The second step is to calculate the bandwidth between each pair of nodes groups UAV. To do this, apply next model.

Each communication line is a line with MIMO antenna system that will provide increased bandwidth for high quality of users service (low probability of bit errors) in difficult conditions multipath space channel with deep fading signals.

S / N Ratio (SNR) in their subchannels is defined by singular numbers channel matrix H. In the most typical for urban conditions in multipath channel with Relay's fading signals these numbers are random and can vary significantly. Therefore, the probability of bit errors will also be different for different subchannels and energetically weaker subchannels will make the main contribution to the probability of bit errors of entire MIMO-system.

To evaluate the matrix H is used the most plausible estimates or estimates based on search minimum mean square error [4] (Fig. 4).

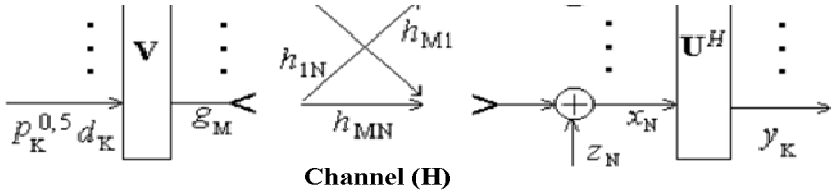

Fig. 4. Formation channels of MIMO-system

At the same time matrix **H** estimated with some error due to the influence of self-noise receivers and changes of the channel between two consecutive assessments. We consider the potential characteristics of MIMO-system matching exactly known matrix **H**.

In this paper proposes to choose MIMO system with configurations ($M \times 2$) and ($2 \times N$) separately. Note that the configuration data is characterized by the fact that they can create one or two their own subchannels.

Note that the eigenvalues λ_i do not change when replacing the transmission antennas on the reception and vice versa. Thus, MIMO-system configurations ($M \times 2$) and ($2 \times N$) are equivalent by bandwidth. Therefore, we assume for concreteness number M transmit antennas arbitrary, and the number of receiving antennas equal to two ($N = 2$).

For this antenna systems configuration speeds on the network can be calculated by equation (1) for each subchannel [11]:

$$R = 10^{\frac{P}{10}} \cdot \frac{1}{kT}, \qquad (1)$$

where $P = P_{\text{tr}} - \left(E_b / N_0\right)_{\text{dB}} + G_{\text{tr}} + G_{\text{rc}} - L - L_{\text{met.cond}}$.

In the last equation G_{tr} and G_{rc} are in accordance antenna gain of the transmitter and receiver, dB; P_{tr} is the transmitter capacity, dB; L is the Distribution losses on radio signal, dB. Defined by one of the radio wave propagation models; $L_{\text{met.cond}}$ are losses due to absorption of atmospheric gases, hydro meteors, fog, etc., dB.

Thus, $L_{\text{met.cond}}$ is determined by the following equation:

$$L_{\text{met.cond}} = L_{\text{smog}} + L_{\text{rain}} + L_{\text{ag}},$$

where L_{smog} is the transmitter capacity losses of radio signal in fog, dB; L_{rain} is the loss of signal strength during rain, dB; L_{ag} is the reduction value of radio signal in atmospheric gases.

The required signal / noise ratio $\left(E_b / N_0\right)_{\text{dB}}$ to ensure the necessary bit error is chosen depending on the type of modulation method. The model for these estimates is presented below.

Density probability ranked eigenvalues λ_1 and $\lambda_2 \left(\lambda_1 \geq \lambda_2\right)$ matrix $\mathbf{HH^H}$ presented in [8]. In the case of MIMO-system with configuration ($M \times 2$) have following expressions for calculating integrated distribution functions ranked eigenvalues λ_1 and λ_2 ($\lambda_1 > \lambda_2$) [7]:

$$F_{\lambda_1}(\lambda) = \frac{\gamma(M-1,\lambda)\gamma(M+1,\lambda) - [\gamma(M,\lambda)]^2}{(M-1)!(M-2)!},$$

$$F_{\lambda_2}(\lambda) = \frac{[\Gamma(M-1) - \gamma(M-1,\lambda)][\Gamma(M+1) - \gamma(M+1,\lambda)] - [\Gamma(M) - \gamma(M,\lambda)]^2}{(M-1)!(M-2)!}, \qquad (2)$$

where $\Gamma(y)=\int_0^{\infty} e^{-t}t^{y-1}dt$ is the Gamma function and $\gamma(y,x)=\int_0^{x} e^{-t}t^{y-1}dt$ is the incomplete gamma function.

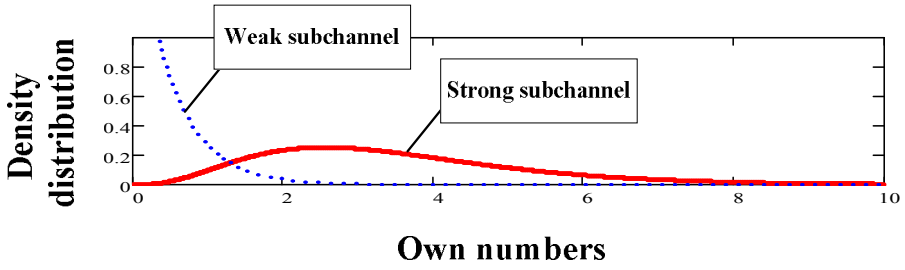

Fig. 5. Density distribution of weak and strong own subchannels

Further will conduct simulations for bit error probabilities in both subchannels for different types of modulation most widely used in modern wireless systems.

Probability of bit error BER_0 in Gaussian noise channel is [9, p. 236]:

$$BER_0(\eta)=0.5[1-\Phi(\sqrt{a\eta})],$$
$$\Phi(x)=\frac{2}{\sqrt{\pi}}\int_0^{x}\exp(-t^2)dt, \qquad (3)$$

where α=2 and α=1 for binary and quadrature phase modulation, respectively.

S / N Ratio in ith own subchannel $\eta_i=\beta_i\rho_0\lambda_i$. Due to rationing probability density and parameter $\rho_i=\beta_i\alpha\rho_0$, formula for the probability of bit errors lets present in the form:

$$BER_i=\frac{1}{2}-\frac{1}{2}\int_0^{\infty} f_i(\lambda)\Phi(\sqrt{\rho_i\lambda})d\lambda,$$

Probability of bit errors P_b for BPSK and QPSK is given in [9]

$$P_b=Q\left(\sqrt{2\gamma_b}\right),$$

where the table function, the value of which is given in [10]:

$$Q(x)=\frac{1}{\sqrt{2\pi}}\int_x^{\infty}\exp(-\frac{u^2}{2})du,$$

γ_b is the ratio of bit energy E_b to noise spectral density N_0.

For Gaussian channel and receiving via matched filters probability of bit errors modulation K-QAM, where $K=2^k$ and k is the even number is determined as follows [9]:

$$BER=\frac{2(1-L^{-1})}{\log_2(L)}Q\left[\sqrt{\frac{3\log_2(L)}{L^2-1}\cdot\frac{2E_b}{N_0}}\right],$$

where $L=\sqrt{K}$ represents the number of amplitude levels in one dimension.

Substituting here expression (1) and conducting the necessary calculations due to the probability of bit errors in a strong (first) and low (second) own channel MIMO-system with an arbitrary number of M transmit antennas will have the following graphic dependence (Figs 6 and 7):

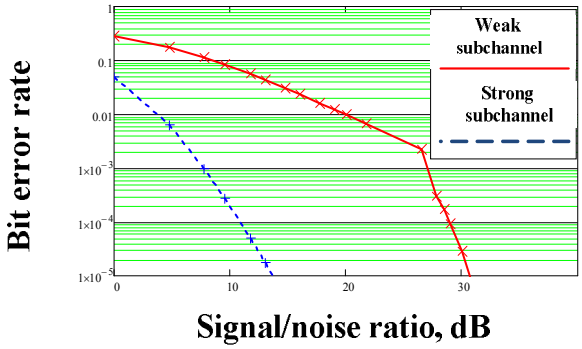

Fig. 6. Logarithmic dependence for bit error probability of signal / noise ratio in the weak and strong own subchannel for modulation QPSK

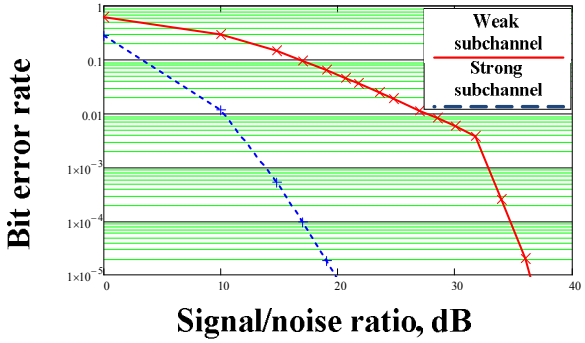

Fig. 7. Logarithmic dependence for bit error probability of signal / noise ratio in the weak and strong own subchannel for modulation QAM-64

Thus, expressing the maximum transfer rate R under certain conditions, gets the value bandwidth ith Channel in MIMO system:

$$R_i=10^{\frac{P_i}{10}}\cdot\frac{1}{kT}.$$

The total capacity of MIMO system will be determined:

$$R_{\max} = \sum_{i=1}^{k} R_i,$$

For example, the dependence of data rate from the distance between the transmitter and receiver (Fig. 8).

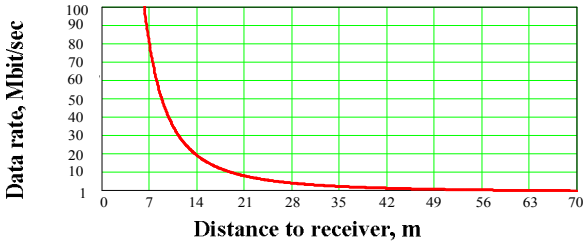

Fig. 8. Dependence of MIMO transmission system data rate in the standard IEEE 802.11n (transmitter power is 17 dBm) from distance

The third stage is the process of determining optimum routes.

To solve the problem under normal load separate Network on data exchange segments under conditions of the load between coordinating UAV and ground station does not exceed the maximum capacity of the channel $R_{13,\,j}$, denote channel bandwidth between end and coordinating UAV C_{Ni}, C_{Nk} – capacity between coordinators, C_{13} – bandwidth from the coordinator to the ground station then necessary fulfill the condition $C_{\max} K_i \succ \sum_{i=1}^{n-p} C_{Ni} \oplus \sum_{k=1}^{p} C_{Nk}$, where $C_{i,j}(K_z)$ related terminal and coordinating UAV. Then get Fig. 9.

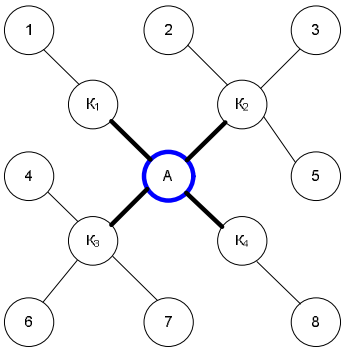

Fig. 9. Segmented topology

According to the algorithm Dijkstra's get shortest route to all the vertices of the graph, namely:

1-K1-A; 2-K2-A; 3-K2-A; 5-K2-A; 4-K3-A; 6-K3-A; 7-K3-A; 8-K4-A.

For second variant $C_{\max} K_i \le \sum_{i=1}^{n-p} C_{Ni} \oplus \sum_{k=1}^{p} C_{Nk}$ in case of exceeding the maximum bandwidth between the terminal station and the coordinator necessary to find another less loaded route. To find such routes may be used routing algorithms analysis of which is presented in [12], [13].

For the second type of traffic i.e. control information for which important condition is efficiency, as an metrics should use the value:

$$c_a = \left[O + \frac{B_t}{r} \right] \frac{1}{1 - e_f},$$

where: O is the constant that defines a channel access, depending on the physical implementation (802.11a, 802.11b); B_t is the number of bits in test package (8192); r is the speed of data transmission in the channel (Mbit / s), which determine algorithm is above; e_f is the probability of occurrence errors in the test package (measured experimentally on packages length B_t) [12].

Assuming that in the packet there are errors independently of each other, the probability of error e_f can be calculated as follows:

$$e_f = 1 - (1 - p_o)^n \approx np_o,$$

where p_o is the probability of occurrence bit errors in transmission; n is the the number of transmitted bits in the package.

V. Conclusions Acknowledgment

So as a result, in study was proposed improved method for routing group UAVs as of communication channels at what as a metric selected two alternatives: bandwidth – to transfer video data and speed of delivery – for managing information. The model of determining effective bandwidth, which is based on using both subchannels using various modulation schemes in the channels using MIMO systems. An exact expression for calculation system capacity with configurations ($M \times 2$) and ($2 \times N$) under uncorrelated Rayleigh fading signals conditions. The results of calculations and simulations confirm the high efficiency of the method.

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Р. С. Одарченко, **С. О. Гнатюк**, **О. П. Ткаліч. Метод маршрутизації в бездротовій мережі БПЛА**

Запропоновано поліпшений спосіб маршрутизації інформації в каналах зв'язку для груп БПЛА, де в якості метрики запропоновано дві альтернативи: пропускну здатність каналу або час передачі пакету. Модель визначення ефективної смуги пропускання, яка заснована на використанні обох підканалів, для MIMO-системи наведена для різних схем модуляції. Результати розрахунків і моделювання підтверджують високу ефективність запропонованого методу.

Ключові слова: маршрутизація; метод; безпілотні літальні апарати; системи MIMO; сигнал.

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Р. С. Одарченко, **С. А. Гнатюк**, **О. П. Ткаліч. Метод маршрутизации в беспроводной сети БПЛА**

Предложен улучшенный способ маршрутизации информации в каналах связи для групп БПЛА, где в качестве метрики предложены две альтернативы: пропускная способность канала или время передачи пакета. Модель определения эффективной полосы пропускания, которая основана на использовании обоих подканалов для MIMO-системы, приведена для различных схем модуляции. Результаты расчетов и моделирования подтверждают высокую эффективность предложенного метода.
Ключевые слова: маршрутизация; метод; беспилотные летательные аппараты; системы MIMO; сигнал.

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