DOI https://doi.org/10.30525/978-9934-26-207-4-7

COMBINED HETEROGENEOUS OVER-THE-HORIZON COMMUNICATION SYSTEMS WITH SUPPORT FOR MULTI-TERMINAL RADIO ACCESS

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INTRODUCTION

The development of modern telecommunication systems and networks follows the path of integration of multilevel structuring of systems and their intellectual self-organization. At the same time, the formation of the structure of a telecommunications network can occur using nodes of different segments: terrestrial, atmospheric, and space. A particularly heterogeneous structure is found in multiple wireless access systems[1]. All this leads to the fact that in one distributed telecommunication system, nodes based on different principles of operation and operating in different frequency ranges, or using the principle of cognition, can be combined. For example, such nodes can be a tropospheric communication station and a mobile wireless terminal, and their location can be both on the surface of the Earth (ground-based) and on an air platform (drone). This allows you to collect in one heterogeneous system the advantages of separate heterogeneous systems and thus create new structures and architectures of telecommunications.

To create such combined telecommunication systems, technologies of active, passive, and cooperative relaying, cognitive access to radio resources, multi-antenna technology, integration with external telecommunications systems, SDR (Software-Defined Radio), SDN (Software-Defined Networking), multicast forwarding, etc. can be used.

Combined heterogeneous telecommunication systems can be built even on the basis of nodes located on very distant platforms – space and ground[2]. However, due to the presence of very long radio links (high attenuation and

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[1] Transition technologies towards 6G networks / T.R. Raddo, S. Rommel, B. Cimoli *et al.* // EURASIP Journal on Wireless Communications and Networking, number 100 (2021) https://doi.org/10.1186/s13638-021-01973-9

[2] Hybrid Satellite-Terrestrial Communication Networks for the Maritime Internet of Things: Key Technologies, Opportunities, and Challenges / T. Wei, W. Feng, Y. Chen, C.-X. Wang, N. Ge, J. Lu // IEEE Internet of Things Journal, Vol. 8, Issue 11, p. 8910–8934 (2021), https://doi.org/10.1109/JIOT.2021.3056091.

signal delays) to the space segment, such systems are not effective for operating at high transmission rates, the growth of which is a requirement of the modern development of telecommunications. The highest coverage density and, accordingly, high transmission rates for their users are provided by terrestrial cellular mobile communication systems. Moreover, an increase in the throughput of one cell can be realized by geometrically reducing the coverage area of a given cell[3,4,5]. For urbanized places, this approach is most acceptable, but for systems that require communication at different distances (significantly more than the standard cell size of cellular communication), it is necessary to use nodes that allow working over long distances – over-the-horizon communication.

In this sense, the purpose of this work is to present the architecture of a telecommunications combined heterogeneous over-the-horizon communication system with support for multi-terminal radio access using reference small-sized tropospheric communication stations and relay intelligent air platforms or artificials formation.

1. Structural architecture of heterogeneous over-the-horizon communication systems

Combined heterogeneous over-the-horizon communication systems can be created on the basis of a number of small-sized reference stations for tropospheric communication with the possibility of their operation in several modes: tropospheric scatter, re-reflection from artificial formations in the atmosphere, using one or a constellation of relay air platforms, several frequency bands and external network interfaces of the air platform on The basis of relaying drones is a self-organizing constellation (swarm) as part of mixed groups, which include drones of various purposes (communications , monitoring, reconnaissance, search for objects, aerial photography, etc.), or as part of autonomously functioning, but coordinated

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[3] Ilchenko M., Kravchuk S., Mobile infocommunication systems, Information and Telecommunication Sciences, Vol. 11, Number 1, pp. 11-19 (2020), (https://doi.org/10.20535/2411-2976.12020.11-19)

[4] Kravchuk S.O., Kaidenko M.M., Meshcherinov M.V. «Sparse Cellular Radio Network», Scientific Collection «InterConf», (№ 95): with the Proceedings of the 2 nd International Scientific and Practical Conference «Scientific Goals and Purposes in XXI Century» (January 19-20, 2022). Seattle, USA (ProQuest LLC, 2022. 915 p. ISBN 978-1-0848-4533-6), p. 746-750, https://doi.org/10.51582/interconf.19-20.01.2022.082.

[5] Long Distance 4G LTE Network Communication Radio. Product Specifications, Deekon Group, Shanghai (2022): https://www.deekonmilitarytextile.com/communication-radio.html?gclid=EAIaIQobChMIoIqp9eCG9gIVQfgYCh2-sQrnEAMYAyAAEgL PsvD_BwE

controlled drones. The group coordinated use of drones in a swarm can significantly increase the efficiency of relay processes and the possibility of implementing multi-station broadband radio access within such a constellation while using technologies for cooperative relaying and machine-to-machine (M2M) interaction. As artificial formations, various passive interferences can be involved, which are the result of the scattering of electromagnetic waves by foil, dipole, corner, and lens radio reflectors, reflecting antenna arrays, ionized media, and aerosol formations.

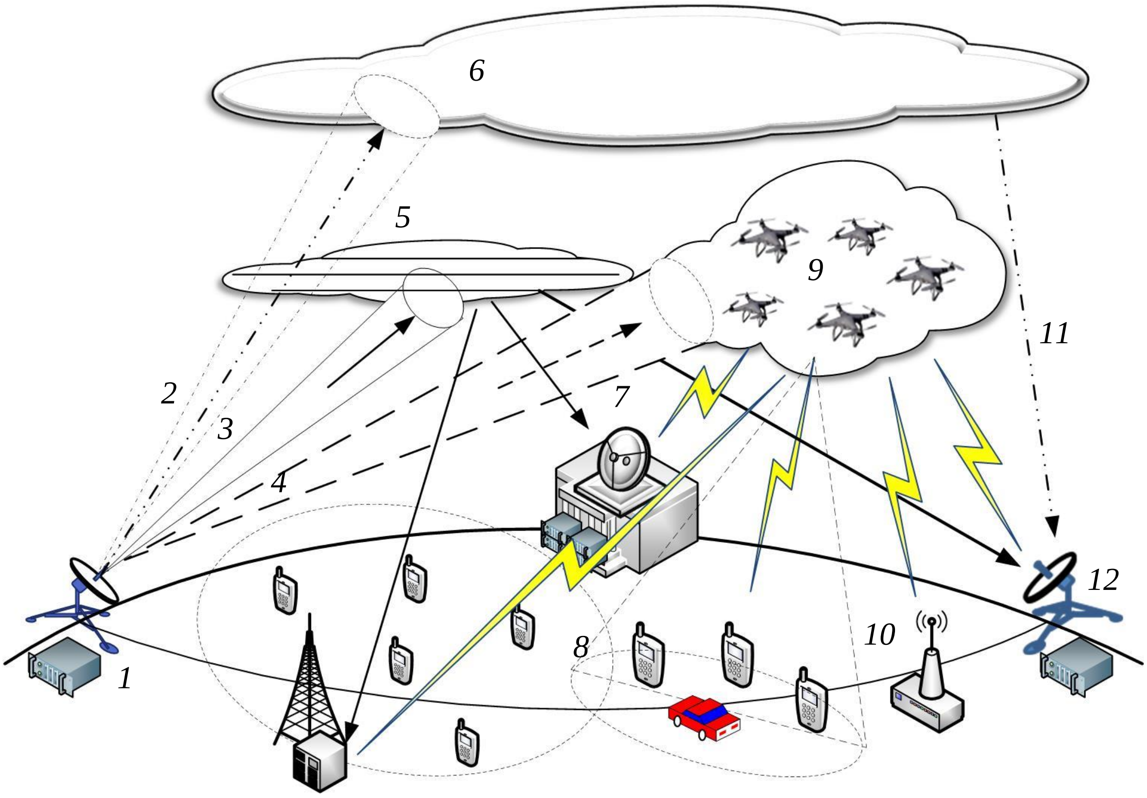

Fig. 1. The structure of the combined heterogeneous over-the-horizon communication system

1, 12 – small-sized reference TRS; 2 – radio beams in the direction of tropospheric scattering; 3 – radio beams in the direction of artificial atmospheric formations; 4 – radio beams in the direction of a swarm of drones; 5 – layered volume of artificial formations in the atmosphere; 6 – layers of the atmosphere, where the formation of the volume of tropospheric scattering is possible; 7, 10 – separate stationary radio facilities; 8 – radio terminals of mobile users; 9 – a layer of a swarm of drones; 11 – radio beam formed as a result of far tropospheric propagation

The structural architecture of heterogeneous over-the-horizon communication systems using small-sized reference stations for tropospheric communication (TRS) and relay intelligent air platforms and artificial formations are shown in fig. 1. Such a system can operate in the «point-to-point» mode at distances from tens to several thousand km, or in the combined «point-to-multipoint» and «multipoint-to-multipoint» modes. In the latter modes, with the help of relay nodes in the air, separate zones of special user radio access can be formed with the provision of spatial, frequency, and temporal resolution[6][7]. In this case, the combined system may extend or form a remote coverage area as part of a cellular mobile or broadband access network. For example, in the context of the need to provide communication services on a remote island or continent (research stations in Antarctica) or in a natural disaster, anti-terrorist operations, or military operations[8]. The block diagram of the interaction of heterogeneous nodes of the combined system is shown in fig. 2.

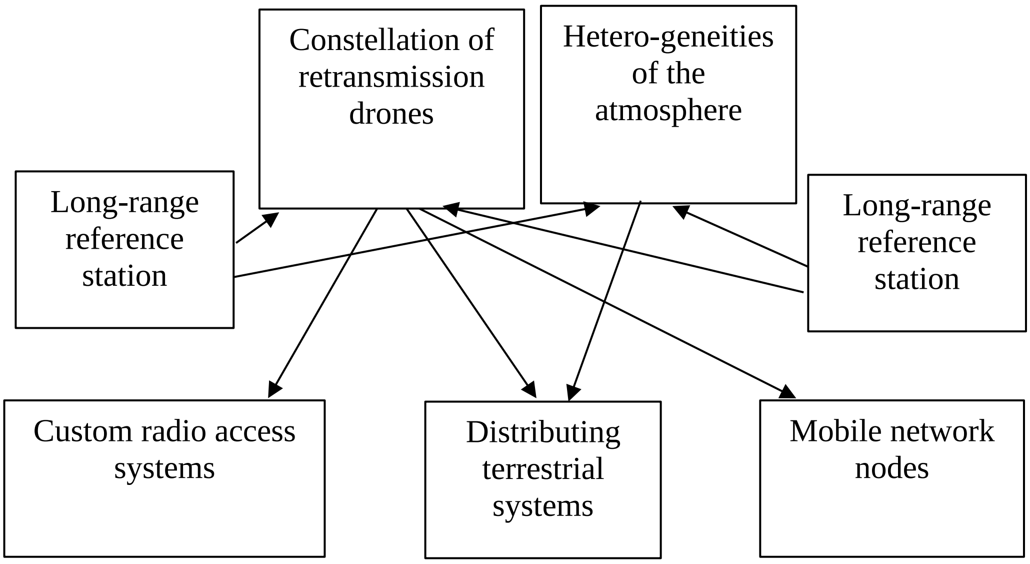

Fig. 2. Block diagram of the interaction of heterogeneous nodes of the combined system

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[6] Ilchenko M., Kravchuk S., Kaydenko M. Combined Over-the-Horizon Communication Systems. In: Advances in Information and Communication Technologies. Processing and Control in Information and Communication Systems. UKRMICO 2018. Lecture Notes in Electrical Engineering, vol 560. Springer, Cham, 2019 – P. 121-145. DOI: 10.1007/978-3-030-16770-7 (https://doi.org/10.1007/978-3-030-16770-7_6)

[7] Ilchenko M.Y., Kravchuk S.O., Kaydenko M.M. Over-horizon systems of communications: розділ в кн. Досягнення в телекомунікаціях 2019 / за наук. ред. М.Ю. Ільченка, С.О. Кравчука. Київ: Інститут обдарованої дитини НАПН України, 2019. С. 182–199.

[8] Afanasieva L., Minochkin D., Kravchuk S. Providing telecommunication services to antarctic stations // Proceedings of the 2017 International Conference on Information and Telecommunication Technologies and Radio Electronics (UkrMiCo) 11-15 Sept. 2017 Year, Odessa, Ukraine. – IEEE Conference Publications (IEEE Xplore Digital Library, DOI: 10.1109/UkrMiCo.2017.8095419), 2017. P. 1–4.

Next, we will consider the possibilities of implementing such an architecture.

2. Reference small stations of tropospheric communication

For Heterogeneous combined over-the-horizon communications systems, a small-sized station based on unified structures has been developed as a supporting TRS according to the block-modular principle. They are created using a modern microelectronic base and software-defined systems[9,10].

The main components of the station are the antenna-rotary device; transceiver unit; modem device; power unit; cables; remote monitoring and control device.

The technical characteristics of such a TRS are as follows:

– operating frequency range 4.4...5.0 GHz:

– the maximum rate of reception/transmission of digital information flow up to 10 Mbit/s;

– information interface 10/100/1000 Base-T, available ports with the ability to encapsulate the external stream of the E1 converter (G.703) to Ethernet;

– protocol and data transfer interface IP (TCP/IP), Ethernet;

– the range of the radio link with an availability factor of at least 0.98 and a bit error rate of at least 10-6 at a bit rate of a digital stream: 512 kbps is up to 130 km and 2.048 Mbps – up to 90 km.

The operating conditions of the TRS are significantly different from the conditions of a line-of-sight radio relay station. In the tropospheric channel, complex fading occurs (often selective, fast and slow fading), which are of a daily and seasonal nature. To compensate for emerging interference, in addition to traditional methods of dealing with them (high transmitter power and the use of channel equalizers), this TRS uses multi-level adaptation to changing station operating conditions.

The station uses four levels of adaptation: frequency, modulation and coding, spatial (in two-channel mode of operation with spatial diversity), and at the MAC level. The TRS connection system may be configured for receive (transmit) diversity or MIMO space-time multiplexing.

TRS modem device provides modulation, demodulation, formation of information, voice and service data streams via radio and wire interfaces,

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[9] Kravchuk S., Kaidenko M. Features of creation of modem equipment for the new generation compact troposcatter stations / Proceedings of the International Scientific Conference «RadioElectronics & InfoCommunications» (UkrMiCo’2016), 11-16 September 2016, Kyiv, Ukraine. : NTUU «KPI», 2016. – P. 365-368.

[10] Kravchuk S.O., Kaidenko M.M. Modem equipment for the new generation compact troposcatter stations // Information and telecommunication sciences. 2016. Vol. 7. Nu. 1. P. 5–12.

multi-level adaptation of the station to changing operating conditions, synchronization, selection of station operation modes, control of the station and its individual blocks, station status monitoring, etc.

The TRS modem device is a full-featured dual-channel modem module that is built on the basis of advanced SDR (Software-defined Radio) technology in conjunction with SoC (System-on-a-Chip) technology. This version of the modem device is intended for use in stations not only in single-channel operation but also in dual-channel operation with polarization or spatial diversity.

3. The level of use of air platforms

Unmanned aerial vehicles (UAVs) are increasingly being used not only for their traditional military use but also in various areas of everyday life. In particular, to check power lines and pipelines, monitor and predict emergency situations, control dangerous objects, monitor traffic conditions, etc.

The main difference between a swarm of UAVs and one individual UAV is the presence of a spatially distributed rather than a concentrated structure, which is much more complicated, but, due to its distributed nature, has higher survivability and flexibility in the provision of communication services. A swarm of small UAVs (drones) is a powerful complex because it provides a number of additional functions compared to a single unmanned vehicle. These functions are supported by high and low-level mechanisms such as autonomy and intelligence, application scenarios, shaping, and dynamic flight control, data and control link support and protection, operating band selection, transmission methods and digital channelization, etc. help a lot in solving many complex problems. These high-level functions are assigned to the cooperation / cooperation that takes place in a swarm and requires the exploration of a number of new mechanisms and technologies. The efficiency of the swarm will be much higher in the case of using nodes that are different in complexity and functions than in the case of using the same nodes if the latter wants to be more technologically advanced. Having a fleet of unmanned aerial vehicles controlled by a single operator requires not only a high level of autonomy for each aerial vehicle but also new control and navigation algorithms to effectively manage the unmanned aerial vehicle network.

An autonomous swarm of UAVs is a set of drones that together perform a given mission in an autonomous manner, without relying on communication with the ground control panel to be locked into the conditions of the mission’s enemy. The UAV swarm must be self-organizing and equipped with swarm intelligence. From the user’s point of view, the swarm is easy and transparent to manage in terms of both functionality and security. The user provides entire missions and initial protections (such as cryptographic keys) to the swarm, and the swarm must perform its mission autonomously. Roy is able to perform optimally in adverse conditions, analyzing the situation and making decisions in real time.

A variety of flying unmanned vehicles of two categories can be used as air platforms for the combined system: individual heavy long-range drones, small (even disposable) gliders and drones. On the basis of drones of the second category, swarms can be formed that have the functions of both external control and self-organization. At the same time, with the help of their individual antenna elements, they are able to form special antenna arrays or any surfaces for reflecting radio waves (Fig. 3). Depending on the angle of inclination of the antenna elements on the drones (or the inclination of the body of the drone itself), one or another service area on the surface of the Earth will be formed. At the same time, such drones serve to implement relay distribution and shielding applications of the combined wireless system.

UAVs of the first category have powerful transceiver equipment and an antenna system that supports radio links with reference TRRS and ground or air wireless terminals distributed over the UAV service area. They can also serve as coordinating hubs for drone swarms and the COTHCS system itself or as a 5th generation mobile communications relay station with IoT and M2M support.

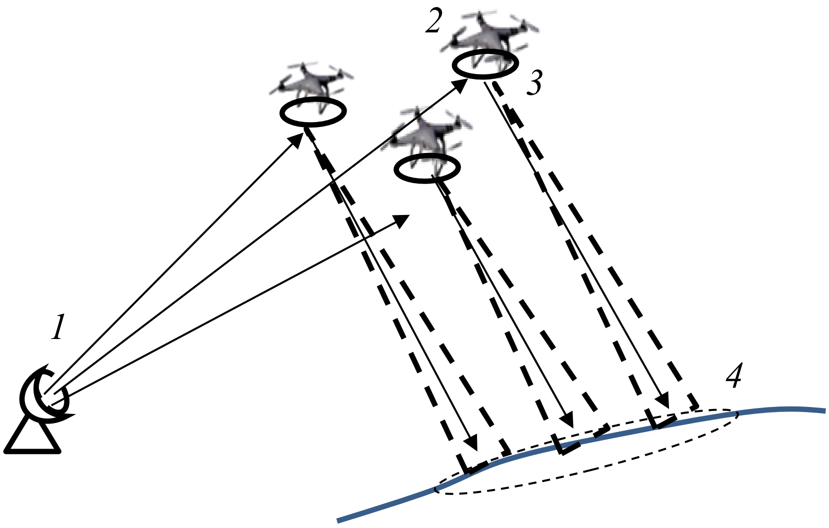

Fig. 3. An example of the formation of a service area for a swarm of drones

1 – beams of the reference TRS radiation pattern; 2 – quadrocopter (drones); 3 – antenna element in the form of a special reflective surface; 4 – service area on the surface of the Earth

The structural and functional principles of building an onboard control and communication system take into account that the system must provide continuous data exchange over the control and telemetry channel with high reliability, as well as continuous data transfer over the data channel in the direction of the ground system with guaranteed quality.

The control system includes:

– control and telemetry channel with an antenna of the appropriate type;

– data transmission channels;

– antenna system with automatic tracking functions;

– on-board processor for control and data processing;

– block of switching and routing;

– a set of cameras for video surveillance and flight control;

– means of flight control and determination of the orientation of the UAV in space.

The control and telemetry channel are used to transmit UAV control data from the ground station and telemetry from the aircraft to the ground station. To ensure continuity of aircraft control at all stages of flight, antennas with a circular pattern are used. The frequency range of 30…470 (510) MHz can be used for the control channel. The data transfer rate in the channel is 19.2...38.4 kbps and can be increased if necessary, up to 100 kbps.

In general, a swarm of UAVs or drones can perform the same functions as a traditional multifunctional heavy UAV. The main difference in this case will be in the very structure of the swarm – spatially distributed, and not concentrated in one construct. That is, compared to a single UAV, a swarm is significantly more complicated both in terms of the design of its nodes and in terms of methods for managing nodes in a swarm. However, precisely because of its distributed nature, the swarm has a higher survivability and flexibility in providing communication services.

Taking into account modern realities and the possibility of group movement, it is important to model the processes of information exchange between UAVs. Neither models based on the representation of motion in the form of differential equations, nor the neural and fuzzy models presented above have such properties and do not have such modeling functions. Because of this, in order to solve modern problems of flight theory, it is necessary to use concepts that allow one to be, as it were, «above» traditional approaches to determining motion. As the study of various methods for representing and describing the behavior of active objects in changing environments (adaptive self-organizing finite automata, etc.) shows, it is advisable to use the paradigm of agent-based systems and the concept of «intelligent agent» (IA) as a high-level abstraction for modeling such situations. formalization of complex situations that are not up to certain[11]. At the same time, it is advisable to describe the own movement of aircraft as the movement of such «intelligent agents» in space.

Intelligent agents are a new class of some software and hardware entities that find and process information that supports the solution of difficult problems, are able to conduct independent «negotiations» in software systems, automate routine operations and cooperate with other software agents when complex problems arise, thereby removing them from human excessive information load. In the general case, an agent is a system that operates inside a certain environment, capable of perceiving the environment with the help of sensors and influencing it (in our case, moving in it) to carry out its own program of actions. The decisive factor in multi-agent systems is the communication system. The ability to exchange information expands the competence of agents, allowing them to use the knowledge of other agents. It also provides conditions for effective redistribution of tasks and coordination of actions.

It is possible to propose the following constructions of some control strategies.

Centralized control with master. The leader node is assigned to the group. His behavior is determined from the Center, which maintains constant contact with the Leader. The rest of the elements can, in accordance with the «flock» natural algorithms, follow the Leader with the formation of an appropriate structure (chain, star, etc.), realizing the behavior of the «do as I do» type, or form a hierarchical structure in which a clear subordination is realized. An option can be implemented in which the Leader determines the whole distribution and issues tasks for the UAV group. Such a strategy, according to some estimates, turns out to be more resistant to opposition from the opposite side of the conflict, and its implementation reduces the requirements for information support for the entire grouping and means of communication. In the general case, the role of the Leader can be assigned to any UAV group that has the necessary competencies. The leader can be changed on command from the Control Center, which can improve the effectiveness of the strategy in various conditions.

Decentralized control with a master. In this strategy, a Leader is also appointed, who is assigned a task for the entire group, but in the future there is no connection between the Center and him, and the decision on the appeal

[11] Kravchuk S., Afanasieva L. Formation of a wireless communication system based on a swarm of unmanned aerial vehicles. *Information and Telecommunication Sciences*. 2019. No 1. P. 11–18. DOI: https://doi.org/10.20535/2411-2976.12019.11-18

and targeted checks of the distribution of the entire group is made by the Leader on his own. This strategy puts a lot of responsibility on the Leader. In fact, this strategy becomes intellectual, but decision-making in it is still based on the principle of unity of command – centralized management.

Collective self-management with information. Such a strategy is related to the fact that control objects act independently, but exchange information with each other to make a decision and then move in accordance with the decisions made. This strategy differs from those previously considered by a clearly expressed collectivism of behavior. The main problem here may be the need to solve conflict problems that will arise with such a management strategy.

Decentralized Predictive Governance. Within the framework of decentralized control with the Leader or collective self-government with the exchange of information, the grouping can appoint / allocate an IA (intelligent agent), which will preliminarily solve problems in a zone dangerous for the movement of the entire group, that is, a kind of scout. The scout, moving along trajectories agreed in advance or selected depending on the situation, can inform other EAs about the degree of danger of the passing route. To select the optimal routes here, for example, «ant» algorithms can be used.

Self-organization without information exchange. This variant of control under conditions of movement in an antagonistic environment with active opposition may be the only possible one. But disunity has never been conducive to the joint implementation of common tasks, and the lack of information exchange can significantly reduce efficiency. In addition, this option also requires premature distribution target checks, which reduces the flexibility of grouping.

The heterogeneity of IAs can introduce certain features into the construction of strategies, which is primarily associated with different flight performance and capabilities of different IAs included in the grouping. Thus, the presence of a single leader can make it difficult to interact in a group; it is expedient to divide it into subgroups of the same type of IAs with the corresponding allocation of their own leaders in them and the delegation of the corresponding tasks for such a similar subgroup. It is also possible to predict a significant difference in the spatio-temporal characteristics of objects of different types acting as part of a grouping. Indeed, provided that the group includes, for example, UAVs of four different types (airplanes, drones, balloons), they can occupy significantly different altitude horizons and move in different azimuth directions.

The life cycle of the swarm, or rather the operation of the drone nodes that form the swarm, mainly depends on the amount of useful energy on board the drone node. The greater the energy reserve and the lower its consumption, the longer the drone can function: move and provide communication. Determining a rational balance between all types of costs for the needs of the operation of drones is vital. Miniaturization and cost are key factors in drone swarm operation. These are the two main problems when creating large groups of drones. Hence, the simplicity of each swarm node must be given special attention, and the swarm intelligence approach to achieve meaningful behavior at the group level rather than at the individual level is justified. Also, a key factor should include the need for a mechanism for the «recovery» of the swarm (or «survival») in case of its damage (disruption of a number of drone nodes or connections between them) or decay.

To combat channel imitation interference in the UAV, algorithms for detecting imitation structured interference are used. These algorithms are based on channel synchronization, maintaining a given level of channel energy and monitoring of energy characteristics in channels, marking data packets. Maintaining a given level of channel energy, which should be the same in both channels, provides additional secrecy of information transmission, reducing the likelihood of interception by the station, which is not in the line of sight. Channel synchronization and maintenance of a given energy level is implemented through the use of software-defined radio technologies and systems on a chip. The available measured channel parameters for detecting interference are the signal-to-noise ratio, the received signal level, the change in their behavior over time, measured as a probability distribution density.

Evaluating the effect of jamming interference on the control channel is not difficult, since a significant decrease in signal-to-noise ratio and measured degradation in bit error rate can be a reliable estimate of jamming in the channel, and these events for two channels may be uncorrelated.

In the case of using channel imitation for interception or interference, the interference detection algorithm is much more complicated due to the fact that it is necessary to determine firstly whether there was imitation interference and, secondly, in which channel it was carried out.

CONCLUSIONS

The basics of building heterogeneous over-the-horizon communication systems using small-sized reference stations for tropospheric communication and relay intelligent air platforms and artificial formations, which will be based on the use of new technologies of cognitive and software-defined radio, cooperative relay, are presented. Interaction between the system, hardware and application protocol levels and simplification of the process of managing and monitoring structural elements, increasing their availability and reliability.

The joint use of SDR and SoC technologies when creating modem equipment for a tropospheric station makes it possible to further upgrade the station without changing the hardware platform by using several software profiles to load the station configuration depending on the selected operating mode.

A strategy for the collective control of a swarm of drones has been developed, which boils down to the selection and execution at the current time by a group of drones of certain group actions that provide an extremum (maximum, if the benefits from the actions of a group of drones are estimated, or a minimum, if costs are estimated) of the target functional, taking into account the vector of opposing forces over a discrete time interval.

The construction of some swarm control strategies is proposed: centralized and decentralized with the Leader, collective self-control with information exchange, decentralized control with prediction, self-organization without information exchange.

SUMMARY

The basics of building heterogeneous over-the-horizon communication systems using reference tropospheric communication stations and relay air platforms and artificial formations, which will be based on the use of new technologies of cognitive and software-defined radio, cooperative relay, are presented. Interaction between the system, hardware and application protocol levels and simplification of the process of managing and monitoring structural elements, increasing their availability and reliability.

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