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Original Research

Development of a mathematical model of video monitoring based on a self-organizing network of unmanned aerial vehicles

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ABSTRACT

The article presents the development of a mathematical model of video monitoring based on a self-organizing network of unmanned aerial vehicles. The necessity of developing models and algorithms for providing geoecological monitoring using a wireless self-organizing network based on unmanned aerial vehicles is shown. Models are presented that allow calculating the speed of information transfer in the network and reducing the number of failures in the process of transmitting video data. With the help of models, it is possible to substantiate the power of network transmitting devices, at which the losses of transmitted packets are significantly reduced. The practical use of the model contributes to the achievement of the required quality of video surveillance in a wireless self-organizing network of unmanned aerial vehicles in the process of geoecological monitoring.

Keywords: flying self-organizing network, FANET, unmanned aerial vehicles, power of network transmitting devices, geoecological monitoring.

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1. Introduction

A promising scientific and technological trend is information transmission on the basis of flying wireless self-organizing networks (Flying Ad hoc NETwork, FANET). The functioning of FANET is based on using unmanned aerial vehicles (UAV), on which the hardware and software of network nodes are installed [1]–[5]. Due to the fact that each node can perform the functions of a sending-receiving retranslate and a packet router, such a decentralized network is able to transmit data flows in conditions of random topology, quick-changing in three-dimensional space. This specific character allows using FANET networks for solving a large variety of problems, connected with aerial photo and video monitoring of extensive or hard-to-reach areas, transmitting research information concerning the measuring data of various parameters (air pollution level, temperature, humidity etc.), providing communication in conditions of emergencies or combat actions, organizing goods delivery [6]–[9]. Wireless ad hoc networks on the basis of UAV can be used for providing geo-ecological monitoring of agro-industrial complex resources, detection of forest fires, inspecting overhead power transmission lines and diagnostics of electrical power network equipment [10-14]. A challenging issue of using FANET is loss of video communication quality, preconditioned by high dynamicity of network topology due to rapid motion of its nodes. The frequent alterations of network configuration and distances between its nodes result, firstly, in a randomly occurring deficit of wireless channels capacity due to quick alteration of their loading because of active forced reallocation of video streams transmission routes, and secondly, in the increase of packet loss due to bit mutilation. There are various methods and algorithms aimed at improving communication quality in wireless ad hoc networks. In order to improve the physical performance of wireless channels the simulation results of radio wave propagation [15] and multichannel retransmission [16] were obtained, and the antennas structures were studied [17-18]. The engineering solutions at the level of access control to wireless channels are presented, the algorithms of FANET-channels balancing with the use of radial-basis functions are developed 19]. Many papers are concerned with analyzing the efficiency of using routing procedures in ad-hoc networks and developing network level algorithms, adapted to the FANET functioning conditions [8], [20-22]. The transport layer protocols within the architecture of message exchange between unmanned systems JAUS (Joint Architecture for Unmanned Systems) were developed [23]. A model of data streaming in wireless networks is created, with restoring lost fragments by application layer means on the basis of automatic request for repeat or retransmission [24]. A number of papers are concerned with developing models and algorithms, aimed at providing the efficient audio communication in a wireless ad hoc network [25-28]. They suggest using redundancy of channels performance to increase the load of wireless channels and improve the quality of voice streams transmissions. These projects, as shown by the analysis results, should be upgraded by considering the high probability of packet losses in FANET networks and the specific nature of transmitting video data taken by UAV cameras. The arguments presented above determine the relevance of carrying out research in simulating a process of video streams transmission over FANET channels to provide the required quality of video broadcasts, used for geo ecological monitoring. The purpose of this work is to find a method to provide the required quality of video broadcast, implemented by means of a flying ad-hoc network, based on developing a model of video streams transmission in wireless channels in conditions of high nodes mobility.

2. Developing a model of video streams transmission process in FANET

The quality of video data streams transmission over the network can be provided under condition of minimizing the values of the following parameters: packet delay, jitter, packet loss. Maintaining the acceptable values of packet delay and jitter can be achieved by redundancy of channel performance for transmitting certain video streams. Due to possible overloads at certain segments of the ad-hoc network, part of requests for video streams transmissions can be buffered, and some of video streams can fail to be transmitted, when there is no free space in the channel buffer for request queue. Besides, there can be cases of low quality of video data streams transmission due to unacceptable level of packet loss, which results in losing broadcasted video segments. Failures to transmit video streams and transmitting video streams with low quality over FANET channels reduce the resulting quality of video broadcast. In this research it is suggested to use parameter p_c – probability of providing the required quality of video streams transmission over a FANET channel. Let α requests for transmitting video streams be sent over a FANET channel during a specified interval of time T. Then we assume that the required quality of video streams transmission over the channel is provided, if the sum of the number of failures to transmit video streams and the number of streams, transmitted with low quality, doesn't exceed β. The required quality of video streams transmission can be achieved if the bit rate in the channel possesses values, which would allow minimizing failures to transmit video streams, and the signal transmission power is so high, that the packet loss becomes negligible and doesn't considerably affect the quality of video streams transmission. At the same time, it is necessary to consider impracticality of the excessive increase of transmitting modules power, due to necessity to save power resources of FANET nodes, equipped with autonomous accumulator power batteries. To obtain the dependence of probability to provide the required quality of video broadcasts on the values of channel bit rate it is necessary to develop a corresponding mathematical model. The process of video streams transmission over a FANET channel at $\alpha = 4$ and $\beta = 1$ is presented as a probabilistic graph in **Figure 1**.

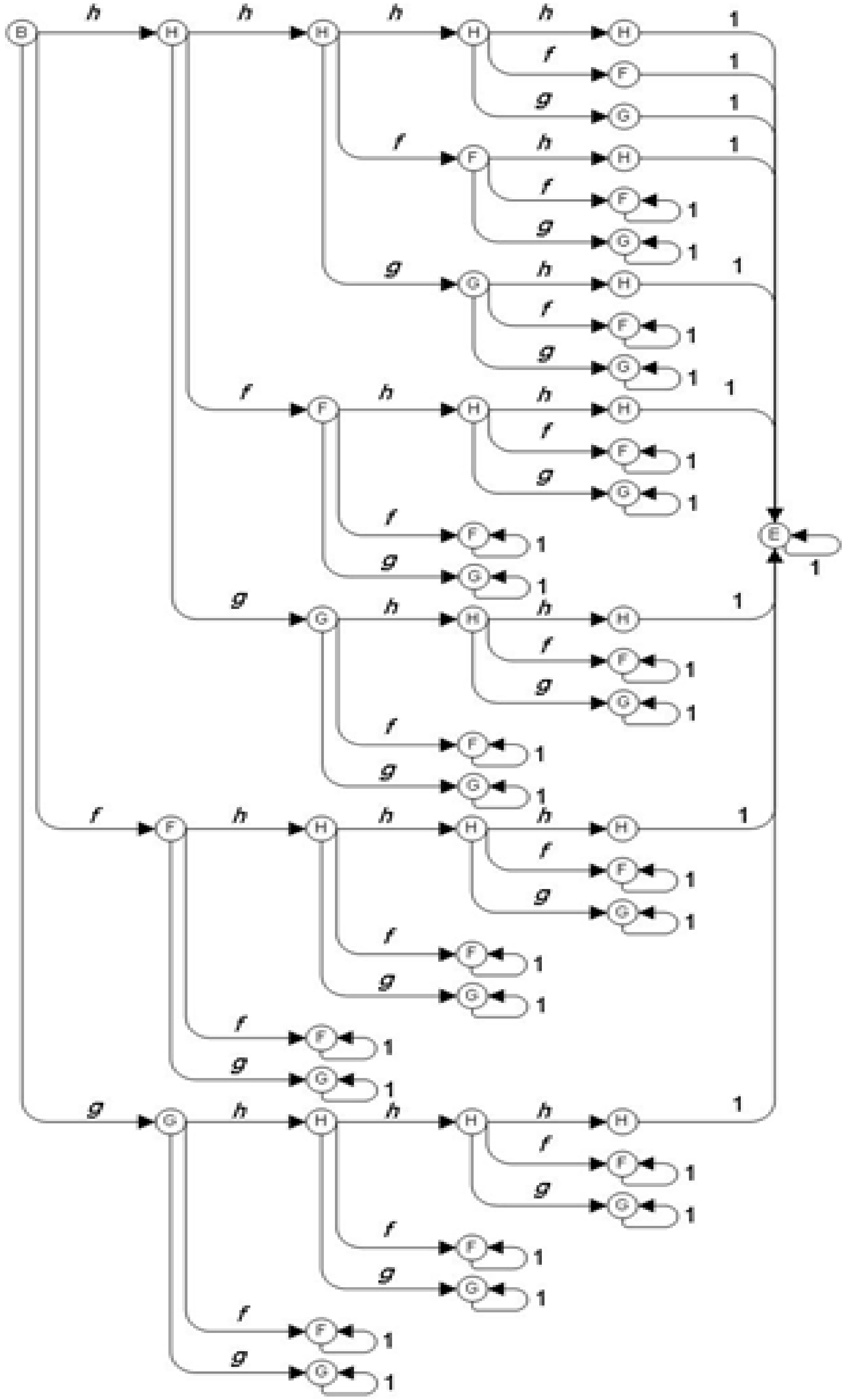

Figure 1.Probabilistic graph of the process of transmitting video streams over the FANET channel

The simulated process is described with a set of states, to which the following graph vertexes correspond: «B» – start of video broadcast process over a channel; «H» – video stream is transmitted with high quality over the channel; «F» – failure to transmit video stream over the channel; «G» – video stream is transmitted with low quality over the channel; «E» – the required quality of video broadcast over the channel is provided. Transition to any «H» vertex is performed with probability h . The value h is the probability of transmitting a video stream with high quality over the channel. Transition to any «F» vertex takes place if there is a failure to transmit video stream due to no free space in the channel buffer for request queue. The probability of such transition is equal to f . The value f is called probability of failure to transmit video stream over the channel. Transition to any «G» vertex simulates a case of transmitting a video stream with low quality, due to unacceptably high packet losses. Such transition is characterized with the value g

1. Probability of transmitting a video stream with low quality over the channel. Finally, vertex «T» is terminal for those graph paths, in which the sum of «F» and «G» vertexes doesn't exceed β . The exhaustive search of possible graph paths, connecting vertex «B» with vertex «T», has allowed obtaining an expression for calculating the probability of providing the required quality of video broadcast over the channel:

$$p_c = h^4 + 4h^3 f + 4h^3 g \quad (1)$$

Similarly the expressions for calculating value p_c at various other values of variables α и β , were obtained. These expressions are presented in **Table 1**.

On the basis of analyzing the expressions, presented in **Table 1,** a formula for calculating value p_c was deduced as follows:

$$p_c = \sum_{x=0}^{\beta} k_{\alpha,x} h^{\alpha-x} \left(f+g\right)^x \quad (2)$$

The values of coefficients $k_{\alpha,x}$ in the systematized form are presented in **Table 2**.

The analysis of data in **Table 2** demonstrates that it is a fragment of binomial coefficients table. This fact allows obtaining the following equation:

$$k_{\alpha,x} = C_{\alpha}^{x} = \frac{\alpha!}{x!(\alpha-x)!} \quad (3)$$

Taking into account expression (3), the formula for calculating probability of providing the required quality of transmitting video streams over the channel can be written as follows:

$$p_c = \sum_{x=0}^{\beta} \frac{\alpha!}{x!(\alpha-x)!} h^{\alpha-x} \left(f+g\right)^x \quad (4)$$

It is reasonable to assume that the required quality of video broadcast over the network would be provided if the required quality of video streams transmission over each channel of the network is provided. Then the probability of providing the required quality of video broadcast over the network can be calculated by the following formula:

$$p_N = \left[\sum_{x=0}^{\beta} \frac{\alpha!}{x!(\alpha-x)!} h^{\alpha-x} \left(f+g\right)^x\right]^K \quad (5)$$

where K – average number of channels, used for transmitting one video stream over the network.

The value f can be calculated as a probability of failure to serve a request in a multichannel system with limited queue length [29]:

$$f = \frac{\frac{(\lambda\tau)^n}{n!}\left(\frac{\lambda\tau}{n}\right)^m}{\frac{(\lambda\tau)^n}{n!}\sum_{u=1}^{m}\left(\frac{\lambda\tau}{n}\right)^u + \sum_{x=0}^{n}\frac{(\lambda\tau)^x}{x!}} \qquad 6$$

where n – number of video streams, which can be simultaneously transmitted with high quality over the channel; m – capacity of request queue buffer for transmitting video streams over the channel; λ – intensity of request rate for transmitting video streams over the channel; τ – average duration of video stream transmission over the channel. The expression (6) is valid at the fulfillment of condition $n > \lambda\tau$.

The number of video streams, which can be simultaneously transmitted with high quality over the channel, is calculated by the expression:

$$n = \frac{R}{r} \qquad 7$$

where R – bit rate of data transmission over the channel, bps; r – capacity of the channel, used for transmitting one video stream with high quality, bps.

To calculate the probability of transmitting a video stream with low quality over the channel the following expression can be used [27]:

$$g = 1 - \left[(1-v)^{\omega} + \sum_{a=1}^{b} y_{\omega,a}(1-v)^{\omega-a}v^{a}\right] \qquad 8$$

where ω – number of packets in the video stream, transmitted over the channel; v – probability of packet loss during transmission over the channel; b – the highest number of lost packets, with which the high quality of video stream transmission is possible.

The value b can be calculated by the formula:

$$b = \left\lceil \frac{\omega - 2\gamma}{\gamma + 1} \right\rceil \qquad 9$$

Coefficients $y_{\omega,a}$ can be calculated at $\omega > 2\gamma$ by the formula:

$$y_{\omega,a} = \begin{cases} \omega - 2\gamma, & a = 1; \\ 0, & a > 1 \quad \omega \le 3\gamma + 1; \\ \sum_{i=2\gamma+1}^{\omega-a-1} y_{i,a-1}, & a > 1 \quad \omega > 3\gamma + 1. \end{cases} \qquad 10$$

Expressions (8) – (10) take into account the possibility of restoring lost packets at the receiving node by means of approximation procedures. But in order to restore a lost packet at the receiving node it is necessary to receive no less than γ previously transmitted packets and no less than γ subsequent packets.

The packet loss probability in the process of transmitting over the channel can be calculated by the following expression [30-31]:

$$v = 1 - \left(1 - BER\right)^{S} \qquad 11$$

where BER – probability of signal distortion during transmission over the channel; S – number of bits in one packet.

Probability of signal distortion during transmission over the channel can be calculated by using Q-function with the formula [32]:

$$BER = Q\left(\sqrt{2\frac{E_b}{N_0}}\right) \qquad 12$$

where E_b – signal power per 1 bit of the received transmission; N_0 – power spectral density of the noise.

The ratio $\frac{E_b}{N_0}$ can be found by means of expression [28]:

$$\frac{E_b}{N_0} = \frac{SNR \cdot W}{R} \qquad 13$$

where SNR – signal-to-noise ratio in the channel; W – channel bandwidth, hz.

For calculating signal-to-noise ratio the following formula can be used [33]:

$$SNR = \frac{P_R}{k \cdot T_R \cdot W \cdot N_F} \qquad 14$$

where P_R – received signal power, W; $k = 1{,}38 \times 10^{-23}$ – Boltzmann constant, W·s·K-1; T_R – temperature, K; N_F – noise ratio.

The value of received signal power in dBm is calculated by means of an expression [34-35]:

$$P_R = P_T + 10\lg\left(\left(\frac{c}{\nu}\right)^2 \Big/ \left(4\pi d\right)^2 L_s\right) \qquad 15$$

where P_T – signal transmission power, dBm; $c = 3 \times 10^8$ – signal propagation speed, mps; ν – signal frequency, hz; d – average distance between transmitting and receiving nodes, m; L_S – system losses.

The value can be calculated by total probability normalization condition [36]:

$$h = 1 - \left(f + g\right) \qquad 16$$

Table 1. Expressions for calculating the indicator p_c

Values α	*Value* β	*Values* p_c
1	0	h
1	1	$h + f + g$
2	0	h^2
2	1	$h + 2h\left(f + g\right)$
2	2	$h^2 + 2h\left(f + g\right) + \left(f + g\right)^2$
3	0	h^3

Values α	*Value* β	*Values* p_c
3	1	$h^3+3h^2(f+g)\ h^6+6h^5(f+g)$
3	2	$h^3+3h^2(f+g)+3h(f+g)^2$
3	3	$h^3+3h^2(f+g)+3h(f+g)^2+(f+g)^3$
4	0	h^4
4	1	$h^4+4h^3(f+g)$
4	2	$h^4+4h^3(f+g)+6h^2(f+g)^2$
4	3	$h^4+4h^3(f+g)+6h^2(f+g)^2+4h(f+g)^3$
5	0	h^5
5	1	$q^5+5q^4(f+g)$
5	2	$h^5+5h^4(f+g)+10h^3(f+g)^2$
5	3	$h^5+5h^4(f+g)+10h^3(f+g)^2+10h^2(f+g)^3$
6	0	h^6
6	1	
6	2	$h^6+6h^5(f+g)+15h^4(f+g)^2$
6	3	$h^6+6h^5(f+g)+15h^4(f+g)^2+20h^3(f+g)^3$

Table 2. The values of the coefficients $k_{\alpha,x}$

α	x			
	0	1	2	3
1	1	1	-	-
2	1	2	1	-
3	1	3	3	1
4	1	4	6	4
5	1	5	10	10
6	1	6	15	20

3. Conducting of computational experiment

With the use of expressions (5) – (16), obtained in the process of simulation development, a series of computational experiments was performed. The input data for calculations are presented in **Table 3**.

The performed calculations results, presented in **Table 4**, demonstrate that at the fixed signal transmission power $P_T = 15$ dBm and the average distance $d = 480$ m between transmitting and receiving network nodes the probability of FANET video broadcasting required quality assurance is over 0.95, if the bit rate of data transmission is 8 Mbps. Increasing the average distance d even by a small amount (10–20 m) results in the fact that at the same power P_T it is impossible to find a value of R, which would allow to achieve the level of p_N no less than 0.95.

Table 3. Initial data

№	Variable	Value	Unit of measurement
1.	T_R	290	K
2.	N_F	5	-
3.	W	40	MHz
4.	L_S	1.08	-
5.	ν	5.18	GHz
6.	S	10^4	-
7.	ω	18×10^4	-
8.	γ	8	-
9.	K	6	-
10.	λ	10	hour^{-1}
11.	τ	0.5	hour
12.	α	10	-
13.	β	2	-
14.	T	1	hour
15.	r	1	Mbps

To increase the probability of providing the required quality of video broadcast up to $p_N = 0,95$ it is possible to increase signal transmission power. The computational experiments for studying the dependence of p_N value on P_T values for different average distances between transmitting and receiving nodes were carried out. The computational results in the form of graphs of dependence $p_N(P_T)$ at $R = 8$ Mbps are shown in Figure 2. Analysis of the presented findings shows that for various values of d such values of signal transmission power can be selected, at which the probability of providing the required quality of video broadcast reaches the level 0.95. Thus, for example, if the average distance between transmitting and receiving nodes in FANET is 500 m, then, at the bit rate of data transmission 8 Mbps, to achieve the probability value $p_N = 0,95$ the power P_T should be set at 15.2 dBm.

Table 4. Values p_N calculated at $P_T = 15$ dBm

d, m	R, Mbps					
	4	5	6	7	8	9
480	0.004	0.155	0.624	0.919	0.982	0.012
490	0.004	0.155	0.624	0.919	0.930	1.253×10-12
500	0.004	0.155	0.624	0.917	0.521	9.850×10-44

Here it is important to note that at $P_T = 15,2$ dBm calculations according to the Shannon's equation

$$R = W \log_2 (1 + SNR) \qquad 17$$

show a theoretical possibility to provide the bit rate of data transmission 83.56 Mbps, which is over by 10 times exceeds value , sufficient for achieving $p_N = 0,95$.

As a result of the research we have calculated the values of power P_T, which are recommended to set at transmitting output modules of FANET nodes to achieve the probability of providing the required quality of video broadcast equal to 0.95 depending on the average distance between transmitting and receiving nodes (see Table 5)

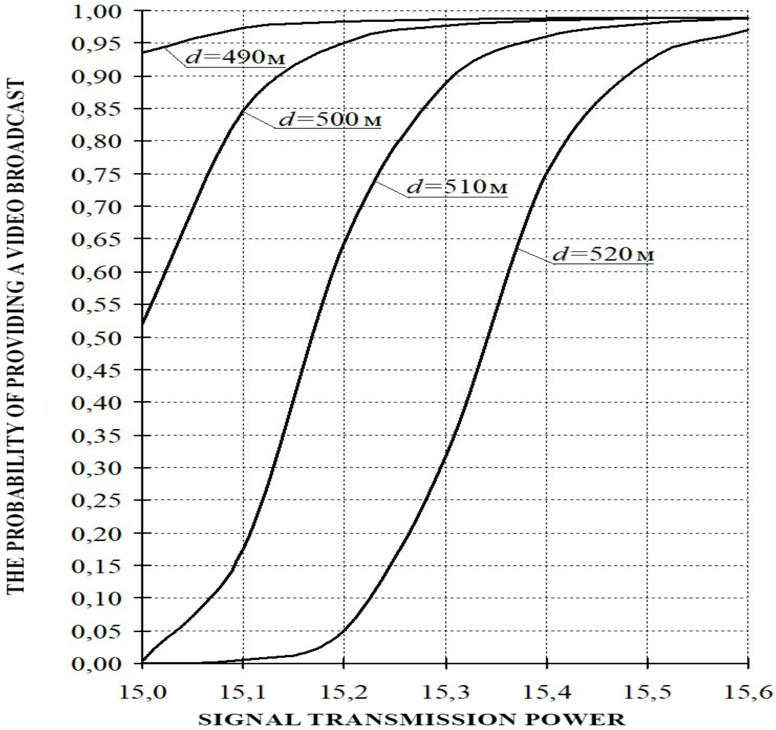

Figure 2. Graphs of dependence $p_N(P_T)$ at $R = 8$ Mbps

Table 5. Recommended P_T values, at which $p_N = 0,95$

d, m	P_T, dBm
500	15.20
550	16.03
600	16.79
650	17.48
700	18.13
750	18.73
800	19.29

4. Conclusions

So, the paper presents the research findings in developing a mathematical model of transmitting video streams in wireless channels in conditions of high nodes mobility. The application of this model allows providing the required quality of video broadcast in a flying wireless ad hoc network, used for geoecological monitoring. The carried-out analysis has demonstrated that the quality of FANET video broadcasts is impaired, firstly, by failures to transmit video streams, caused by deficit of channel capacity, and, secondly, by the cases of transmitting video streams with low quality, conditioned by unacceptable level of packet loss, which results in losing broadcasted video segments.

The developed model makes it possible to calculate the values of bit rate of data transmission over FANET channels, recommended for minimizing failures to transmit video streams. Besides, this model allows calculating the recommended signal transmission power values of the network nodes, the setting of which in transmitting modules would help reducing packet losses and, consequently, providing the required level of quality of video broadcast over the network.

The object of the further work within the research topic will be creating algorithms and software for implementing the model suggested in this paper.

Declaration of competing interest

The authors declare that they have no known financial or non-financial competing interests in any material discussed in this paper.

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References

[1] A. Chriki, H. Touati, H. Snoussi, and F. Kamoun, “FANET: Communication, mobility models and security issues,” *Computer Networks*, vol. 163, p. 106877, Nov. 2019, doi: 10.1016/j.comnet.2019.106877.

[2] A. Srivastava and J. Prakash, “Future FANET with application and enabling techniques: Anatomization and sustainability issues,” *Computer Science Review*, vol. 39, p. 100359, Feb. 2021, doi: 10.1016/j.cosrev.2020.100359.

[3] M. Khan, I. Qureshi, and F. Khanzada, “A Hybrid Communication Scheme for Efficient and Low-Cost Deployment of Future Flying Ad-Hoc Network (FANET),” *Drones*, vol. 3, no. 1, p. 16, Feb. 2019, doi: 10.3390/drones3010016.

[4] A. Pandey, P. K. Shukla, and R. Agrawal, “An adaptive Flying Ad-hoc Network (FANET) for disaster response operations to improve quality of service (QoS),” *Mod. Phys. Lett. B*, vol. 34, no. 10, p. 2050010, Apr. 2020, doi: 10.1142/S0217984920500104.

[5] C. Liu and Z. Zhang, “Towards a robust FANET: Distributed node importance estimation-based connectivity maintenance for UAV swarms,” *Ad Hoc Networks*, vol. 125, p. 102734, Feb. 2022, doi: 10.1016/j.adhoc.2021.102734.

[6] S. Kaivonen and E. C.-H. Ngai, “Real-time air pollution monitoring with sensors on city bus,” *Digital Communications and Networks*, vol. 6, no. 1, pp. 23–30, Feb. 2020, doi: 10.1016/j.dcan.2019.03.003.

[7] A. Pandey, P. Shukla, R. Shukla, A. Agrawal, and A. Khare, “Grasshopper Optimization Based Clustering Algorithm (GOCA) For Adaptive Flying Ad-Hoc Network (FANET) To Enhance The Quality Of Service (Qos),” 2019.

[8] I. U. Khan, I. M. Qureshi, M. A. Aziz, T. A. Cheema, and S. B. H. Shah, “Smart IoT Control-Based Nature Inspired Energy Efficient Routing Protocol for Flying Ad Hoc Network (FANET),” *IEEE Access*, vol. 8, pp. 56371–56378, 2020, doi: 10.1109/ACCESS.2020.2981531.

[9] G. Rohi, O. Ejofodomi, and G. Ofualagba, “Autonomous monitoring, analysis, and countering of air pollution using environmental drones,” *Heliyon*, vol. 6, no. 1, p. e03252, Jan. 2020, doi: 10.1016/j.heliyon.2020.e03252.

[10] F. De Rango, G. Potrino, M. Tropea, A. F. Santamaria, and P. Fazio, “Scalable and ligthway bio-inspired coordination protocol for FANET in precision agriculture applications,” *Computers & Electrical Engineering*, vol. 74, pp. 305–318, Mar. 2019, doi: 10.1016/j.compeleceng.2019.01.018.

[11] I. A. Aljazaery, and J. Q. Kadhim, "Enhancement of Online Education in Engineering College Based on Mobile Wireless Communication Networks and IOT," International Journal of Emerging Technologies in Learning (iJET), vol. 18, no. 02, 2023.

[12] O. H. Yahya, and I. Aljazaery, "Reducing the Data Rate in Internet of Things Applications by Using Wireless Sensor Network," International Journal of Online and Biomedical Engineering (iJOE), vol. 16, no. 03, pp. 107-116, 2020.

[13] N. A. Hussien, A. A. Daleh Al-Magsoosi, and F. T. Abed, "Monitoring the Consumption of Electrical Energy Based on the Internet of Things Applications, "International Journal of Interactive Mobile Technologies," vol. 15, no. 7, 2021.

[14] K. Polshchykov, A. H. T. Shabeeb, S. Lazarev, and V. Kiselev, “Justification for the decision on loading channels of the network of geoecological monitoring of resources of the agroindustrial complex,” *PEN*, vol. 9, no. 3, p. 781, Sep. 2021, doi: 10.21533/pen.v9i3.2281.

[15] I. Abualhaol and M. Matalgah, “Outage Probability Analysis in a Cooperative UAVs Network Over Nakagami-m Fading Channels,” in *IEEE Vehicular Technology Conference*, Hyatt Regency Montreal, Montreal, QC, Canada, Sep. 2006, pp. 1–4. doi: 10.1109/VTCF.2006.564.

[16] I. Y. Abualhaol and M. M. Matalgah, “Performance analysis of cooperative multi-carrier relay-based UAV networks over generalized fading channels,” *Int. J. Commun. Syst.*, vol. 24, no. 8, pp. 1049–1064, Aug. 2011, doi: 10.1002/dac.1212.

[17] H. T. Kung, C.-K. Lin, T.-H. Lin, S. J. Tarsa, and D. Vlah, “Measuring diversity on a low-altitude UAV in a ground-to-air wireless 802.11 mesh network,” in *2010 IEEE Globecom Workshops*, Miami, FL, USA, Dec. 2010, pp. 1799–1804. doi: 10.1109/GLOCOMW.2010.5700251.

[18] N. Ahmed, S. S. Kanhere, and S. Jha, “Link characterization for Aerial Wireless Sensor Networks,” in *2011 IEEE GLOBECOM Workshops (GC Wkshps)*, Houston, TX, Dec. 2011, pp. 1274–1279. doi: 10.1109/GLOCOMW.2011.6162388.

[19] S. Temel and I. Bekmezci, “LODMAC: Location Oriented Directional MAC protocol for FANETs,” *Computer Networks*, vol. 83, pp. 76–84, Jun. 2015, doi: 10.1016/j.comnet.2015.03.001.

[20] A. I. Alshabtat and L. Dong, “Low latency routing algorithm for unmanned aerial vehicles ad-hoc networks,” *International Journal of Electrical and Computer Engineering*, vol. 5, no. 8, pp. 989–995, 2011.

[21] A. T. Albu-slaih and H. A. Khudhair, “ASR-FANET: An adaptive SDN-based routing framework for FANET,” *IJECE*, vol. 11, no. 5, p. 4403, Oct. 2021, doi: 10.11591/ijece.v11i5.pp4403-4412.

[22] L. A. L. F. da Costa, R. Kunst, and E. Pignaton de Freitas, “Q-FANET: Improved Q-learning based routing protocol for FANETs,” *Computer Networks*, vol. 198, p. 108379, Oct. 2021, doi: 10.1016/j.comnet.2021.108379.

[23] G. S. Vasilyev, D. I. Surzhik, O. R. Kuzichkin, and I. A. Kurilov, “Algorithms for Adapting Communication Protocols of Fanet Networks,” *JSW*, pp. 114–122, Jul. 2020, doi: 10.17706/jsw.15.4.114-122.

[24] A. V. Abilov, A. V. Chunaev, A. I. Nistyuk, and I. A. Kaisina, “Data Transmission Model with Lost Fragments Recovery Based on Application Layer ARQ,” *Vestnik IzhGTU imeni M.T. Kalashnikova*, vol. 24, no. 3, pp. 104–111, 2021, doi: 10.22213/2413-1172-2021-3-104-111.

[25] I. Konstantinov, K. Polshchykov, S. Lazarev, and O. Polshchykova, “Mathematical Model of Message Delivery in a Mobile Ad Hoc Network,” in *2017 IEEE 11th International Conference on Application of Information and Communication Technologies (AICT)*, Moscow, Russia, Sep. 2017, pp. 1–4. doi: 10.1109/ICAICT.2017.8686883.

[26] K. Polshchykov, S. Lazarev, and A. Zdorovtsov, “Multimedia Messages Transmission Modeling in a Mobile Ad Hoc Network,” in *2017 IEEE 11th International Conference on Application of Information and Communication Technologies (AICT)*, Moscow, Russia, Sep. 2017, pp. 1–4. doi: 10.1109/ICAICT.2017.8686961.

[27] K. Polshchykov, S. Lazarev, V. Kiselev, and E. Kiseleva, “Model of real-time flow packet transmission in amobile ad hoc network,” *Journal of Advanced Research in Dynamical and Control Systems*, vol. 11, no. 8 Special Issue, pp. 2861–2864, 2019.

[28] K. Polshchykov, A. H. T. Shabeeb, and S. Lazarev, “Algorithm for receiving the recommended bandwidth of a wireless self-organizing network channel,” *Periodicals of Engineering and Natural Sciences*, vol. 8, no. 3, Art. no. 3, 2020, doi: 10.21533/pen.v8i3.1654.

[29] P. P. Bocharov, C. D’Apice, and A. Pechinkin, “Queueing theory,” in *Queueing Theory*, 2004.

[30] R. S. Prabhu and B. Daneshrad, “An Energy-Efficient Water-Filling Algorithm for OFDM Systems,” in *2010 IEEE International Conference on Communications*, Cape Town, South Africa, May 2010, pp. 1–5. doi: 10.1109/ICC.2010.5502818.

[31] I. A. Kaisina, D. S. Vasil’ev, A. V. Abilov, D. S. Meitis, A. E. Kaisin, and A. I. Nistyuk, “Comparative analysis of the effectiveness of streaming data retransmission in a flying network,” *Bulletin of IzhSTU*, vol. 22, no. 1, pp. 108–115, 2019.

[32] Istikmal, A. Kurniawan, and Hendrawan, “Selective Route Based on SNR with Cross-Layer Scheme in Wireless Ad Hoc Network,” *Journal of Computer Networks and Communications*, vol. 2017, pp. 1–13, 2017, doi: 10.1155/2017/1378374.

[33] J. A. Shaw, “Radiometry and the Friis transmission equation,” *American Journal of Physics*, vol. 81, no. 1, pp. 33–37, Jan. 2013, doi: 10.1119/1.4755780.

[34] H. Frid, H. Holter, and B. L. G. Jonsson, “An Approximate Method for Calculating the Near-Field Mutual Coupling Between Line-of-Sight Antennas on Vehicles,” *IEEE Trans. Antennas Propagat.*, vol. 63, no. 9, pp. 4132–4138, Sep. 2015, doi: 10.1109/TAP.2015.2447003.

[35] K. O. Polshchykov, S. A. Lazarev, and E. D. Kiseleva, “Mathematical Model of Multimedia Information Exchange in Real Time Within a Mobile Ad Hoc Network,” *International Journal of Computer Science and Network Security*, vol. 18, no. 6, pp. 20–24, 2018.

[36] T. N. Mahdi, J. Q. Jameel, K. A. Polshchykov, S. A. Lazarev, I. K. Polshchykov, and V. Kiselev, “Clusters partition algorithm for a self-organizing map for detecting resource-intensive database inquiries in a geo-ecological monitoring system,” *Periodicals of Engineering and Natural Sciences (PEN)*, vol. 9, no. 4, pp. 1138–1145, 2021.