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Use of unmanned aerial systems for communication and air mobility in Arctic region

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Abstract. The current state of telecommunications infrastructure in the Arctic does not allow providing a wide range of required services for people, businesses and other categories, which necessitates the use of non-traditional approaches to its organization. The paper proposes an innovative approach to building a combined communication network based on tethered high-altitude platform station (HAPS) located at an altitude of 1-7 km and connected via radio channels with terrestrial and satellite communication networks. Network configuration and composition of telecommunication equipment placed on HAPS and located on the terrestrial and satellite segment of the network was justified. The availability of modern equipment and the distributed structure of such an integrated network will allow, unlike existing networks (Iridium, Gonets, etc.), to organize personal mobile communications, data transmission and broadband Internet up to 100 Mbps access for mobile and fixed subscribers, rapid transmission of information from Internet of Things (IoT) sensors and unmanned aerial vehicles (UAV). A substantiation of the possibility of achieving high network capacity in various paths is presented: inter-platform radio links, subscriber radio links, HAPS feeder lines - terrestrial network gateway, HAPS radio links - satellite retransmitter (SR), etc. The economic efficiency of the proposed solution is assessed.

Keywords: gateway; high altitude platform station (HAPS); low earth orbit (LEO); radio channel; radioisotope power system (RPS); unmanned aerial vehicle (UAV)

1. Introduction

The area of the Arctic, which refers to the territory above the Arctic Circle, is approximately 21 000 000 km² with the population of more than 4 230 000 people. For example, the Russian part of the Arctic, where 12-15% of the country's GDP is created and provides about a quarter of Russia's exports, covers an area of 9 000 000 km² with a population of 2 500 000 people. Currently, the provision of communication services in the Arctic is extremely limited due to the lack of a modern telecommunications infrastructure in this territory, and the entire range of communication services is implemented on the basis of:

- communication systems based on geostationary satellites "Yamal" (Gazpromcosmos 2022), "Express" (Information Satellite Systems 2022), Inmarsat (Immarsat 2022), etc.;

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• Low Earth Orbit Satellite (LEO) Iridium (Iridium 2022, Gavish 1997), providing personal telephone communication and data transmission at a speed of 2.4-4.8 kbit/s;

• Russian LEO Gonets (Gonets Leosat System 2022), which allows organizing data transfer at a speed of 9.6-64 kbit/s and delivery in e-mail mode;

• transceiver equipment in Very High Frequency (VHF)-, Shortwave (SW)-, Medium Frequency (MF)-bands, providing personal telephone communication and data transmission at a speed of up to 4.8 kbit/s.

In addition, the provision of telephony services is carried out through rather narrow-band channels of Molniya/Meridian-M satellites located in a highly elliptical orbit and using cellular communications in large cities and in individual settlements.

Currently in the Arctic, the following services must be provided:

• fixed and mobile telephony;

• Internet access at speeds from 25 Mbit/s to 100 Mbit/s;

• television and radio broadcasting;

• transfer of various types of information from stationary objects, including IoT data;

• ensuring personal communication and air mobility, primarily control and communication with UAV, monitoring the waters of the Arctic Ocean, urban infrastructure, various industrial and energy facilities;

• organization of corporate and departmental communication networks.

However, none of the above communication systems can provide the listed range of services. This is due to the fact that:

• there are technical limitations, namely: the use of geostationary and highly elliptical satellites is possible only at low elevation angles of ground-based antennas, and this leads to interruptions in communication during movement, an increase in the length of the beam path in the atmosphere and an in signal energy attenuation by 10 dB (in C-band) and 14 dB (in Ku-band) (Gritsenko and Yuriev 2014, Anpilogov and Gritsenko 2021), and a large value of the Earth noise, which leads to a significant decrease in the quality factor and the inability to provide the specified energy characteristics of communication channels for personal communications and UAV;

• there are economic limitations: the very high cost of creating satellite communication systems, reaching tens of billions of dollars, the high cost of subscriber terminals for both fixed communications and personal communications, reaching from ten to hundreds of thousands of dollars for each subscriber terminal (Habr 2022). All this leads to the unprofitability of existing communication systems and extremely narrows the range and market of their application.

In this article, for the first time, a scientific justification was made for the possibility of an effective (in terms of technical and economic parameters) organization of an integrated communication network built on new technological principles in the northern territories of the world, which does not have the above disadvantages and limitations, which ensures the provision of the required range of fixed and mobile communication services in northern latitudes. The implementation of this network based on stationary tethered unmanned aerial systems (UAS) located at a relatively low altitude of 1-7 km, unlike existing studies based on stratospheric airships (GSMA 2021, Xing *et al.* 2021, Liu *et al.* 2016, Tozer and Grace 2001, Ilchenko and Kravchuk 2010, Anpilogov and Gritsenko 2021, Gritsenko and Yuriev 2014, NASA 2022, Summerer *et al.* 2007, Gazpromcosmos 2022, Information Satellite Systems 2022, Immarsat 2022, Habr 2022, Gerasimov *et al.* 2014, U.S. Government Accountability Office 2012, U.S. Department of Defense 2012, Congressional Budget Office 2011, Izet-Ünsalan and Ünsalan 2011), in combination with terrestrial and satellite communication systems will provide a full range of modern information services for the population, businesses and government agencies, is a rational, competitive, with low technical risks and an economically effective solution for the provision of communication services with a short period of its commissioning into commercial operation.

2. Theoretical basis

One of the possible solutions to the above communication problems in the Arctic is a combined communication network based on the integration of several terrestrial gateways that have access to the main lines of the main communication operators, cellular and satellite systems with additional intermediate communication nodes based on UAS, the most preferred of which are tethered HAPS (GSMA 2021, Xing *et al.* 2021, Liu *et al.* 2016, Tozer and Grace 2001, Ilchenko and Kravchuk 2010, Anpilogov and Gritsenko 2021, Gritsenko and Yuriev 2014). These platforms, there relay radio complexes are installed, can be located at an altitude from 1-7 km (the border of the troposphere and stratosphere in the Arctic) to 20-22 km. One of such aerial platform, depending on the height of its placement h, can provide a service area with a diameter of $D \approx 2h/tg(\alpha)$ from 70 to 1100 km, which is illustrated in the Table 1, where α is the minimum elevation angle of terrestrial user antennas.

Table 1 Diameter of the visibility zone depending on the height of HAPS and the elevation angle of subscribers' antennas

α, angle	h=5 km	h=7 km	h=20 km
α=2°	286	400	1 140
α=3°	190	268	764
α=4°	144	200	580
α=6°	96	134	380
α=8°	72	100	284

Table 2 Budget of the radio link "HAPS-subscriber" at an altitude of 20 km

Parameter	Value
Bandwidth, MHz	5
Carrier frequency, MHz	1 800
Type of duplex channel	TDD
Number of subcarrier frequencies	300
Cyclic prefix	Normal
Type of modulation	64QAM/16QAM/QPSK
Transmission rate	25 Mbit/s
Transmitter power, dBm	43
Antenna gain, dBi	18
EIIRP, dBi	61
Receiver sensitivity, dBm	-77…-103
Signal energy loss in the radio line, dB	138…164
Signal energy loss at the service area boundary, dB	135

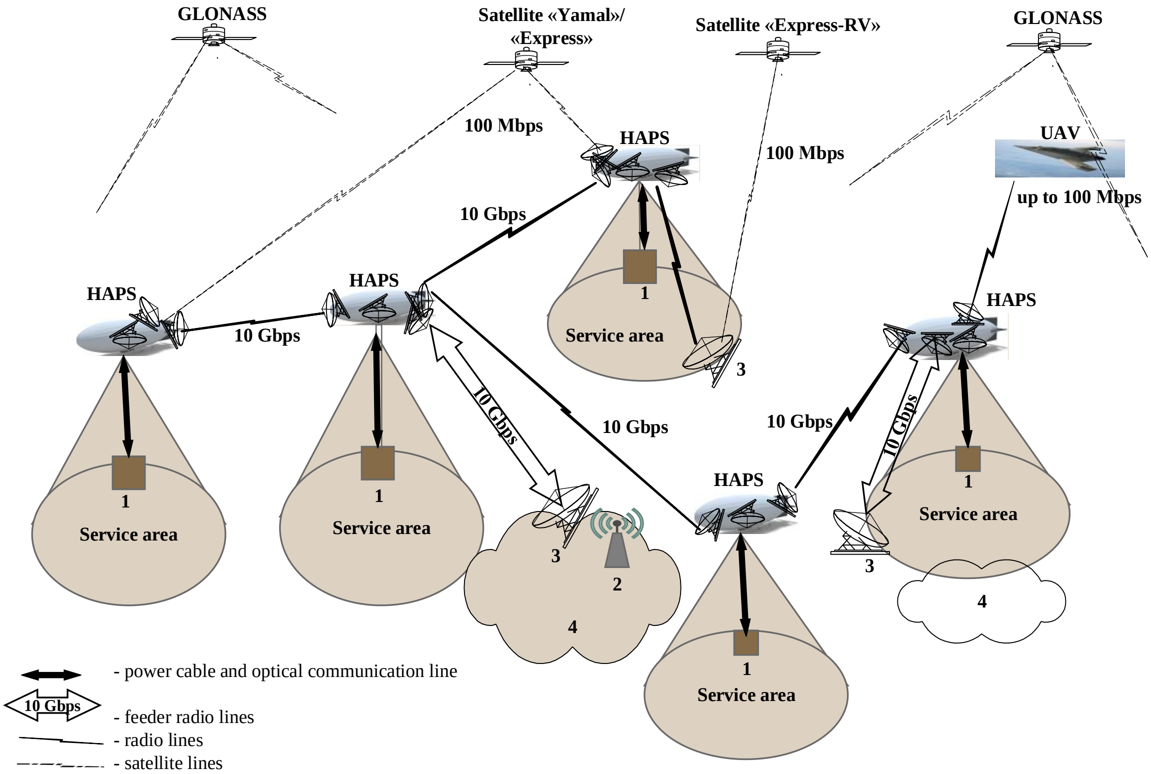

Fig. 1 Communication network configuration based on HAPS

In (Gritsenko and Yuriev 2014, Anpilogov and Gritsenko 2021), it is proposed to organize a communication network in the Arctic using stratospheric (*h*=20 km) platforms and an approximate budget for a radio link from HAPS to a personal phone is given. The calculation results confirming the possibility of achieving a transmission rate of at least 25 Mbit/s are presented in the Table 2.

This network assumes the use of a network of geostationary SR as a core network and completely excludes the terrestrial infrastructure of backbone communication lines. However, this concept has the following significant technological and economic limitations:

1. Almost all projects of HAPS (stratospheric airships) at an altitude of 20 km use solar panels as a power plant. But in the Arctic, during the polar night, which lasts about 6 months, this possibility is extremely limited to 2-3 hours;
2. The use of nuclear power plants on HAPS in the free flight of airship is practically unacceptable due to high technological risks and high international regulations for ensuring the safety of nuclear installations;
3. To provide the bandwidth required for modern and future communication systems from several hundred Mbit/s to 10 Gbit/s when using HAPS at an altitude of 20 km, a radio link of the same bandwidth of the communication channel between the platforms and geostationary relay satellites will be required, which is currently and in the near future unrealizable;
4. The implementation of a stratospheric HAPS platform has significant technical risks.

3. Methodology

In view of the foregoing, a rational option for building a communication network in the Arctic is to use a network of tethered HAPS (aerostats) at lower altitudes of 1-7 km and their integration with terrestrial backbone and satellite communication networks. In this case, it is possible to use standard technological solutions that have already proven themselves as HAPS. The advantage of this option is not only the much lower cost of air platforms, but also the possibility of using power cables or placing a less dangerous power plant on the platform.

Since the service area of aerial platforms at a height of 1-7 km is significantly smaller than that of platforms at a height of 20 km, more of them will be required to create a continuous service area. However, in the Arctic there is no need to create such a continuous zone, since the distribution of the population is uneven and mainly industrial and residential facilities are concentrated in large settlements or within 50-100 km from them. Therefore, in the Arctic, it is advisable to create a service area from a set of several dozen small service areas (“spots”), but it is precisely such service areas that can be created quite simply by platforms at a height of 1-7 km.

The Fig. 1 shows the configuration of a combined communication network based on high-altitude air platforms, where 1 is the ground unit HAPS, 2 is the central station of the mobile operator, 3 is the gateway, and 4 is the terrestrial and cellular networks. This configuration includes:

1. Network of tethered HAPS located at an altitude of 1-7 km;
2. Several ground transceiver stations with access to the main fiber-optic communication lines of telecom operators with reference to the public switched telephone network, fixed and cellular communication networks, as well as to the Internet, private transmission networks data and satellite communication networks. These stations also perform the functions of network gateways for a communication network based on HAPS;
3. GLONASS navigation system.

The airborne radio complex, located on HAPS and on the terrestrial and satellite segments of the network, includes:

- base station of cellular communication 4G in the range of LTE-1800 (4G, LTE) 1800 MHz (Band 3);
- on-board equipment of feeder communication lines with ground stations-gateways;
- receiving and transmitting on-board equipment from sensors of IoT system;
- on-board equipment of communication lines between HAPS in *Q/V*-band with a bandwidth of 10 Gbit/s;
- equipment of GLONASS system for controlling the platform and antennas of interplatform communication lines;
- on-board equipment in *Ku*-band (14/12 GHz) or in *Ka*-band (30/20 GHz) for organizing communication lines with geostationary SR (“Yamal” or “Express”) or non-geostationary SR (“Express-RV”), as well as UAV.

The Fig. 2 shows an example of one of the options for a possible topology of communication network.

The availability of modern switching equipment in conjunction with the distributed structure of the network determines its competitive advantages over existing systems and allows the provision of a wide range of information services, taking into account the specifics of the Arctic, including:

- personal mobile communications precisely in those areas where it is in demand;
- data transmission, including broadband Internet access for mobile and fixed subscribers at the

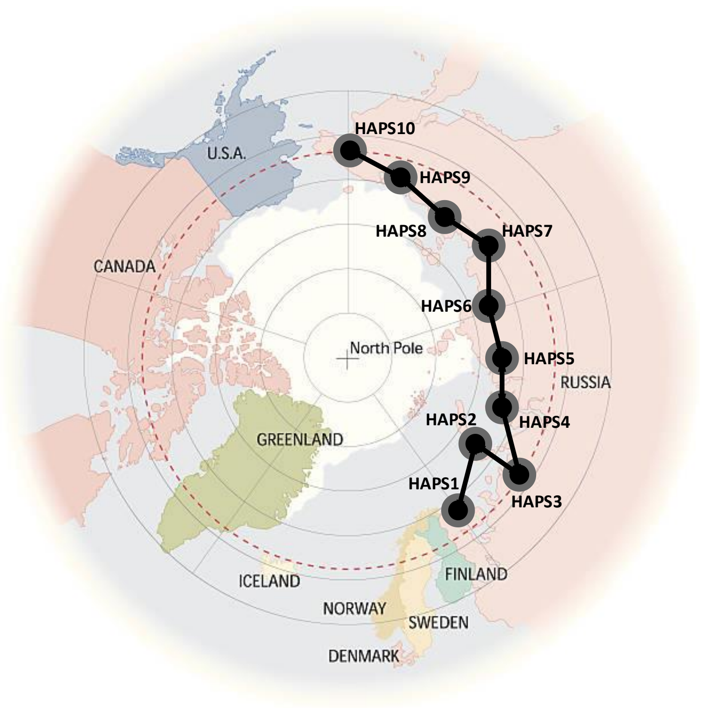

Fig. 2 Variant of the topology of communication network in the Arctic of the Russian Federation

speed of 100 Mbit/s and higher (this service is currently available only in a few large Arctic cities);
• data collection from sensors of IoT systems (gas pipelines, urban communications, specially protected and hazardous objects, etc.) based on foreign protocols LoRa, LoRaWAN, Sigfox, NB-IoT (Chiani and Elzanaty2019, Sigfox 2022, Nolan *et al.* 2016, Kumaritova and Kirichek 2016), and Russian Strizh, Vaviot and SNBWAN (Sartakov 2020);
• control and transmission of information from UAV when monitoring ice conditions in the waters of seaports, energy facilities, public utilities, etc;
• collection of meteorological information in the atmosphere.

The implementation of this network will not only expand the service area of existing ones and increase the level of communication services in the Arctic, but also ensure the efficiency of activities in the field of civil defense, protection of population and territories from emergencies of natural and man-made character.

4. Results

4.1 Assessment of the energy characteristics of radio communication lines and network capacity

Signal-to-noise ratio (SNR) at the input of the receiver of communication lines is determined by the well-known formula (Kamnev *et al.* 2010)

$$SNR = P_t + G_t + G_r + \eta_t + \eta_r - L_t - L_r - L - L_{add} - P_n \text{ [dB]}, \quad (1)$$

where $P_n = 10 \lg (kT_nB_n/10^{-3})$ (dBm) is the total thermal noise power in dBm, where k is the Boltzmann constant, $T_n = T_a + T_e$ is the equivalent noise temperature, T_a is the total loss in the antenna and noise (background) of the sky, $T_e = T_0 (F_{sys} - 1)$ is the receiver noise temperature ($T_0 = 290$°K, $F_{sys} = 10^{NF/10}$ is the receiver noise factor and B_n is the noise bandwidth, which can be estimated as $(1.002 \div 1.57)B$, where B is the receiver bandwidth, P_t is the transmitter power (dBm), η_t and η_r are the efficiencies of antenna-feeder transmitting and receiving paths, G_t and G_r are the transmitting and receiving antenna gains, respectively (dBi), L_t and L_r are the losses in the antenna-feeder transmitting and receiving paths (dB), L is the signal energy loss along the propagation path (dB), L_{add} are the extra link loss (dB).

The bandwidth of the communication line is defined as (Kamnev *et al.* 2010)

$$C = \frac{P_s}{h_p^2 kT} = \frac{P_t G_t S_r}{4\pi h_p^2 r^2 LkT} = \frac{\lambda^2 P_t G_t G_r}{16\pi^2 h_p^2 r^2 LkT}, \quad (2)$$

where h_p^2 is the threshold SNR, P_s is the signal strength at the receiver input, λ is the wavelength, r is the distance between receiver and transmitter (radio link length), S_r is the effective area of the receiving antenna. We should note that the maximum distance $r = R_{max}$ depends on the curvature of the Earth and the height of the transmitter antennas (h_1) and receiver (h_2) and is equal to (Ilchenko and Kravchuk 2010): $R_{max} = (2R_z)^{0.5}(h_1^{0.5} + h_2^{0.5})$ and at $R_z = 6371.032$ km defined as $R_{max} = K_r(h_1^{0.5} + h_2^{0.5})$, where K_r is the refraction coefficient equal to 3.57 for direct geometric visibility and 4.12, taking into account the refraction of the radio beam in the atmosphere. Therefore, for example, in order to implement a radio link with a receiver located at ground level and having a radio link budget that provides transmission over a distance of more than 112 km, the transmitter must be located at a height of more than 1 km.

The initial data for calculating the radio links "HAPS-UAV" and "HAPS-HAPS" and analyzing the requirements for radio equipment is presented in the Table 3.

The calculation results are presented below in the Table 4. In the calculation, it was assumed that active phased array antenna (APAA) is used on HAPS and UAV, the length of HAPS-HAPS radio links is 500 km, and the platform heights were chosen 5 km with a change due to instability up to +/- 0.8 km and angular visibility of +/- 100, frequency 27 GHz and FDD mode implemented.

As we can see from the Table 4, with sufficiently typical initial data of radio equipment, the budget of radio links is realizable.

The total throughput of the combined communication network will be higher than the throughput of cross-platform radio links of 10 Gbit/s, because the network will include several

Table 3 Initial data for calculating the radio links "HAPS-UAV" and "HAPS-HAPS"

Paremeter	HAPS	UAV	Notes
Height, km	5	to 10	
Carrier frequency, GHz	23	23	Frequency division duplex (FDD) mode
Transfer rate, Mbit/s:			
- transmission	5	50	
- reception	50	5	
Radius of the service area, km	100	100	radio link range
Angular radio visibility zone, degree	sphere	sphere	

Table 4 Radio link budget

Parameter	HAPS → UAV Speed=5 Mbit/s	UAV → HAPS Speed=50 Mbit/s	HAPS – HAPS, Speed=1 Gbit/s	HAPS – HAPS, Speed=10 Gbit/s
$EIIRP=P_tG_t\eta_t$, dbW	30	23	36	40
Beam width HAPS, angle	11	21	6.5	6.5
Number of antenna beams HAPS/UAV	9 (depends on the number of UAV served)	9/400	4, antenna area is 0.4×0.4 m	4 (depends on HAPS hold accuracy), antenna area is 0.4×0.4 m
Antenna type HAPS	APAA	APAA	PAA with fan switchable 4 beams	APAA with fan switchable 4 beams
$G_r/T°$, dB/K	-20	7	8	14
Beam width UAV/HAPS, angle/G_r, dBi	85/6	17	6.5	6.5
Antenna type UAV/HAPS	conformal APAA with an area of emitters 32 sm^2	conformal APAA with an area of emitters 32 sm^2	PAA with fan switchable 4 beams	PAA with fan switchable 4 beams
SNR, dB	10	7	8.5	8.5

junction points with geographically dispersed gateways of terrestrial core networks, existing and future as a result of the construction of branches from the above-mentioned fiber-optic communication lines of the Northern route.

In the proposed communication system based on a network of HAPS, it is possible to use hardware and software modifications, for example, LoRaWAN protocol, to provide IoT services, or use the tools built into 4G protocol, which greatly simplifies the implementation of this communication system.

The use of satellite communication lines is assumed as a reserve for the feeder communication lines “HAPS-Gateway”. The service areas of the Russian Yamal and Express-RV RS (Gritsenko and Yuriev 2014) allow concluding that it is possible to organize communication lines “HAPS-RS” in northern latitudes above 70°.

4.2 Choice of options for building an of air platform options and its power supply

As the analysis of various options for building HAPS (d’Oliveira *et al.* 2016) shows, stratospheric balloons, airships, aerostats and UAV are most often used in existing and prospective projects. For example, the European Space Agency (ESA) considers the stratospheric airship Stratobus (FINABEL European Army Interoperability Centre 2020) and the unmanned vehicle Zephyr (Airbus 2018) as possible options for air platforms located at an altitude of 20 km. Stratobus is being developed by Thales Alenia Space and can carry about 250 kg of payload. Zephyr UAV uses only the energy of the sun, charging batteries during the day and consuming the accumulated energy at night, and is able to stay in the sky for 54 hours. For the Arctic, the preferred option is a tethered soft balloon with a volume of approximately 10 000-20 000 m^3, located at an altitude of 1-7 km with a payload of approximately 500 kg and a total maximum power consumption of 10-15 kW (during descent/ascent of HAPS) and up to 4 kW in operating mode.

As it was already noted, the option of using solar batteries during the polar night to power the telecommunications equipment and the propulsion system of the air platform is practically eliminated, so two possibilities remain:

- use on HAPS of several radioisotope thermoelectric generators (RTG) with electric power up to about 10 kW;
- supply of electricity from the ground station through the power cable.

Russia has experience in the development and operation of miniature on-board nuclear installations with a capacity of 1.5-3.5 kW and RTG. NASA and ESA have similar developments on onboard RTG, while RTG developed by them with a mass of 45–60 kg have a power of several hundred W (Zakrajsek *et al.* 2016, Summerer *et al.* 2007, NASA 2022). With a power of one RTG of about 250 W, to provide the required power of 10 kW, about 40 such generators with a total weight of about 2 tons will be required to power the onboard radio engineering complex and the propulsion system. However, the cost of RTG is quite high and this option is unacceptable from an economic point of view.

In the second option of power supply to the air platform, power is supplied to it via a power cable from a ground power plant (gas or diesel generators), and even if the platform is at an altitude of 5 km, the weight of such a cable does not exceed 3 000 kg. One of the problems of such a power supply scheme is the icing of the cable and the removal of static electricity.

4.3 Evaluation of the economic efficiency of the network

It is obviously, that to determine the economic efficiency of the project, it is necessary to conduct marketing research in order to assess the volume of the communication services market, the needs of various users, the costs of creating and maintaining the network, etc. However, it can be estimated as follows.

The estimated cost of implementing a network of 20 HAPS and 2-3 gateways will be approximately 10 000 000 000-15 000 000 000 rubles in 2021 prices. At the same time, the cost of one HAPS will be about 900 000 000 rubles: 600 000 000 rubles will be the cost of directly HAPS, 200 000 000 rubles will be the cost of payload, 100 000 000 rubles will be the cost of ground segment. For comparison, the cost of creating Express-RV satellite communication network for servicing, including the Arctic region, will amount to about 300 000 000 000 rubles.

At present, the tariffs of telecom operators, such as Iridium and AltegroSky for satellite communications (data transmission at a speed of 2 Mbit/s and telephony) range from 10 000 to 40 000 rubles per month. Tariffs in the network based on HAPS for various subscribers can be made in the range from 3 000 to 15 000 rubles, while offering subscribers unlimited telephone traffic and a data transfer rate of 100 Mbit/s. Considering that the population of large cities in the Arctic is almost a million people, it is quite realistic to attract at least 8 000 subscribers under such conditions at the initial stage. Taking into account the above, the annual income from only one HAPS platform will be approximately 1 000 000 000 rubles, which follows from the Table 5, where TS is the telephone service, BWA is the broadband wireless access, and DS is the data service.

Taking into account the fact that the estimated cost of one network segment based on one HAPS is approximately 1 000 000 000 rubles, even such a rough estimate of the potential income from the provision of a wide range of modern information services indicates a fairly high economic efficiency of a communication network based on HAPS, which favorably distinguishes it from other projects for the organization of communications in the northern latitudes.

Table 5 Approximate evaluation of the economic efficiency of a communication network segment based on one air platform

№	Subscriber type	Service	Subscriber number	Tariff, 3 rub/month	Total for month, mln.rub	Total for year, mln.rub
1	Mass	TS, BWA	2 500	6 000	15	180
2	Corporate (Gazprom, Lukoil, etc.)	TS, BWA	1 000	15 000	15	180
3	Departmental (administration of region/district, Ministry of Emergency Situations, Rosatom, etc.)	TS, BWA	2 500	15 000	37.5	450
4	Sensors IoT	DS	2 000	6 000	12	144
5	Roshydromet, UAV, etc.	DS	10	3 000	0.03	0.36
	TOTAL		8 010		79.53	954.36

5. Discussion

The principles of building an integrated communication network in the Arctic involve the implementation of innovative solutions. Obviously, its implementation is impossible without a detailed study of such technical issues as:

- the choice the height of HAPS placement;
- the determination of the required specification and parameters of on-board equipment;
- the organization of power supply platform;
- the assessment of the influence of the accuracy of platform stabilization on the energy characteristics of the radio links of the communication network;
- the ensuring the operability of the network in the event of an emergency descent of an air platform or a failure of its onboard equipment.

The authors also agree that in-depth marketing research is needed to determine the economic efficiency of the project and its payback period. The development and commissioning of such a network is associated with significant material costs and requires the participation of not only the state, but also business. However, the development of the Arctic and, in particular, the infrastructure of the Northern Sea Route is possible only through the introduction of new technological solutions in the field of telecommunications.

6. Conclusions

The development of the Arctic is impossible without creating a modern telecommunications infrastructure, which requires innovative approaches to solving this problem. One of its possible solutions is the organization of a communication network based on aerial platforms located at a relatively low altitude and integrated with ground and satellite communication networks. The article offers a configuration of such an integrated network that includes a number of tethered HAPS, ground receiving and transmitting stations with access to public telephone networks and the Internet, as well as the GLONASS navigation system. Its implementation in the Arctic will provide:

- personal mobile communication on new technological means;
- high-speed data transmission speed and Internet access;

- collection and transmission of IoT information;
- prompt transmission of information from UAV when monitoring ice conditions, urban infrastructure and power facilities;
- collection and transmission of meteorological information.

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References

Airbus (2018), Airbus Zephyr Solar High Altitude Pseudo-Satellite flies for longer than any other aircraft during its successful maiden flight. https://www.airbus.com/en/newsroom/press-releases/2018-08-airbus-zephyr-solar-high-altitude-pseudo-satellite-flies-for-longer.

Anpilogov, V.R. and Gritsenko, A.A. (2021), *Broadband Access System in the Arctic based on High-Altitude Platforms and Geostationary Inclination Satellites. Satellite Communications and Broadcasting*, Grotek, Moscow.

Chiani, M. and Elzanaty, A. (2019), "On the LoRa modulation for IoT: Waveform properties and spectral analysis", *IEEE Int. Thing. J.*, **6**(5), 8463-8470. https://doi.org/10.1109/JIOT.2019.2919151.

Congressional Budget Office (2011), Recent Development Efforts for Military Airships, Congressional Budget Office. www.cbo.gov/publication/42725.

d'Oliveira, F.A., Melo, F.C.L. and Devezas, T.C. (2016), "High-altitude platforms-present situation and technology trends", *J. Aerosp. Technol. Manage.*, **8**(3), 249-262. https://doi.org/10.5028/jatm.v8i3.699.

FINABEL European Army Interoperability Centre (2020), Stratobus: A Feature Hybrid of Unmanned Air Vehicles for the European Air Defence Structure. https://finabel.org/stratobus-a-feature-hybrid-of-unmanned-air-vehicles-for-the-european-air-defence-structure.

Gavish, B. (1997), "Low earth orbit satellite based communication systems-Research opportunities", *Eur. J. Oper. Res.*, **99**(1), 166-179. https://doi.org/10.1016/S0377-2217(96)00390-6.

Gazpromcosmos (2022), Satellite Internet. https://www.gazpromcosmos.ru.

Gerasimov, A.V., Gerasimov, V.B., Kudzh, S.A. and Solovyov, I.V. (2014), "Long-term stratospheric communication and observation platforms. New stage of development", *Bull. MSTU MIREA*, **2**(3), 13-35.

Gonets Leosat System (2022), https://gonets.ru/eng.

Gritsenko, A.A. and Yuriev, R.N. (2014), "Providing communications at high latitudes. Development of information and telecommunications environment in the Arctic", *VII International Forum-Exhibition Professional Radio Communications and Navigation*, Moscow, October.

GSMA (2021), High Altitude Platform Station. Towers in the Skies. https://www.gsma.com/futurenetworks/wp-content/uploads/2021/06/GSMA-HAPS-Towers-in-the-skies-Whitepaper-2021-1.pdf.

Habr (2022), Why Starlink from Musk is a scam. https://habr.com/ru/company/getmatch/blog/649227.

Ilchenko, M.E. and Kravchuk, S.A. (2010), *Telecommunication Systems based on High-Rise Air Platforms*, Naukova Dumka, Kyiv.

Immarsat (2022), www.inmarsat.com.

Information Satellite Systems (2022), https://www.iss-reshetnev.ru.

Iridium (2022), https://www.iridium.com.

Izet-Ünsalan, K. and Ünsalan, D. (2011), "A low cost alternative for satellites-tethered ultra-high altitude balloons", *Proceedings of 5th International Conference on Recent Advances in Space Technologies-RAST2011*, 13-16.

Kamnev, V.E., Cherkasov, V.V. and Chechin, G.V. (2010), *Satellite Communication Networks*, Military Parade, Moscow.

Kumaritova, D. and Kirichek, R. (2016), "Overview and comparative analysis of LPWAN network", *Telecom IT*, **4**(4), 33–48.

Liu, X., Liu, C., Liu, W. and Zeng X. (2016), “High altitude platform station network and channel modeling performance analysis”, *Math. Comput. Sci.*, **1**(1), 10-16.

NASA (2022), Radioisotope Power Systems. https://rps.nasa.gov.

Nolan, K.E., Guibene, W. and Kelly, M.Y. (2016), “An evaluation of low power wide area network technologies for the internet of things”, *International Wireless Communications and Mobile Computing Conference (IWCMC)*, 439-444.

Sartakov, A. (2020), “Comparison of LoRaWAN, SNBWAN and other technologies for the internet of things”, *Wirel. Techn.*, **1**, 42-47.

Sigfox (2022), https://www.sigfox.com/en.

Summerer, L., Gardini, B. and Gianfiglio, G. (2007), “EAS’s approach to nuclear power sources for space applications”, *Proceedings of ICAPP*, **13**, 18.

Tozer, T. and Grace, D. (2001), “High-altitude platforms for wireless communications”, *Electron. Commun. Eng. J.*, **13**(3), 127-137. https://doi.org/10.1049/ecej:20010303.

U.S. Department of Defense (2012), Summary Report of DoD Funded Lighter-Than-Air Vehicles, Office of the Assistant Secretary of Defense for Research and Engineering, Rapid Reaction Technology Office, US Senate.

U.S. Government Accountability Office (2012), Future Aerostat and Airship Investment Decisions Drive Oversight and Coordination Needs. www.gao.gov/products/GAO-13-81.

Xing, Y., Hsieh, F., Ghosh, A. and Rappaport, T.S. (2021), “High altitude platform stations (HAPS): Architecture and system performance”, *2021 IEEE 93rd Vehicular Technology Conference (VTC2021-Spring)*, 1-6.

Zakrajsek, J.F., Woerner, D.F., Cairns-Gallimore, D., Johnson, S.G. and Qualls, L. (2016), “NASA’s Radioisotope Power Systems planning and potential future systems overview”, *2016 IEEE Aerospace Conference*, 1-10.

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