії активної розробки. Проте, виникає проблема обмеженого запасу енергії в акумуляторах БПЛА, що обмежує їхню ефективність. Це призводить до потреби регулярної зупинки для зарядки, що зменшує тривалість їхніх місій. У статті пропонується новий підхід до цієї проблеми за допомогою тросових безпілотних літальних апаратів (тБПЛА). Основна ідея полягає в створенні мережі, де тросові безпілотні літальні апарати (тБПЛА) підтримуватимуть постійне живлення та передачу даних через трос, який з'єднує їх з наземною станцією (НС). Цей підхід дозволить уникнути втрати зв'язку з тБПЛА під час підзарядки, забезпечуючи неперервний моніторинг та контроль. У статті детально розглядається концепція підключення тБПЛА до НС за допомогою спеціального тросу, який постачає електроенергію і передає дані одночасно. Цей підхід дозволяє постійно живити тБПЛА та отримувати від них важливу інформацію без необхідності їхньої сильної обмеженості через потребу у підзарядці. Підключення тросом, що постачає електроенергію та передає дані, дозволяє тросовим безпілотним літальним апаратам (тБПЛА) залишати зону покриття мережі лише на короткий час, наприклад, під час технічного обслуговування та ремонту. У статті проводиться порівняльний аналіз між тБПЛА та безпілотними літальними апаратами (БмПЛА), які працюють без прив'язки до тросу. Оцінюються переваги та недоліки кожного підходу з урахуванням їхньої продуктивності та можливостей підтримання безперервного зв'язку в умовах обмеженої енергії. Результати моделювання, що демонструють можливість досягнення до 30% збільшення ймовірності охоплення за допомогою тросового безпілотного літального апарата (тБПЛА) з довжиною троса 120 метрів в порівнянні з безприв'язним безпілотним літальним апаратом (БПЛА), свідчать про потенційну ефективність цієї технології. Стаття також розглядає виклики, які можуть виникнути при впровадженні запропонованої моделі у практиці, і ставить під сумнів на завдання для подальших досліджень, які можуть сприяти розвитку цієї інноваційної технології. Шляхи для подальшого удосконалення технології можуть включати в себе поліпшення довжини троса, оптимізацію енергоефективності та зменшення витрат на обслуговування. Дослідження може сприяти розвитку більш передових та продуктивних систем безпілотних

літальних апаратів і відкрити нові можливості для їх застосування у різних галузях, від військового застосування до комерційних і цивільних цілей.
Ключові слова: *безпілотний неприв'язаний літальний апарат, тросовий безпілотний літальний апарат, безпілотний літальний апарат, базові станції, макробазові станції, наземна станція.*

Introduction. The use of unmanned aerial vehicles (UAVs) becomes extremely useful with the introduction of sixth generation (6G) mobile communications. First of all, it allows you to deploy a communication network in a country where the construction of traditional infrastructure was difficult or impractical. UAVs can fly at high altitudes and cover large widths, making them ideal for covering large areas and regions with difficult terrain. This is especially important for communication in sparsely populated or mountainous areas.

The use of BPLA in 6G networks can provide fast Internet access and communication in emergency situations, such as natural disasters or accidents, where existing infrastructure may be damaged or unavailable. UAVs can be used to provide network coverage in densely populated urban areas where large network capacity is required. They can provide additional bandwidth and improve communication quality, reducing the load on existing infrastructure. In general, the use of BPLA in the implementation of 6G mobile communication expands the network capabilities and enables communication in various conditions, including hard-to-reach areas and emergency status.

The aim of the study. The purpose of implementing a 6G mobile communication technology network based on UAVs is to provide reliable, extremely high-speed and effective communication coverage in various conditions and regions, including hard-to-reach areas, emergency situations and densely populated urban areas.

The objects of research are unmanned aerial vehicles and various possibilities of ensuring the duration of their operation.

The subject of research dedicated to the implementation of a network based on 6G mobile communication technology based on UAVs is the development and optimization of the infrastructure, the identification of potential applications in various fields, including transport, communications and emergency situations, as well as the study of the impact of this technology on society and technical aspects its implementation.

Analysis of recent research and publications. Current terrestrial network capabilities are still far from meeting the 6G requirements for global coverage. A large-scale network is required that can also integrate non-terrestrial networks to support a variety of applications such as aviation and navigation. The 6G architecture will be cellular, large and four-layer. Network levels include space, air, ground and underwater [1]. For example, with the space network layer, space internet services (which can be critical for space travel) will be in the coverage area thanks to satellites [2]. For the ground level, terabit speed data transmission will be provided to increase the 6G coverage area using terahertz frequency bands. Thus, the frequency will increase, causing an increase in path loss. The range of 6G will be less than that of current generations. In this case, it will be necessary to use a larger number of base stations, which will make the 6G network significantly more crowded and dense.

With the use of 5G, the concept of IoT networks refers to the billions of intelligent devices that connect systems, people and other applications to collect and share data. With 6G, this concept will expand and evolve to real-time monitoring and response, not limited to connection and communication detection. The "Tactile Internet" describes the real-time discovery, control, access, and operation of virtual objects as defined by the IEEE 1918.1 standard [3].

Due to current resource and detector limitations, the terahertz spectral range is not fully utilized. Photonic solutions have been an advanced technology that is expected to enable this frequency range to be used in a variety of ways. Photonic methods are the preferred solution for millimeter wave and THz generation in terms of energy efficiency, bandwidth, and control range. Terahertz frequency generation techniques based on photonic heterodyne mixing techniques can overcome the bandwidth limitations of electrical components and effectively contribute to the seamless integration of fiber optic and wireless networking. This will make the fiber-terahertz-fiber streaming system a promising choice [4], [5]. Visible Light Communication (VLC) systems are important for 6G. VLC works in the frequency range from 400 THz to 800 THz. Unlike RF technologies, which use antennas in the low terahertz range, visible light communication relies on light sources (such as LEDs, image sensors, or photodiode arrays) to communicate with transceivers. In several non-terrestrial scenarios, such as aviation or maritime applications, visible light communication outperforms RF technology in terms of propagation performance.

Presentation of the main research material. It is believed that UAV base stations (UAS) are an integral part of the 6G cellular architecture [6], [7]. The inherent mobility flexibility and relative ease of deployment can be useful for many requirements of next-generation cellular networks, such as providing coverage in hotspots and areas with scarce infrastructure, such as disaster recovery environments or rural areas. The high probability of establishing line-of-sight (LOS) with ground users due to high altitude leads to more reliable communication channels and a wider coverage area [8], [9]. Potential use cases for airborne BSs include offloading macro base stations (MBSs) in urban and densely populated areas and providing coverage to rural areas that typically suffer from low cellular coverage due to lack of operator incentives.

These potential advantages of airborne BSs have prompted the research community to study many aspects of UAV-enabled cellular networks, such as air-to-ground (AG) channel characteristics, optimal UAV placement, and trajectory optimization [10]. In addition, there are two key challenges in designing UAV-enabled systems, which will be discussed in more detail in this article. The first is the limited energy resources available on board, which makes the flight time less than one hour in most commercially available UAVs [11], [12]. The second key design issue is wireless backhaul [13].

Generally, the energy consumption of a UAV is twofold: propulsion energy, which is the energy consumed by the UAV for flight and hovering, and payload energy, which captures the energy consumption for communication and on-board processing. Many research works were aimed at developing energy-efficient communication schemes for UAVs in order to extend their service life. However, since the propulsion energy is much greater than the payload energy, energy-efficient communication will not greatly affect flight time. This short flight duration may not be a problem for some use cases, such as delivery by drones between nearby locations or the distribution and collection of data from sensor networks. however, when it comes to UAV installations, longer flight time is vital to ensure stable and uninterrupted cellular communications.

Unlike ground base stations, which have wired communication channels (usually using fiber optic cables), UAVs rely on wireless communication channels. Compared to wired connections, wireless reverse connections are susceptible to higher latency, interference, and lower achievable data rates. Therefore, it is important to find the best technology for establishing wireless feedback on UAVs [14]. The available solutions in the article include: satellite communication, millimeter wave communication, optical communication in free space (OZVP) and in-band transit communication. Each of these four solutions has its advantages and disadvantages. For example, satellite communication provides a more reliable transit link, but suffers from higher latency. On the other hand, millimeter waves and OZVP provide a much higher data transfer rate compared to in-band communication. However, both solutions are highly vulnerable to jamming and are only reliable over short distances. In modern literature, the most attention is paid to the use of intraband transit communication. This solution has lower latency compared to satellite backhouse. It does not require a PvP channel for effective communication, like millimeter waves or OZVP. However, due to the high flight altitude of the UAV, it suffers from higher levels of interference, which can significantly reduce the achievable rate of transit feedback. This paper proposes a system setup based on tethered UAVs (tUAVs). The proposed technology solves the two technical problems described above: short flight time due to limited on-board power and establishing reliable feedback. The interface between the BS and the UAV consists of two components: power supply and data transmission channel. The power supply is carried out from the BS to the tUAV through a wired connection, which allows the tUAV to maintain a much longer flight time. Similarly, the data transmission channel between the UA and the tUAV is also physical through fiber optic communication, which provides reliable high-speed data communication between the tUAV and the base station. Both the power and data wires are bundled inside the binding. Currently commercially available UAVs can stay in the air continuously for several days, with a proven ability to withstand harsh weather conditions. Due to its weight, the length of the cable is usually limited and ranges from 80 m to 150 m [14]. In a recent case, Puerto Rico deployed UAVs to provide cellular coverage to affected areas after Hurricane Maria [15].

The main disadvantage of tUAV is the limited length of the cable, which limits the mobility and flexibility of movement of the drone. Thus, a compromise between UAVs and UAVs naturally arises, which looks as follows. On the one hand, the tUAV has a much longer flight time compared to the UAV due to the stable power supply via the cable. However, it can hover or move only in a limited space defined by the length of the cable and the surroundings of the object of observation. On the other hand, the UAV has complete freedom to move anywhere to maximize network performance. However, due to the limited capacity of the on-board battery, it is forced to regularly interrupt its work to recharge or replace the battery. Unfortunately, today we do not have the technology that can provide a long flight time while maintaining free mobility.

The proposed system consists of three main components:

– UAV;
– rope;
– NS.

The UAV is placed in a carefully selected location that satisfies two conditions: it has a reliable connection to the main grid and it has a stable power source, such as a grid connection or a generator. These two connections (power supply and mains) extend to the UAV using a cable. Thus, the cable provides uninterrupted power supply to the UAV, which allows it to remain operational with a significantly longer flight time. In addition, the cable also connects the UAV to the main network via a wired connection, providing stable, reliable and secure feedback. The UAV can hover only within a certain range, which mainly depends on the length of the cable. If we assume that the NS, which is the launch point of the tUAV, is placed on the roof, then the tUAV can hover around the roof within a truncated hemisphere with a radius equivalent to the length of the cable, centered on the roof. The general area in which the UAV can hover is limited by the height of nearby buildings. Motion planning methods can be used to determine achievable three-dimensional (3D) locations for a given environment [16]. This area will be referred to as the hang area later in this article. The UAV carries antennas and a set of computing units. These computing units are connected to the NS through an optical fiber that transmits data along the cable. Although antennas and processor units are considered heavy components for typical UAVs, modern commercial systems are capable of carrying up to 60 kg of additional payload [17]. The UAV must hover within the hover area and find an optimal 3D location that maximizes cellular coverage for ground users. In addition to its main task – ensuring the connection with the main network and energy resource, NS is responsible for cable control. In particular, the emergency operator must monitor the tension of the cable and ensure that it is always taut. During the movement of the tUAV, the EMS should sense whether the tUAV needs to release a longer cable to reach the destination, or retract an additional length to ensure the tension of the cable [18], [19]. From the above considerations, it is clear that a reasonable selection of the location of the emergency vehicle is of great importance for the performance of the tUAV system. For example, placing an emergency vehicle on a roof surrounded on all sides by tall buildings will reduce its hovering area almost to the area above its own roof. A smaller hover zone leads to a more complex UAV 3D placement problem and limits the UAV's mobility. The process of choosing the location of an emergency station must take into account many aspects, such as the spatial distribution of traffic demand and the availability of the necessary infrastructure. In addition to productivity, economic efficiency should be considered when designing a UAV system. There are certain differences in terms of capital expenditure (CA) and operating costs (OS) between tUAVs and UAVs. The capital investment that exists only in tUAV systems is mainly related to the cable and its mechanical controller and ground station. At the same time, the capital investment that exists only in UAVs is related to the charging stations required for recharging/replacing the UAV batteries. On the other hand, the operating costs that exist only in tUAV systems are mainly related to the rental of the roofs that are used to host the ground station.

Monte Carlo simulations will show the trade-off between tUAVs and UAVs in terms of unlimited mobility with limited flight time for UAVs and limited mobility with unlimited flight time for tUAVs. First, the setup of a system consisting of an MBS, a cluster of users and a UAV deployed to serve this user cluster and offload the MBS will be considered. User locations are evenly distributed within the cluster with a radius of 100 m. In case of UAV, we assume that it hovers in the center of the cluster for maximum coverage. However, due to battery limitations, the UAV must leave its location in the air and fly back to the charging station to charge/replace the battery. During this time, users are served only by MBS. Hence, we present the availability of the UAV as the fraction of time it is actually operational. On the other hand, in the case of using a tUAV, we assume that it has an unlimited flight time. However, its mobility is limited by a cable connecting it to the MBS with a length of 120 m, similar to the specifications of the UAV [20]. So, here we assume that the tUBLA is an MBS.

In this simulation, one circular cluster of users is considered, and the users are evenly distributed inside a disk with a radius of 100 m. The availability of the UAV determines part of the time during which the UAV is working, and the rest of the time it is charging/replacing the battery. The UAV is connected to the MBS via a cable 120 m long [20]. 3 scenarios are compared: scenario 1, when an UAV is used and the main limitation is its availability, scenario 2, when a tUAV is used and placed in the optimal place in the hover area, and scenario 3, when the UAV is placed directly above its NS (optimal placement is not considered).

In this simulation, the coverage of uniformly distributed users within a disk with a radius of 100 m is studied. The MBS is located 160 m from the disk center. The tUBLA base station is placed on the nearest available roof to the center of the disk. The availability of roofs determines the share of buildings where emergency deployment is allowed. The building density is 500 buildings/km2. 2 scenarios are compared: scenario 1, when an UAV is used and the main limitation is its availability, scenario 2, when a tUAV is used, and the BS is placed on the closest available roof to the center of the cluster [21].

In case of readiness, 0.8 tUAV outperforms UAV if the distance between the MBS and the center of the cluster is less than 193 m. This threshold increases when UAV availability decreases.

The performance of the tUAV is compared for two deployment scenarios: the tUAV hovers exactly over the NS with the cable stretched to the maximum and the tUAV is placed in an optimal location within its hover zone that maximizes the coverage probability. The results show the importance of optimal placement of the tUAV. The problem of optimizing the placement of tUBAS differs from the typical problems of 3D placement of UAVs, which are described in the article. This is mainly due to the limited mobility of the tUAV, which reduces its availability in 3D locations. Note that this deployment problem is different from the scenario of setting the maximum allowable altitude for UAVs. For the latter, a UAV can hover anywhere as long as it maintains its altitude below a set value, which cannot be said for a tUAV.

As mentioned earlier, the NS does not necessarily have to be the MBS. It can be the roof of any building, as long as it has access to a stable energy resource and a reliable connection to the main grid. Obviously, these conditions are not always satisfied by any randomly selected building. Additionally, not every building that meets these conditions will provide an operator with access to deploy their EMS on the roof. Hence, for a given building density, rooftop accessibility is introduced as the ratio of buildings that meet the above conditions and are willing to provide access to their rooftops. A similar setup is considered, with the deployment of the NS on the nearest available roof to the center of the cluster, instead of deploying it on the MBS. In addition, the distance between the MBS and the center of the cluster is fixed at 160 m. The location of buildings is modeled using the Poisson point process (PTP) with a density of 500 buildings/km2, which is a typical building density in urban areas. The characteristics of tUAVs and UAVs for different values of roof accessibility are compared. It is observed that the minimum required rooftop accessibility for a tUAV to outperform an UAV decreases as the cable length increases. For example, when the availability is 0.9, the required roof availability decreases from 0.25 to 0.05 as the maximum cable length increases from 80 m to 120 m. This result shows the effect of the maximum cable length on system performance. Given that the availability of rooftops is a significant part of the capital cost of the system, these results show that increasing the maximum cable length is indeed important for a cost-effective tUAV deployment.

The complications with the tUAV deployment model are as follows. First, aerial communication systems in general require new regulatory policies, then tUAV systems may require some special considerations. For example, new safety regulations must be implemented for areas where ropes are allowed. Safety margin around buildings and above ground around buildings and above ground to avoid accidents due to entanglement or any malicious attempts to entangle the cable.

Secondly, in contrast to typical studies on the optimization of UAV deployment, the problem of tUAV deployment is different. During operation, each tUAV must be physically connected to the emergency room on the roof by means of a cable. Therefore, the problem is more limited and needs careful study. The problem of choosing a roof can be solved using different approaches, depending on the main goals of the operator in terms of quality of service. In addition to cellular coverage considerations, cost-effectiveness should also be considered during the roof selection process.

Third, with regard to the location chosen for the deployment of the emergency vehicle, it is important to know exactly what the hover area looks like. Given the constraints of not impinging on neighboring buildings, providing sufficient distance from public access, and creating a buffer over all surrounding buildings for safety, the hang zone on each roof is truly unique. For example, if the roof is surrounded on all sides by lower buildings, it will have a larger flight area and therefore more freedom of movement for the tUAV. The hovering zone depends on the distance to the surrounding buildings and their relative height. In order to solve the problem of 3D optimization of the placement of the UAV, it is first necessary to obtain an analytical model for the hovering area. first you need to get an analytical model of the hover region.

Conclusions. The paper considered the potential of tUAVs for cellular coverage and increasing capacity. The proposed setup can be seen as a compromise that aims to replace the current performance limitations of UAVs due to limited on-board energy with mobility limitations due to tethering. tUAV systems have been shown to have promising advantages over UAVs despite tethered mobility limitations. Some potential use cases and applications were described where a tUAV-mounted BS would be of great benefit, such as increasing bandwidth in urban areas, expanding coverage in rural areas, and densifying the network. Finally, some open issues and research problems have been described that need to be thoroughly investigated to better understand the performance limitations of the proposed setup.

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