INFORMATION AND MEASUREMENT TECHNOLOGIES IN MECHATRONICS AND ROBOTICS

MODELING A NETWORK OF UNMANNED AERIAL VEHICLES

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https://doi.org/0.23939/istcmtm2021.03.042

Abstract. The research concerns the methods of UAV group control in networks with duplex communication between nodes built on the “client-server” architecture. Such systems belong to self-organized networks with variable topology. It is important to study the allowable parameters of deviation from the task in the management of a group of UAVs and analysis of the network topology for the group flighting. The network was optimized according to the Ant Colony algorithm ACO. The application of different types of algorithms prevents routing problems in networks, such as ANTMANET, AntNet, ACODV and others. Methods of coordination of group joint actions are considered. A method is proposed by which the optimal number of UAVs operated by one operator can be determined and the traffic intensity of the communication channel is calculated, as well as the bandwidth and packet transmission delay are estimated.

Key words: UAV; AntNet algorithm; ABC algorithm; Queuing system.

1. Introduction

In recent decades, there has been a significant development of unmanned aerial vehicles (UAVs), which are based on technology in various fields of R&D and production. IT-advances have radically changed the perception of UAVs and made it possible to adapt them to perform intelligent tasks, law enforcement, communication relay, environmental control, search and rescue operations, disaster response, process monitoring, and more.

It should be noted that the growing number of aircrafts pose significant threats to their operation, which requires the development and implementation of specialized standards and compliance with legislation. The introduction of standardization tools is necessary for aviation safety as well as and for electromagnetic compatibility of UAVs and dispatching services insurance. Therefore, the European Aviation Safety Agency (EASA) has published a document [1] on the safety of aircraft, which regulates the use of UAVs and their interaction with other aircraft, aiming the further legislation on air safety enhancement.

Numerous experiments in the development of control and navigation algorithms for surveying, data collection, monitoring, and object tracking have involved quadcopters. This choice was due to the flight characteristics and attractive cost.

Developments aimed at improving the characteristics of UAVs in different weather conditions are underway. The task of designing pilot controllers that meet the current requirements for navigation and maintenance of onboard equipment has not lost its relevance. Based on the performance characteristics and principles of quadcopter piloting, this task includes an analysis of ways to control the flight of the aircraft according to a certain algorithm (for example, guarantee of flight modes such as automatic takeoff and landing, maintenance of flight parameters, fault tolerance). Their provision makes it possible to perform complex tasks, namely the maintenance of not one drone, but a group, which requires studying of specialized piloting algorithms and methods of information exchange between the operator and the UAV, and between other units of the group.

Usually a UAV is not a stand-alone device, but part of the system for obtaining information. Such a system can be attributed to an unmanned aerial system (UAS), which is controlled by operators from the ground remote control point and guarantees the efficiency of its operation. The UAVs perform tasks effectively while providing the necessary operating conditions, flight safety, in particular, with the support of the automatic control system. The presence of autopilot in the system helps to perform a number of autonomous tasks, which significantly increases efficiency. The implementation of artificial intelligence and extended topology determines the main advantages of the development of UAVs, which guarantees significant information support in the performance of tasks and a high level of automation of piloting. All of these are complex systems that require permanent improvement of control.

2. Goal of the Paper

The aim is due to study the methods of UAV control during their long-term and continuous development, to improve the control algorithms and network communication protocols.

3. The control algorithms of UAV group

When servicing large facilities or ensuring high quality monitoring, there is a need to apply not only individual UAVs, but the specialized groups of devices, which make the fulfillment of tasks complex, objective [2]. To standardize group UAV pilots, we propose to classify the types of UAV group flights (Fig. 1).

The "one UAV – one operator" model is inherent in the development prospects, nevertheless for specialized applications. Standardization of this area covers mostly the rules of selection of individual elements of the device, materials and software unification [3]. No less important is the coordination of the operator's actions in accordance with the flow of data. The quality of the information gathered in this way requires the development of a number of measures to verify it. This is especially important if the state of the object is constantly changing. For example, predicting the formation of congestion on the highway when the traffic situation changes during the flight.

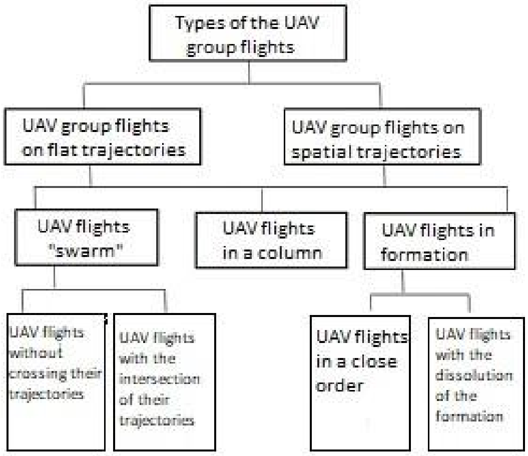


Fig. 1. The types of the UAV group flights

These requirements can be solved by a group of UAVs [4], controlled by one or more operators that are in the control and monitoring network. The task can be optimized by the number of UAVs per operator, the choice of piloting method, the efficiency of service protocols and the standard of the wireless communication channel. The locations of the UAV group's launch pads should also be optimized to ensure a minimum approach time for each.

The movement of the UAV group can be presented in typical scenarios. Fig. 2 shows examples of flat group trajectories of a group of 4 UAVs that perform a horizontal flight in the shunting coordinate system M_{xyz} with velocities, $k = (1\ldots 4)$ at altitude $h = const$. Here UAV2-4 move to the object of observation, and UAV1 is in standby mode for additional study of the object, which is such a function as, for example, retransmission in the case of a significant level of interference, while UAV2-UAV4 collect information at different altitudes of the group's flights along spatial trajectories.

To ensure the spatial survey of the object, it makes sense to consider the movement of a group of UAVs of the "swarm" type when performing a flight task on independent trajectories without their intersection, f. i. the so-called "double snake" mode. Fig. 3 shows the flat trajectories of two UAVs flying in a horizontal plane in the "double snake" mode.

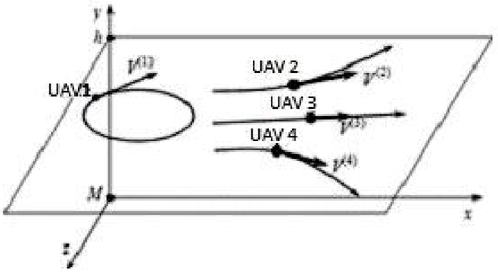


Fig. 2. Movement on flat trajectories of a group of 4 UAVs

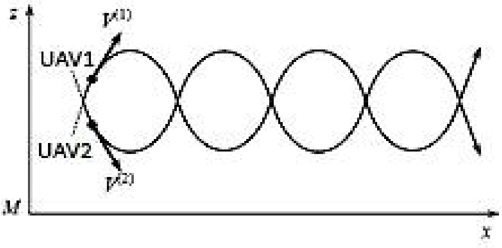
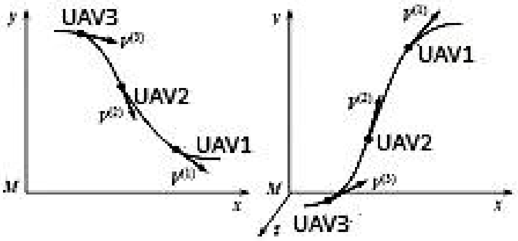


Fig. 3. The movement of two UAVs that fly in the horizontal plane in the mode of "double snake"

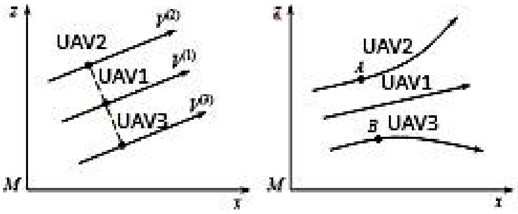
Let's consider another manner of UAVs group piloting. In Fig. 4 the movements of 3 UAVs group column are given.



a *b*

Fig. 4. UAVs' movement: a – a column in the vertical plane on a single trajectory; b – a parametric representation of the flight path of the group on the selected coordinate system Mxyz

Parametric representation of the flight path of the group on the selected coordinate system M_{xyz} is presented as $x = x(t)$; $y = y(t0)$; $z = z(t)$. For this type of group flight is important to ensure a given distance between the UAVs in the column. The trajectory of UAVs' flights is shown in Fig. 5. To ensure the group monitoring in the vertical plane, a line trajectory type is studied (Fig. 5*a*), which, after completing the task, can be disbanded to the type shown in Fig. 5*b*.



a b

Fig. 5. The group of UAVs moving by line type (a); the group disbanding becomes possible at the points A and B (b)

Radio control of UAVs is provided for information exchange. Using a group of UAVs turns them into a mobile network that can be deployed at a specific location and time. Such networks belong to mobile wireless networks with dynamic topology MANET (Mobile Ad hoc Network); they consist of mobile nodes each of which is UAV. Their infrastructure varies and centralized management is absent. The specialized motion algorithms and data transmission protocols promote self-organization. Such networks become more complicated, but unlike conventional networks, do not require expensive infrastructure. Each of the nodes in such networks is multifunctional; it acts both as a router and a host. Data transfer between nodes is carried out without centralized control.

Maintenance of a group requires of standardized algorithms for self-organizing systems. Consider the control algorithm named as "swarm". It can be implemented in a system of numeral objects that form a communication network. Their simple interaction determines the so-called collective adaptation. Intelligence is formed on the basis of the "set of behaviors" of such objects. Examples of such a system are a swarm of bees, a flock of birds and an Ant Colony Optimization ACO [5–6]. To describe its behavior, the mentioned algorithm is optimal. Namely, a polynomial algorithm based on the meta-heuristic method of swarm solution of which is effective for the colony scout and considers the combinatorial optimization of distributed nonstationary systems for voyager in the form of a graph model.

Two main algorithms are used: the AntNet algorithm and the ABC algorithm.

3.1. ABC algorithm

The latter is studied to balance the communication network in the form of a graph, the nodes of which are the control points on the ground, and the edges – the communication lines. Each node contains a so-called "pheromone" routing table which consists of N–1 columns and N_k rows. Here N is the number of network nodes, and N_k is the number of nodes adjacent to node k. At a certain moment, the ant of each node begins its movement to the random destination node. The movement of objects depends on the data listed in the "pheromone" table, which affects the choice of intermediate node. Let j be the destination node, and let P_{ij} be the probability of the object transitioning to the neighboring node i. The "pheromone" table is updated when the object reaches the next intermediate node. To update the table data use formulas (1):

$$\begin{cases} P`_{n,src} = \dfrac{P_{n,src} + \Delta P}{1+\Delta P} \\ P`_{i,src} = \dfrac{P_{i,src}}{1+\Delta P}, i = 1..N_k, i \neq n \end{cases} \qquad (1)$$

Here n is the node, from which came the ant (object); src is the node of origin that have formed the ant; $P_{n,\ src}$, $P'_{n,\ src}$ are the previous and current values of the elements of the "pheromone" table; ΔP is an increment of "pheromone". The duration of the ant's existence is limited and determined by the number of nodes passed to the final node, i.e. by the length of the path. After passing the final node, the ant no longer exists. The lifespan of an ant affects the increment of the "pheromone" ΔP:

$$\Delta P = \frac{0{,}08}{age} + 0{,}005. \qquad (2)$$

When the ant chooses a shorter path with less load, the transmission time decreases, and ΔP increases. Therefore, data from an object moving along such a route are transmitted by a shorter distance at the lowered load on the network.

3.2. AntNet algorithm

As with the previous algorithm, objects inherit the behavior of ants. The choice of motion when using the AntNet algorithm is determined by the probabilities, which reduces the occurrence of network congestion. The state of the passed network channels forms a packet, which is an agent. The algorithm assumes the existence of two types of ants: Forward ants of F-type and Backward ants of B-type. F-ants travel in the direction from the source to the destination, and B-ants – in the opposite direction. These types of objects differ in their behavior, and are characterized by the same structures.

The routing table is updated only for B-ants. F-ants collect statistical information about the state of the network. When the F-ant reaches the destination node, a B-ant is formed with the information received by the F-ant. The F-ant ceases to exist. The "pheromone" routing table is updated only after the B-ant starts moving in the opposite direction. A routing table T_k and a local traffic model structure M_k are created for each network node k. The network interface of the node is represented by a column of the table T_k, and the network node acts as its row. The table itself forms a probability matrix P_{nd}. The data in the routing table for each node d and for each neighboring node n is stored when that d-node is the receiving one – see (3). The local parametric model of traffic distribution for k-node represents the array M_k:

$$\sum_{n \in N_k} P_{nd} = 1, d \in [1, N], \qquad (3)$$
$$N_k = \{k_{\text{neighboring nodes}}\}.$$

The model formed for each *d*-node is stable with mathematical expectation μ_d and variance σ_d for the time of object; it forms an array of a dynamic observation window W_d. At the time when the B-ant is in the *k*-node, the moment $o_{k\to d}$ of arrival at the *d*-node is written to the array W_d. The calculation of characteristics by the algorithm is performed applying an exponential model (4)–(5):

$$\mu_d = \mu_d + \eta(o_{k\to d} - \mu_d), \tag{4}$$

$$\sigma_d^2 := \sigma_d^2 + \eta(o_{k\to d} - \mu_d)^2 - \sigma_d^2, \tag{5}$$

here η is the weight factor. When estimating the lower time limit W_{bestd} reaching *d*-node from the current *k*-node, the array of the dynamic observation window W_d is used. The arrays *{Tk}* and *{Mk}* form the local memory of the nodes. Each node stores its own information. The *Mk* model can contain a distance / time ratio to each of the network nodes, and the routing table *Tk* can estimate the quality of the transition for each “communication line – host node”. Fluctuations in network traffic lead to a change in the route of ants. The probability of creating in the *src*-node of F-ant with the host d-node is calculated by:

$$p_d = \frac{f_{scr,d}}{\sum\limits_{d`=1}^{N} f_{scr,d}}. \tag{6}$$

where $f_{src,\,d}$ is the data stream from *s*-node to *d*-node. The F-ant selects the host node based on the traffic model. Being in *k*-node, it chooses a route through intermediate *n*-node, from those nodes where it has not visit before. If all nodes of the network have been visited, the transition is made to the node with probability:

$$P`_{nd} = \frac{P_{nd} + \alpha \cdot l_n}{1 + \alpha(N_k - 1)}, \tag{7}$$

here P_{nd} is a routing table element; α is the weighting factor; l_n is the length of the queue in bits to the communication line between nodes *k* and *n*. When an F-ant cycle is detected in a route the information about such a node, the latter is deleted. The use of a priority queue provides a high rate of information transfer from F-ants to B-ants. When the B-ant has reached *k*-node from the previous *f*-node, the *k*-node updates the traffic model M_k and the routing table elements T_k to the host *d*-node. The probabilities P_{fd} in the table T_k increase (i. e. the probabilities of selecting the previous *f*-node to the *d*-node-receiver). Also, the other probabilities P_{nd} are minimized by normalizing:

$$P_{fd`} := P_{fd`} + r(1 - P_{fd`}), \tag{8}$$

$$P_{nd`} := P_{nd`} - rP_{nd`}, n \notin N_k, n \neq f, \tag{9}$$

here $r \notin [0,1]$ is the stabilization factor that is an analogue of pheromones. The routing tables computing increases the performance of the algorithm by 30–40 %.

4. Routing protocols and their analysis

The choice of object motion algorithms allows optimizing the flight path. Since the purpose of the flight is mainly to obtain information that needs to be transmitted further and the radius of the transceiver zone in wireless networks is limited, to solve the problems of UAVs’ application (mobility at significant interference, low output facility of link channels and high power consumption) is recommended involvement of reactive, proactive or hybrid protocols.

Let's analyze the following routing protocols corresponding to the ant algorithm: AODV-protocol (Ad hoc On-Demand Distance Vector, i.e. dynamic routing protocol for mobile ad-hoc networks with remote-vector routing algorithm), DSDV-protocol (Destination-Sequenced Distance-Vector), DSR--protocol (Dynamic Source Routing, i.e. dynamic routing from a source in the presence of a “grid” topology) and AntHocNet. The difference between the protocols is mainly in the way the path information is updated.

Analysis of performance metrics, such as average output facility and average delay, when changing packet size and object speed, on the NS2 simulator demonstrate the following. When using the AntHocNet protocol (number of objects and their speed are increasing, the obtained results are slightly better than for other protocols (Fig. 6): for a small number of objects, the difference in through delay for all protocols is insignificant. However, as the number of objects increases, the delays for the DSR, DSDV, AODV protocols intensify significantly, and for the AntHocNet protocol they remain unchanged.

Fig. 7 shows the dependence of service traffic on the number of objects. The AntHocNet protocol is characterized by significant costs compared to the AODV and DSDV protocols; costs are commensurate with the DSR protocol. As the number of objects for AODV and DSDV protocols goes up, the delays begin to increase, while for AntHocNet protocol they remain unchanged or indicate a slight growing.

The dependence of the output facility on the number of objects (Fig. 8) indicates the following. As the number of objects increases, the output facility for AntHocNet protocol becomes higher than for DSR, AODV, or DSDV protocols. DSR output facility is higher than AntHocNet, despite the same or higher routing costs. It is due to AntHocNet routing packets filling of whole channel capacity.

Fig. 9–11 show the study conducted for a fixed number of objects at different speeds: Fig. 9 – the dependence of the through delay and speed of objects. Here, as the mobility of objects grows, effect of network delay is unnoticed for AntHocNet protocol. It does not apply to other protocols, and AODV protocol seems to be the most sensitive. Fig. 10 indicates that, despite the significant costs, the AntHocNet protocol provides best network output facility compared to others, and Fig. 11 shows the dependence of service traffic on the speed of objects: here AntHocNet protocol indicates higher performance with increasing objects’ mobility compared to other protocols.

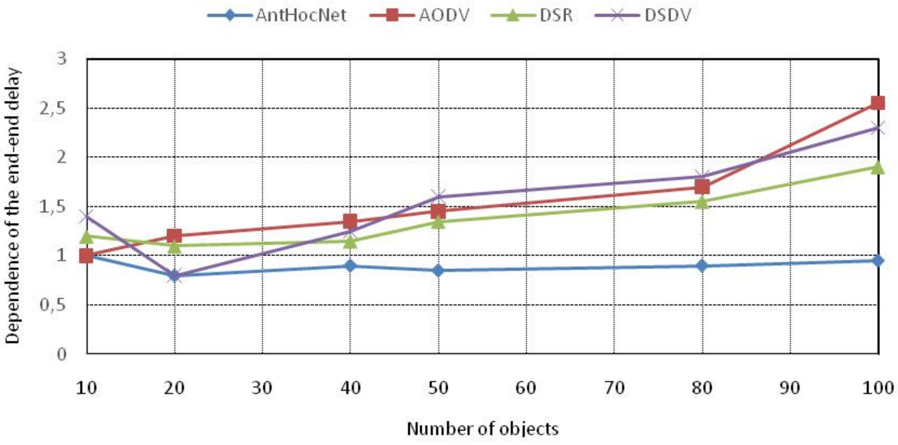


Fig. 6. Dependence of end-to-end delay on the number of objects

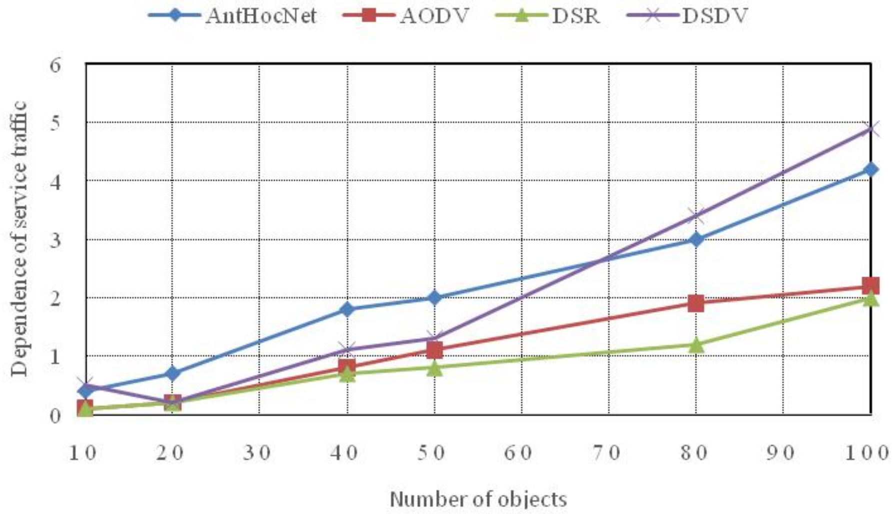


Fig. 7. Dependence of service traffic on the number of objects

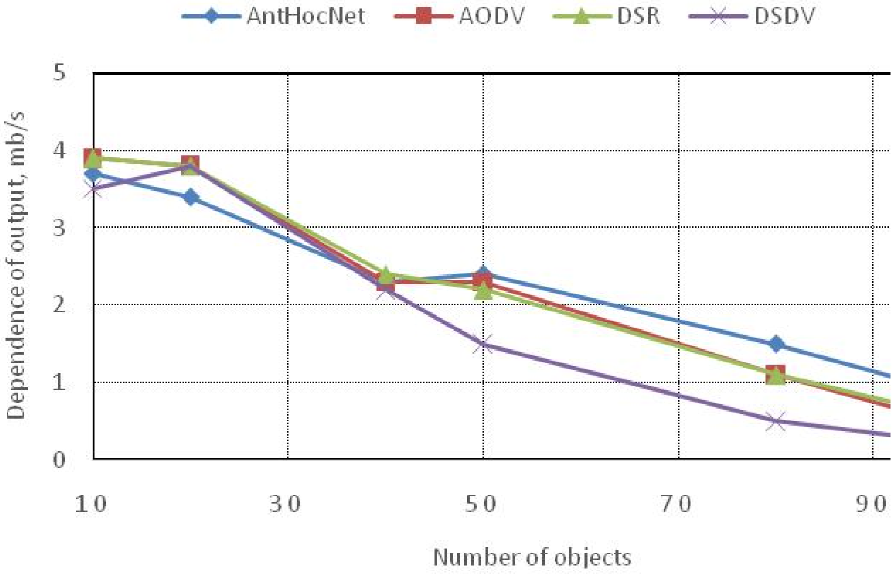


Fig. 8. The dependence of the output on the number of objects

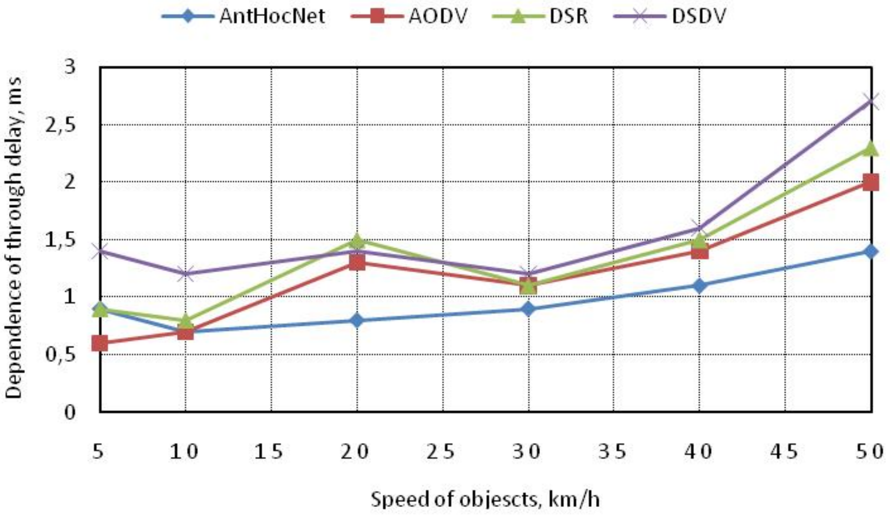


Fig. 9. Dependence of the through delay on the speed of objects

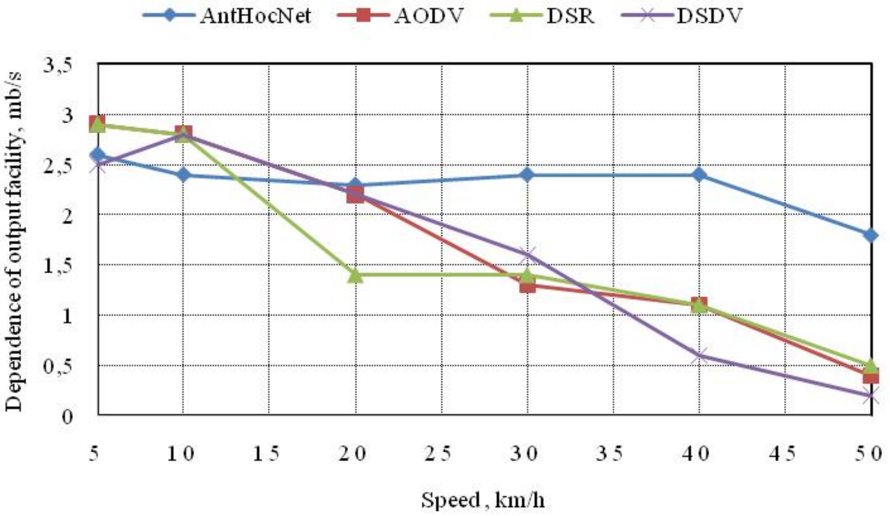


Fig. 10. Dependence of output facility on the speed of objects

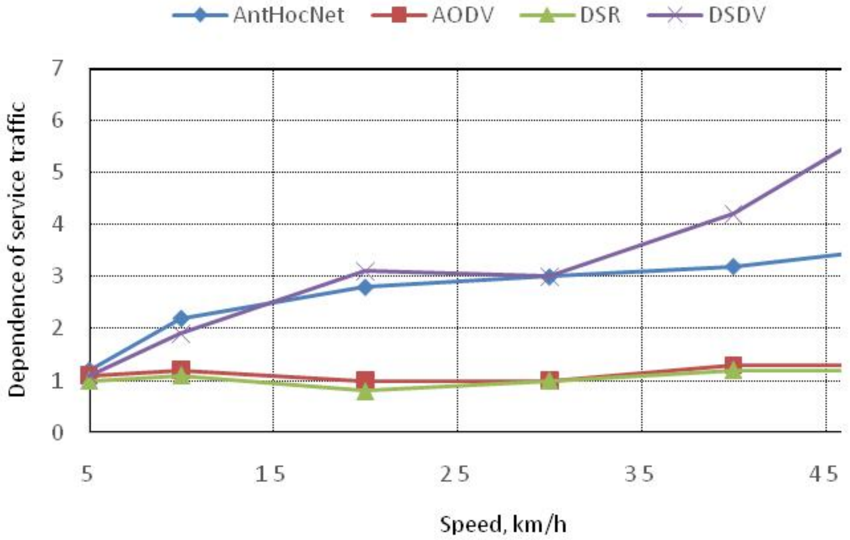


Fig. 11. Dependence of service traffic on the speed of objects

5. Conclusions

To control a UAVs' group with different structure order, a study of the ant colony algorithm based on heuristic-probabilistic approaches is considered. Based on the simulation studies in the group with self-organization, the possibilities of load intensification and a number of other operational characteristics have been evaluated. Compared to protocols such as DSR, AODV and DSDV, the effectiveness of AntHocNet protocol in terms of output facility, performance, and end-to-end delay is noted. In addition, this protocol provides scalability and is suitable for creating FANET networks with high objects' mobility and data rate.

6. Gratitude

The authors express their gratitude to the staff of the Department of Information-Measurement Technologies of the Lviv Polytechnic National University, Ukraine, for the comprehensive assistance in preparing the article.

7. Conflict of Interests

The authors declare that there is no financial or other possible conflict regarding the paper.

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