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# TESTING OF THE DRONE SWARMS AS A COMMUNICATION RELAY SYSTEM

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**Background.** Intensive development of the unmanned aerial vehicle manufacturing industry has led to the emergence of many of their options for various applications. A separate class of low-flying drones, the work of which takes place within the framework of a certain self-organizing (robotic) group, was made up of drones, combined in a constellation or swarm. All drones of such a swarm together can perform one common function as an independent robotic complex.

**Objective.** The aim of this work is experimental testing and development of the basic principles of controlling a swarm (constellation) of drones and the formation of a cooperative relay system.

**Methods.** The structural and functional methods of constructing a wireless network based on a drone swarm are investigated.

**Results.** Testing a swarm of drones was carried out according to two relay scenarios: passive using metallized reflectors and active using additional SDR radio units. Drones were formed on the basis of the quadcopter model Syma X8 PRO. For testing, radio channels in the 2.4 and 5.8 GHz bands were involved.

The developed kit based on the Raspberry Pi and ADALM-Pluto programmable modules allows you to use them very flexibly both on drones and on the ground control station by changing the software on them.

Each of the drones has many degrees of freedom with respect to the choice of wireless connection to other swarm drones or external devices, including ground control station. This increases the noise immunity, fault tolerance and functionality of such a system, as well as the possibility of building it up.

**Conclusions.** Experimental testing and testing of the basic principles of controlling a swarm (constellation) of drones and the formation of a cooperative relay system were carried out. Scenarios for centralized and distributed construction of a collective drone swarm management network for communication services have been developed.

**Keywords:** swarm of unmanned aerial vehicles; drone swarm; wireless communication system; life cycle; cooperative relay; control drone network

## I. Introduction

Currently, the development of telecommunication systems is on the path to implementing intelligent distributed architectures. Such an implementation is associated with the use of a large number of system nodes and sublevels in both hardware and software. Accordingly, the role of effective interconnection (infrastructure) with minimal time delays between nodes both at the level of signaling (control) and at the level of information channels [1]-[4] is growing. Such an approach led to the transition from the traditional deployment of a complex system of subscriber radio access, especially cellular mobile communications, in the 2D plane of ground-based to three-dimensional construction of 3D using telecommunication systems based on airport platforms, which are most often unmanned aerial vehicles [5]-[8].

Intensive development of the unmanned aerial vehicle manufacturing industry has led to the emergence of many of their options for various applications. A separate class of low flying drones, the work of which takes place within the framework of a certain self-organizing (robotic) group, was made up of drones combined in a constellation or swarm [9], [10]. All drones of such a swarm together can perform one common function as an independent robotic complex. In this paper, we consider only the telecommunication function of a drone swarm - relaying signals in a cooperative mode of operation [11].

High flexibility and the very adjustment of the work of a drone swarm of as a telecommunication system or its node attracts high attention of developers. So, in [9], an architecture of a drone swarm is proposed, which increases the autonomy of the swarm by using the cellular infrastructure of mobile wireless communications. However, this architecture focuses only on 5G terrestrial cellular mobile communications. In [12] analyzes the evolution of various SDR (Software Defined Radio) modules for use in mobile systems and the implementation of modulation methods for successful wireless data transmission using the ADALM-PLUTO SDR platform from Analog Devices. It also confirms the promise of using this platform as an inexpensive and affordable SDR module for small mobile objects.

A new cooperative spatial retreat (CSR) technique has been proposed, which takes advantage of the interaction of drones in network formation by leaving (evacuating) from a zone with poor communications [13]. With this technique, drones move only in strictly defined directions, which leads to efficient movement with economical use of battery power. In [14], a WPCN (wireless-powered communication network) system, which uses several unmanned aerial vehicles, was considered. Ground users (GU) first collect energy from a mobile drone using the WET method (wireless energy transfer), and then use this energy to transmit their information to a flying data collector. The obtained numerical results show the effectiveness of the proposed algorithm in various scenarios. In [15], a review of research works is presented in which ML (machine-learning) methods were used to maintain a communication network based on unmanned aerial vehicles. This allowed us to improve various design and functional aspects (evaluation of communication channels, resource management, positioning and security). The work [16] is aimed at solving the problem of the functioning of the drone network using mobile agents and unknown characteristics of the wireless channel. Here, only online measured information is used about the received signal strength RSS (received signal strength) and the positions of the operators. The task is complicated due to an unknown and dynamically changing electromagnetic environment caused by the actions of agents and drones. In [17], a centralized strategy was proposed for locating drones as flying access points that form a mesh network and provide communication with ground nodes. The geographical location of the drones is optimized based on the MOEA (Multi-Objective Evolutionary Algorithm). To find a set of optimal positions for the deployment of unmanned aerial vehicles taking into account the positions of ground nodes, the NSGA-II (Non-Dominated Sorting Genetic Algorithm II) was used. At the same time, coverage of all ground nodes is realized using the minimum number of unmanned aerial vehicles, while maximally fulfilling their requirements for data transfer speed. The work [18] is devoted to increasing the autonomy of the work of drones in the monitoring mode by using special algorithms to generate alternative options for the trajectories (coordination) of drone flights. In [19], new applications of unmanned aerial vehicles that support IoT and 5G technologies are presented. Also proposed is a structure that provides a holistic IoT architecture and protection of unmanned aerial vehicles as separate "flying" objects in a shared network environment. However, the effect of drones in a cooperative swarm was not evaluated here. In [20], a communication system was developed and tested in which a relay was implemented between two drones. Drones were created, used as an on-board platform, a set of programs and a protocol were developed for autonomous flight control, relay control communications and ground control for drones. However, the option of cooperation of drones as constellations is not considered here.

Thus, the implementation of a swarm of drones as a distributed modern communication system remains relevant. In [21] - [28], a theoretical basis for the formation of a swarm and scenarios of its work was presented. In particular, scenarios for centralized and distributed construction of a collective drone swarm management network have been developed, a scheme for the phased implementation of the swarm life cycle for communication services, a scenario for the spatial self-organization of swarm drone nodes, etc. However, experimental testing of theoretical positions is required to determine their adequacy to real deployment scenarios swarm of drones for telecommunication applications.

The main purpose of this work is experimental testing and development of the basic principles of controlling a swarm (constellation) of drones and the formation of a cooperative relay system.

## II. THE STRUCTURE OF THE DRONE SWARM TEST SYSTEM

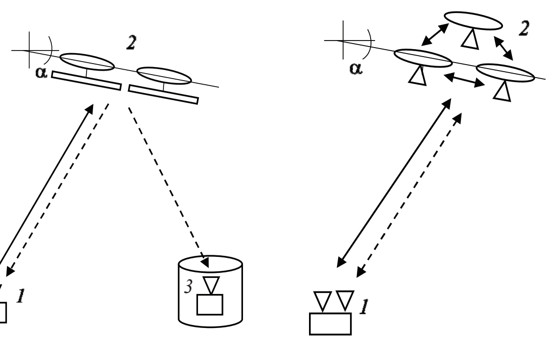
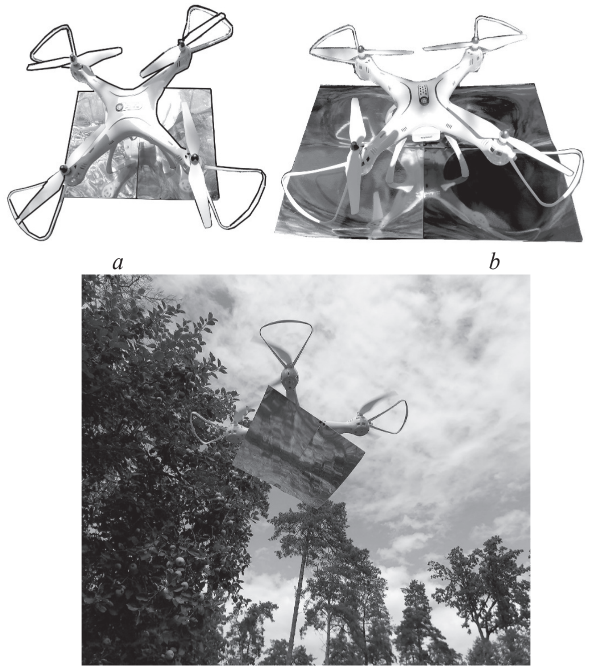



Fig. 1. Relay scenarios: passive (*a*) using flat rectangular foil reflectors and active (*b*) using SDR radio units (*1* - ground control station; *2* - drones; *3* - additional receiver on the screen)

The test system of the relay swarm of drones consists of a ground control point (NPU) and the swarm itself. The latter is formed of three drones equipped in accordance with the scenario being performed. Two scenarios are considered (Fig. 1): passive relaying using flat rectangular foil reflectors and active relaying using additional SDR radio units. The first and second scenarios are designed to verify the theoretical positions that were previously developed in [28] and [27], respectively.

The main provisions of the principles of swarm management, which were applied during testing, are described in [21], [24] and [26]. The principle of self-organization proposed for the test is based on the following provisions [29]: autonomy - interaction in the outside world is acceptable, but control from the outside world is unacceptable; adaptability and robustness in relation to changes - the ability to respond appropriately to changes in the external environment; order increase - in accordance with the increase in the organization of the system, which can lead to a decrease in the number of possible states of the system, the appearance of spatial, temporal and functional structures.



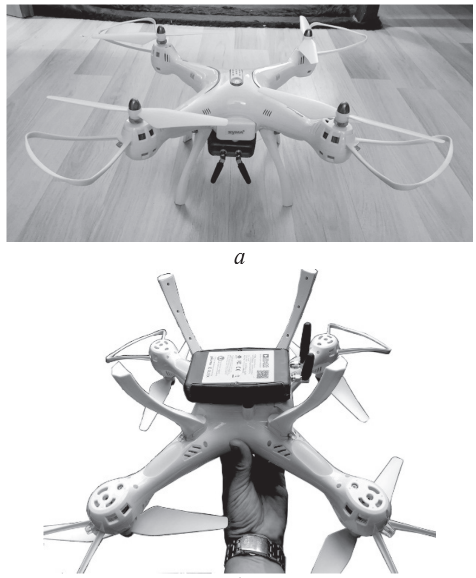
*a* *b* c

Fig. 2. Images of a Syma X8 PRO quadcopter with a foil reflector with an area of 420x300 mm (a) and 600x420 mm (b), as well as a photo of a drone hovering (c)

The selected self-organization strategy for the tested swarm of drones is as follows. Nodes (drones) know only about their neighbors (quantity, and their characteristics). Each agent has a certain number of anticipated "things" (properties, objects). The self-organization strategy initiates the exchange of such things so that in the end all agents have the same amount (all necessary data items are filled). The strategy provides the corresponding dynamics and at the same time agents have different dynamics of exchange, otherwise statistically nothing will change. For example, an exchange can be arranged so that each agent exchanges in one step the number of things proportional to the number of things that he has, i.e. it should work faster if it has a lot of things. In addition, he must exchange at a rate proportional to the number of his neighbors, otherwise he may “overflow”.

Drones for the swarm were formed on the basis of an unprofessional model of the Syma X8 PRO quadrocopter and, depending on the testing scenario, were equipped with: 1) foil reflectors based on a mirror aluminum film and a cardboard base with an area of 420x300 mm and 600x420 mm (Fig. 2); 2) using ADALM-Pluto Radio modules and a Raspberry Pi single-board computer with WiFi module (Fig. 3, 4).

The quadcopter Syma X8 PRO is a fairly large aircraft (500x500x190 mm), the flight of which is quite stable in calm weather and in light winds. Chatter occurs at a wind speed of 4-5 m/s and above. Flight time is largely dependent on weather conditions, but does not exceed 8-9 minutes. The control range reaches 200 m. The quadrocopter is equipped with classic collector engines that provide a smooth and even flight. Additional load capacity Syma X8 Pro is 200 g.



*a* *b*

Fig. 3. Types of quadcopter Syma X8 PRO with the equipped module ADALM-Pluto Radio: top (a) and bottom (b)

An integrated pressure sensor allows the machine to maintain altitude, and in combination with a GPS unit and a 6-level gyroscope, also maintain a position (Hover function). The flight safety system is represented by several varieties of the automatic return (RTH) mode and the "headless" mode. Quadcopter Syma X8 PRO is equipped with FPV (Wi-Fi) HD-camera, which allows you to record photos and videos on a memory card, and transfer to the phone in real time. During first-person flights, the drone is capable of flying at 70 meters. The video broadcasting channel is ordinary Wi-Fi, which operates in the 2.4 GHz band.

Fig. 4. Image of a quadcopter Syma hovering with ADALM-Pluto Radio module

The Syma X8Pro drone has a separate control panel (controller), which performs the following functions: regulation of the rise and fall of the drone, as well as rotation around the axis; accurate preflight calibration; control of flight speed, forward and backward movements, as well as tilt angles; activation of Headless mode; inclusion of auto take-off / auto landing; return home automatically; smartphone connection; holding photo and video shooting. The control panel supports two wireless interfaces of Wi-Fi and Bluetooth standards. The application for connecting a quadrocopter to a smartphone can be downloaded on the Play Market or the App Store.

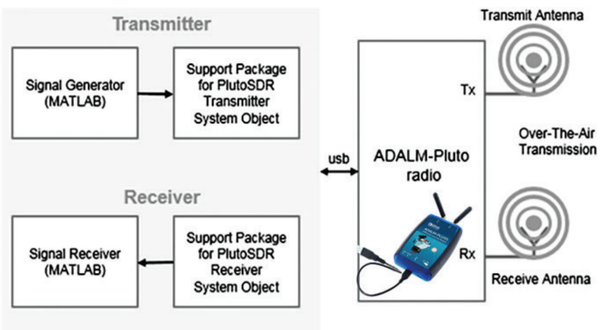



Fig. 5. Structural diagram: the interactions between Simulink, the Pluto transmitter unit and the radio equipment

The ADALM-Pluto Radio portable stand-alone Analog Devices module is built on top of the highly integrated high-frequency SDR (software-defined radio) transceiver SD9363 from Analog Devices and the SoC (System-on-a-Chip) FPGA Zynq Z-7010 from Xilinx (Fig. 5). The module operates in the frequency range from 325 MHz to 3.8 GHz (software upper limit can be increased to 6 GHz), working bandwidth up to 20 MHz, variable data rate, 12-bit ADC and DAC, contains one transmitter and one receiver can work both in full-duplex, and in half-duplex mode. Matlab, Simulink, and GNU Radio can be used as software to support ADALM-Pluto Radio.

To control the module, software developed using the «Communications Toolbox Support Package for Analog Devices ADALM-Pluto Radio» library was used [30].

The ground control station (Fig. 6) consisted of: Syma UAV control panels connected via Bluetooth channels to a control computer (CC) so that the CC could control their flight (each separately); transmit-receive units based on ADALM-Pluto Radio, which are connected to the same CC, whose main function was to provide radio channels for data exchange with drones and cooperation between them.

Fig. 6. Components of the ground control point of one drone: virtual reality glasses, ADALM-Pluto module, quadrocopter control panel, computer, Wi-Fi unit and network switch

## III. TESTING ACCORDING TO SCENARIO 1

The scheme of scenario 1 - passive relaying - is presented in Fig. 1 a. The main objective of scenario 1 is to verify the theoretical models presented in [28]. The test system for the first scenario uses one or two drones, to the supports of which reflectors made of metal foil on the mirror surface are attached, having a low weight but a large windage. The latter makes it impossible to launch such drones in windy weather and greatly limits their maneuverability. However, to conduct an experiment, it is only necessary to bring drones to a given height and adjust the angle of inclination of the plane of their reflector with respect to the horizon line $\alpha$ (Fig. 7).

The flight control of the drones was carried out using the standard Syma remote control via radio channels in the Wi-Fi standard in the 2.4 GHz band (Fig. 8). Through Bluetooth channels, the Syma remote control is connected to the control computer, which simulates and displays the entire process of flight and roll of the drone: on the remote, the operator uses the joysticks to make an angular effect on the roll system of the drone, and the numerical values of this effect are displayed on the computer. The task of a drone or a pair of drones is to reflect the signal in the 5.8 GHz band, which is created by one ADALM-Pluto radio module (its transmission channel), controlled from a computer. Reception of the signal reflected from the drones is received on the same ADALM-Pluto radio module, which serves as a transmitter for the passive relay process, and another ADALM-Pluto radio module in a metal screen (standard metal barrel 1 m high). The height of the drone hovering was determined using a manual laser range finder.

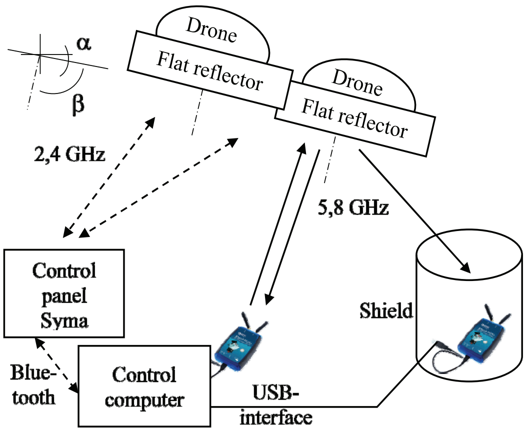
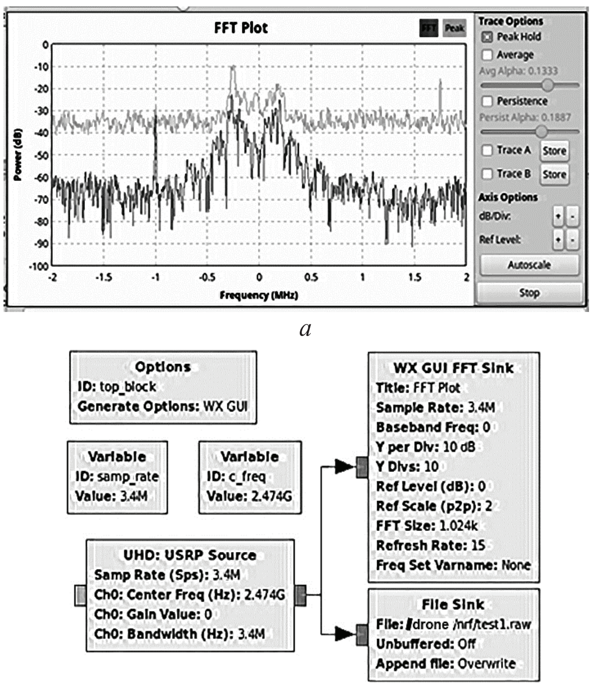



Fig. 7. Scheme of the Scenario 1




*a*

*b*

Fig. 8. The spectrum of the transmitted signal in the channel of the Syma drone system (*a*) and its description in the control system (*b*)

The geometry of the scenario is shown in Fig. 9. Experimental measurements of the signal power should be dependent on the angle of inclination of the plane of the reflector of the drone. But due to the fact that the reflector suspension is rigidly attached to the drone, the implementation of the tilt of the reflector is associated with the tilt of the entire drone, and this is possible only when it moves - moving away from the hovering point and changing the position. Therefore, instead of adjusting the inclination of the reflector plane by the drone, the distance ($d_1$ or $d_2$) changed, which is equivalent to changing the angles α (arctan [$h_0$ / $d_i$], $i$ = 1, 2).

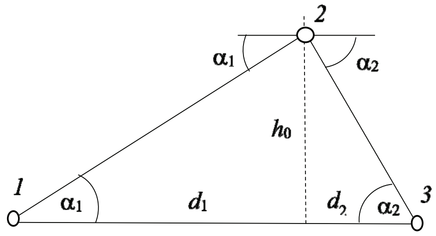



Fig. 9. The geometry of the location of the first (*1*) and second (*3*) radio modules ADALM-Pluto, a drone with a reflector (*2*)

All measurements of the signal power $\Delta P$ (on a partially shielded radio module that is only receiving) were performed as a change in the reference power level at reception for the selected drone hovering height $h_0$ = 14.5 m and angles $\alpha_1 = \alpha_2$ = 13 ±0.25 grad, which is practically corresponds to $d_1 = d_2 \approx 60$ m. A partial screening of the second radio module is needed only so that it cannot receive the signal from the first radio module along the line of sight above the Earth's surface, but only receives the signal through the repeater.

Table 1. One drone with two different reflectors

| Parameter | | Indicator | | | | | |
|---|---|---|---|---|---|---|---|
| Угол $\alpha_1/\alpha_2$, grad | | 13/ 13 | 17/ 17 | 21/ 21 | 29/ 29 | 42/ 42 | 70/ 70 |
| $d_1 = d_2$, m | | 60 | 45 | 35 | 25 | 15 | 5 |
| The difference in signal levels, $\Delta P$, dB, with a reflector: | $S_1$ | 0 | 0 | 2.94 | 3.38 | 3.89 | 3.79 |
| | $S_2$ | 0 | 6.61 | 6.94 | 7.38 | 7.89 | 7.80 |

The measurements for one drone with two different reflectors are given in table. 1. Zero values in the table mean that there is no signal at the input of a partially shielded receiver. This "zero" noise level is taken as the reference for measurements.

The rise of two drones with reflectors of area $S_2$ was carried out sequentially separately (Fig. 10) to the same hovering height as in the previous case of one drone.

Initially, there was a distance of about 5 m between the drones, and subsequently their controlled approach reached 0.2...0.3 m. The measurement results are presented in Fig. 11.

Fig. 10. Hovering drone swarm at a height of 10… 15 m according to the 1st scenario (April 2020)

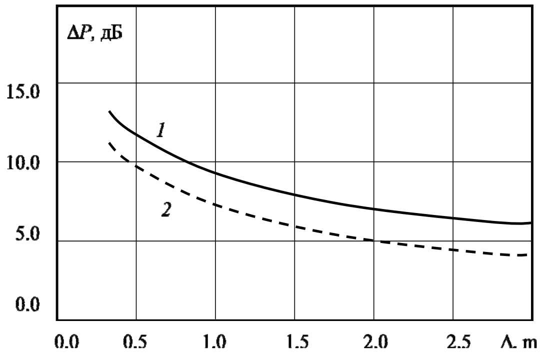



Fig. 11. The dependence of the difference in the measured value of the received signal levels, ΔP, dB on the distance between the drone reflectors Δ for $d_1 = d_2$, m = 35 (*1*) and 45 (*2*) (reflectors $S_2$)

## IV. Testing according to scenario 2

Scenario 2 of active relaying (1, *b*) using additional radio units mounted on three drones is shown in Fig. 12.

On each of the drones, a transceiver based on ADALM-Pluto Radio with an amplifier was installed (the transceiver body with antennas is clearly visible in the photo of the drone) and a single-board Raspberry Pi computer with WiFi module (Fig. 13). The GCP included one transceiver based on ADALM-Pluto Radio, Raspberry Pi with a WiFi module (with support for the router function) and a control computer (Fig. 14).

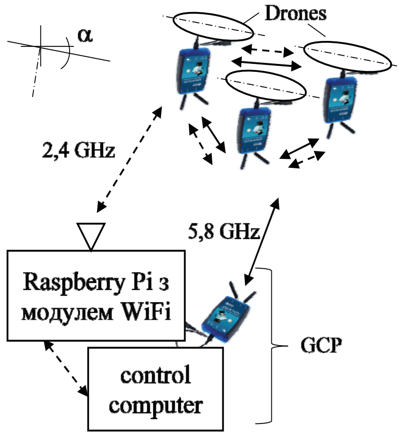



Fig. 12. The general scheme of scenario 2

The functions of ADALM-Pluto Radio consisted in organizing a channel for controlling a swarm of drones with increased range and noise immunity. The control channel was organized in a common data transmission channel, which also included a video transmission channel. The control channel was implemented by a distributed architecture: partly in the form of a core (logical block with complete functionality) IP Core (Intellectual Property Core) on FPGA, partly on installed GNU Radio software, because FPGA SoC (Zynq Z-7010), which is integrated into it , has restrictions on the number of DSP blocks. The operating frequency range of ADALM-Pluto Radio was expanded programmatically to 6 GHz, which made it possible to organize a channel at frequencies in the 5.8 GHz range with a bandwidth of 20 MHz. This made it possible to provide a total transmission rate of up to 20 Mbit / s with QPSK modulation and 3/4 coding rate.

The Raspberry Pi is built on Broadcom's BCM2835 system-on-chip (SoC), which includes a 700 MHz ARM processor, VideoCore IV graphics processor, and 512 or 256 megabytes of RAM. The Raspberry Pi served as the interface between the ADALM-Pluto Radio and the drone control transceivers in router mode. An additional function was the broadcast of video from a swarm of drones by the choice of an individual drone in the video transmission channel.

In this scenario, 6 channels (time duplex) in the 2.4 GHz band (WiFi burst structure, subchannels 25, 33, 41, 57 63 and 73) and 4 channels in the 5.8 GHz band (full duplex) were used. Thus, in this drone swarm system, all channels can operate simultaneously, both for transmitting information and control signals. Drones were controlled directly through the control computer using the joystick (additionally via the virtual reality helmet). Drones were brought to the working altitude separately using both the WiFi channel built into the quadrocopter and the additional 5.8 GHz channel. Moreover, the last channel has a significantly higher energy budget radio lines than WiFi.

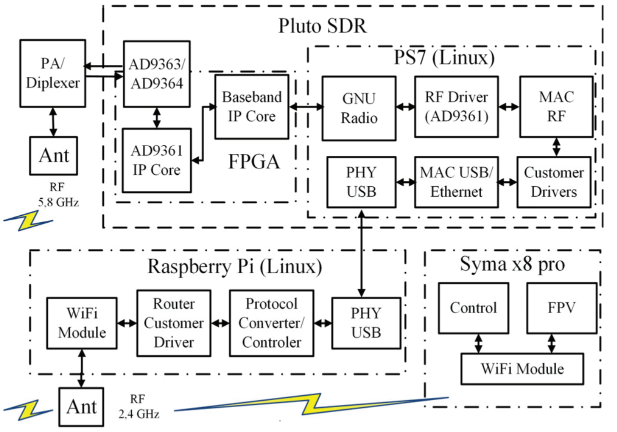



Fig. 13. The organization structure of the radio channels on the drone

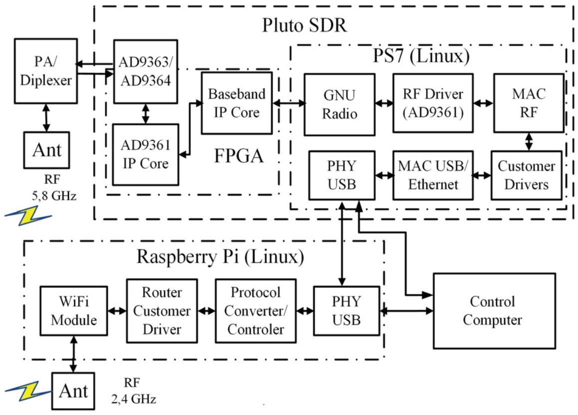



Fig. 14. The organization structure of the radio channels on the ground control point

The survivability of such a system is enormous, as is the enormous possibility of various connections to external devices (Internet things, subscriber devices, objects in motion or flight) with radio interfaces in the 2.4 and 5.8 GHz bands. A flexible bundle of programmable modules Raspberry Pi and ADALM-Pluto allows you to use them both on drones and on GCP.

Three experimental drones were brought to a hovering height of 20 m and connected in series (16 Mbps data stream was supplied) so that the signal at the GCP receiver was minimal, but at the same time the radio communication channel was still possible with an acceptable level of bit errors (approximately $10^{-5}$ QPSK modulation) (Fig. 15). In this case, the signal-to-noise ratio SNR (Signal-to-noise ratio) from drones was 8-9 dB. All the time (at the beginning of the next packet transmission), the modules were synchronized to compensate for the instability of the reference generators of various modules.

Fig. 15. Hanging of a swarm of drones at a height of 10… 15 m according to the 2nd scenario (April 2020)

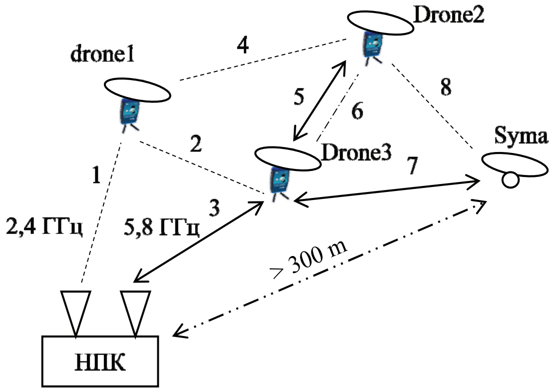



Fig. 16. Connection scheme between drones in cooperative relay mode for transmitting a video signal from a base Syma quadrocopter

An example of using the mode of relaying a swarm of drones was the experiment of connecting a separate quadcopter Syma X8 PRO through a swarm, equipped with a video camera. In fig. 16 shows a diagram of connections between drones in cooperative relay mode for transmitting a video signal from a Syma base quadrocopter. The quadcopter was brought to a distance (of the order of 350 m), exceeding the required standard operating range of the Syma X8 PRO in the 2.4 GHz band (of the order of 70 m). The distances to the drone1 were 60...65 m, to the drone2 - 200 m, and to the drone3 - 140 m. At these ranges, a standard control channel in the 2.4 GHz range from the GCP was possible only for drone1, and in the range of 5.8 GHz - for drone 3. On dron2 and a quadrocopter with a video camera, the direct control channel was not supported. Since the distance from the quadrocopter to drones 2 and 3 is almost the same, to implement the cooperative cooperation scheme with the target receiver, the quadrocopter could equally effectively use both of these drones. The operation of communication channels between swarm nodes was carried out in different ranges as shown in Fig. 16. The transmission of video from a quadrocopter for such a swarm location was possible with the use of cooperative relay technology in the 5.8 GHz band.

Any switching of the drone control signals both in the direction (GCP-drone1-drone2-drone3 in series, or GCP to all drones simultaneously, or GCP-drone1- GCP-drone2- GCP-drone3) and in the frequency range did not cause time delays, which were causing failures in management packs.

## V. Conclusion

Experimental testing and development of basic principles digging control (constellation) drones and forming cooperative relaying system. Scenarios for centralized and distributed construction of a collective drone swarm management network for communication services have been developed.

Testing a drone swarm was carried out according to two relay scenarios: passive using metallized reflectors and active using additional SDR radio units. Drones were formed on the basis of the quadcopter model Syma X8 PRO. For testing, radio channels in the 2.4 and 5.8 GHz bands were involved.

The results of testing according to scenario 1 demonstrated the great potential of a drone swarm with respect to controlled flexible spatial rearrangement of their reflective surfaces for the formation of directional relay radio channels with various objects. Moreover, it is possible to change the reflective area by reducing and expanding drones in space.

The developed kit based on the Raspberry Pi and ADALM-Pluto programmable modules allows you to use them very flexibly both on drones and on the ground control station by changing the software on them. This kit made it possible to implement scenario 2, where cooperative relaying of the signal to a remote quadrocopter was carried out through the drones of the swarm, direct communication with which from the GCP was impossible.

Each of the drones has many degrees of freedom with respect to the choice of wireless connection to other swarm drones or external devices, including GCP. This increases the noise immunity, fault tolerance and functionality of such a system, as well as the possibility of building it up.

The results of field testing of the functioning of the swarm of drones confirmed the theoretical basis for the formation of the swarm and possible scenarios of its operation, developed earlier in [21] - [28].

Further research will be aimed at improving the self-organization of the developed drone swarm.

## Acknowledgment

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*Кравчук С.А., Кайденко М.М., Афанасьєва Л.А., Кравчук І.М.*

**Тестування рою дронів в якості ретрансляційної системи зв'язку**

**Проблематика.** Інтенсивний розвиток галузі виробництва безпілотних літальних апаратів призвело до появи множини їх варіантів для різних застосувань. Окремий клас низько літаючих безпілотників, робота яких проходить в рамках певної самоорганізуючої (роботизованої) групи, склали дрони, об'єднані в сузір'я або рій. Всі дрони такого рою спільно можуть виконувати одну спільну функцію як самостійний роботизований комплекс.

**Мета**. Метою даної роботи є експериментальні тестування і відпрацювання базових принципів управління рою (сузір'я) дронів і формування кооперативної системи ретрансляції.

**Методи**. Досліджуються структурно-функціональні методи побудови безпроводової мережі на основі рою дронів.

**Результати**. Тестування рою дронів було проведено згідно двом сценаріям ретрансляції: пасивної за допомогою металізованих відбивачів і активної з використанням додаткових радіоблоків SDR. Дрони були сформовані на базі моделі квадрокоптера Syma X8 PRO. Для тестування були задіяні радіоканали в діапазонах 2,4 і 5,8 ГГц.

Розроблений комплект на основі програмованих модулів Raspberry Pi і ADALM-Pluto дозволяє дуже гнучко використовувати їх як на дронах, так і на наземному пункті управління шляхом зміни на них програмного забезпечення.

Кожен з дронів має множину ступенів свободи щодо вибору безпроводового підключення до інших дронів рою або зовнішніх пристроїв, в тому числі до наземного пункту управління. Це підвищує стійкість, відмовостійкість і функціональність такої системи, а також можливість її нарощування.

**Висновки**. Проведено експериментальне тестування і відпрацювання базових принципів управління рою (сузір'я) дронів і формування кооперативної системи ретрансляції. Відпрацьовано сценарії централізованої і розподіленої побудови мережі колективного управління рою дронів для послуг зв'язку.

**Ключові слова**: рій безпілотних літаючих апаратів; рій дронів; безпроводова система зв'язку; кооперативна ретрансляція; мережа управління дронами

***Кравчук С.А., Кайденко Н.Н., Афанасьева Л.А., Кравчук И.М.***

**Тестирование роя дронов в качестве ретрансляционой системы связи**

**Проблематика**. Интенсивное развитие отрасли производства беспилотных летательных аппаратов привело к появлению множества их вариантов для различных применений. Отдельный класс низко летающих беспилотников, работа которых проходит в рамках определенной самоорганизующейся (роботизированной) группы, составили дроны, объединенные в созвездие или рой. Все дроны такого роя совместно могут выполнять одну общую функцию как самостоятельный роботизированный комплекс.

**Цель**. Целью данной работы является экспериментальные тестирование и отработка базовых принципов управления роя (созвездия) дронов и формирования кооперативной системы ретрансляции.

**Методы**. Исследуются структурно-функциональные методы построения беспроводной сети на основе роя дронов.

**Результаты**. Тестирование роя дронов было проведено согласно двум сценариям ретрансляции: пассивной при помощи металлизированных отражателей и активной с использованием дополнительных радиоблоков SDR. Дроны были сформированы на базе модели квадрокоптера Syma X8 PRO. Для тестирования были задействованы радиоканалы в диапазонах 2,4 и 5,8 ГГц.

Разработанный комплект на основе программируемых модулей Raspberry Pi и ADALM-Pluto позволяет очень гибко использовать их как на дронах, так и на наземном пункте управления путем изменения на них программного обеспечения.

Каждый из дронов имеет множество степеней свободы в отношении выбора беспроводного подключения к другим дронам роя или внешним устройствам, в том числе к наземному пункту управления. Это повышает помехоустойчивость, отказоустойчивость и функциональность такой системы, а также возможность ее наращивания.

**Выводы**. Проведено экспериментальное тестирование и отработка базовых принципов управления роя (созвездия) дронов и формирования кооперативной системы ретрансляции. Отработаны сценарии централизованного и распределенного построения сети коллективного управления роя дронов для услуг связи.

**Ключевые слова**: рой беспилотных летающих аппаратов; рой дронов; беспроводная система связи; кооперативная ретрансляция; сеть управления дронами