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THE PROGRAM FOR ASSESSING THE CONNECTIVITY OF NODES OF WIRELESS EPISODIC NETWORKS UNDER THE CONDITION OF USING UAVS

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Background. Based on analytical mathematical models, the duration of connectivity of mobile subscribers (nodes) (MS) of a wireless episodic network (WEN, consisting of MS and UAV) was investigated in conditions of direct radio visibility and considering the relaying.

Objective. The purpose of the work is to find methodological approaches to ensure the connectivity of WSN nodes, which is a necessary condition for obtaining information from WSN in the absence of communication infrastructure.

Methods. Simulation modelling based on MAPLE 14 software package and analytical calculation methods are used.

Results. It is shown that the duration of connectivity is directly proportional to the size of the coverage area and inversely proportional to the movement speed of nodes. The mobility nature (scenario) of nodes also affects the duration of connectivity. The simulation of the nodes' movement was carried out under 4 scenarios: "march", "incoherent", "random wandering in the field" and "random wandering in the city". The largest values of the connectivity duration correspond to the third scenario, and the smallest - to the second (with a fixed radius of the coverage area and the movement speed of nodes). Thus, the average connectivity duration of the UAV-pedestrian connection in the event of an "incoherent" will be about 36 minutes, and the UAV-car connection - about 5 minutes.

Conclusions. The system and functional parameters of the networks, which were obtained as a result of the research, will form the basis of the initial data and limitations of the mathematical model, and will also make it possible to determine the initial placement of the UAV network at the planning stage.

Keywords: *wireless episodic network; unmanned aerial vehicle; connectivity of nodes.*

Introduction

The connectivity of a pair of nodes is determined by the characteristics of different levels of OSI information interaction, such as radio range, channel bandwidth, information transmission delay, etc. This research offers the calculation of these characteristics and their analysis depending on the system parameters of the network.

It is proposed to assess the connectivity of a pair of nodes according to the following program (methodology):

1. Assessment of geometric connectivity (in the narrow sense), which is limited by the maximum range of radio visibility at the physical level (with a given signal/noise ratio at the receiver) and the vulnerability interval of a given multiple access protocol at the channel level.
2. Assessment of information connectivity (in a broad sense) that considers the availability of not only a physical connection of a given reliability but also the availability of a free channel resource (a given channel bandwidth), a given amount of transmission delay at a given traffic limit value.
3. Assessment of the connectivity duration considering the mobility of network nodes.

The result of this research will be the system and functional parameters of the network, which will form the basis of the initial data and limitations of the mathematical model, and will also make it possible to determine the initial placement of the UAV network at the planning stage.

Calculation and analysis of characteristics of the wireless episodic network

1. Assessment of radio visibility range of a "node-node" pair

A wireless episodic network of data transmission typically operates within the direct radio visibility of nodes.

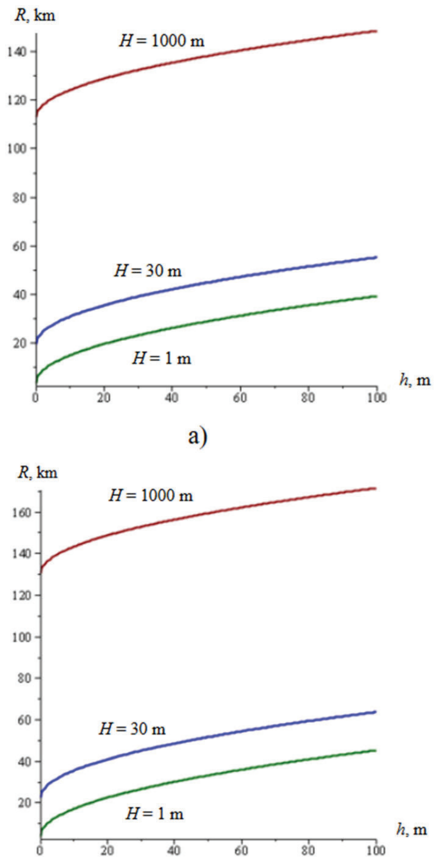
When working on the flat surface of the Earth, the radius of the zone of direct (geometric) visibility (R, km) is determined by the heights of the placement of the transmitting (H, m) and receiving (h, m) antenna: $R = 3{,}57(\sqrt{KH} + \sqrt{Kh})$, where K – correction factor that considers the refraction of radio waves.

Fig. 1 shows the radii of direct visibility at K=1 (a) and K=4/3 (b).

As seen from the graphs, the typical value of the geometric visibility of a pair of subscribers (pedestrians) located on flat terrain can ideally be 7-

10 km. While the range of direct visibility between a pedestrian and a UAV reaches more than 130 km.

In addition, the communication range is determined by the energy of the radio line, in which the signal-to-noise ratio at the reception point is not less than a specified value to ensure a given bit error probability (BER) at a given type of modulation (corresponding transmission rate). Let's consider this in more detail.



b)

Fig. 1 - Range of direct visibility considering the height of the suspension of antennas with different correction factors: a) - *K*=1, b) - *K*=4/3

To calculate the range of radio communication, we will use the formula for calculating losses in free space:

$$FSL = 32{,}45 + 20(lg\,F + lg\,D) \quad (1)$$

where *FSL* (Free Space Loss) – losses in free space, dB; *F* – central frequency at which the system operates, MHz; *D* – distance between receiver and transmitter, km.

On the other hand, *FSL* is determined by the total gain of the system *Y* (dB):

$$Y = P_t + G_t + G_r - P_{rmin} - L_t - L_r \quad (2)$$

where P_t - transmitter power, dBmW; G_t - gain coefficient of the transmitting antenna, dBi; G_r - gain coefficient of the receiving antenna, dBi; P_{rmin} - sensitivity of the receiver at the specified transmission speed, dBmW; L_t - losses in the antenna-feeder path (AFP) of the transmitter, dB; L_r - losses in the AFP of the receiver, dB.

Then *FSL* can be defined as follows:

$$FSL = Y - SOM \quad (3)$$

where *SOM* (System Operating Margin) – radio line energy reserve (dB), which considers possible negative factors that affect the communication range.

Usually *SOM* is taken equal to 10-15 dB [1-9].

Thus, the communication range will be determined by the following formula:

$$D = 10^{\left(\frac{P_t + G_t + G_r - P_{rmin} - L_t - L_r - SOM - 33}{20} - lgF\right)} \quad (4)$$

Considering the characteristics of typical wireless access points of the 802.11a,b,g standard [5-9] and setting $G_t = G_r = 0$ dBi, $L_t = L_r = 0$ dB, *SOM* = 10 dB, *F* = 2437 MHz, we obtain from (4) the value of the maximum range of stable radio communication depending from the energy parameters of the radio line (Table 1).

Table 1. Dependence of the maximum range of stable radio communication on the energy parameters of the radio line for typical 802.11a,b,g wireless access equipment.

Transmitter power P_t, dBmW	**Receiver sensitivity P_{rmin}, dBmW**	**Data transfer speed *V*, Mbps**	**Maximum range of radio communication *D*, km**
16	-66	54	0,037
16	-71	48	0,065
16	-76	36	0,116
16	-80	24	0,183
16	-83	18	0,259
16	-85	12	0,326
16	-86	9	0,366
16	-87	6	0,410
16	-94	1	0,918

From Table 1, we can see that the maximum range of stable radio communication at the minimum speed (1 Mbps) does not exceed 1000 m.

The real relief of the earth's surface and the presence of buildings, trees, high-voltage transmission lines and etc. can further limit communication range. There are many empirical models that allow predicting the average transmission loss in the conditions of a modern city.

According to the Hata model [5-9], the average transmission loss can be expressed by the following formula:

$$L = 69{,}55 + 26{,}15\, lg\, F - 13{,}82\, lg\, H - \\ -\alpha(h) + (44{,}9 - 6{,}55\, lg\, H)\, lg\, D \quad (5)$$

where in the conditions of a big city $\alpha(h) = 3{,}2(lg\, 1\, 1{,}75h)^2 h - 4{,}97$.

Hence, the maximum range of radio communication will be equal to:

$$D = 10^A, \quad (6)$$

where $= \frac{Y - 69{,}55 - 26{,}15\, lg\, F + 13{,}82\, lg\, H + 3{,}2(lg\, 11{,}75h)^2 h - 4{,}97}{44{,}9 - 6{,}55\, lg\, H}$.

Substituting the following initial data in (6): *H*=*h*=1m, *F*=2437MHz, *Y*=100dBmW, we get D^*=0,630 km. In other words, in city conditions, the typical range of "node-to-node" radio communication in episodic networks does not exceed 500-600 m.

2. Assessment of the bandwidth of WEN channels

The main characteristics that determine the effectiveness of the multiple access protocol to the common channel resource are [5-9]: average transmission speed, average transmission delay and the traffic limit value at which the limit of sustainable network operation is reached (sustainability limit). These parameters are determined as a function of system parameters, among which the main ones are traffic intensity, transmission speed, packet length, geometric dimensions of the network, or their generalized vulnerability interval.

To analyse the above characteristics and determine their potentially possible values, we will use analytical models built using the elements of recovery and assumption theory that the number of subscribers is infinitely large, each of which generates packets at an infinitely low speed. The latter is actually an assumption about the Poisson nature of the process of receiving packets for transmission over the radio channel. At the same time, the intensity of the arrival of packets is measured by the number of packets per transmission time *T* and is denoted by the letter *G*. The average transmission speed *S* is also measured by the number of packets per time *T*, but which are transmitted conflict-free. It is also assumed that all packets have the same length L. These models operate with the average values of time segments of the state of the radio channel. We will also assume that the service packets (receipts) confirming the successful reception of the data packet have a standardized length and are transmitted over a separate channel without conflict.

By the intensity *G* of incoming packets for transmission, which was indicated earlier, we will understand the total intensity, which includes both the incoming stream of primary packets Z_1 and the stream of retransmitted packets Z_2. The stream Z_1 of each node is formed by both its own packets and those that need to be retransmitted from other nodes (defined according to the given gravity matrix *Г*), and the flow Z_2 is determined by the procedural characteristics of the MA protocol and the values of its system parameters, namely the time interval before retransmission. In practice, for stable operation of the network, the current traffic intensity should not exceed 0,8*g*, where *g* – the stability threshold determined by the MA protocol type [2-4].

In practice, the protocol of random carrier-sense multiple access (CSMA) is usually used for MSs interaction at the channel level. For our case, we will choose a flexible CSMA strategy, then according to [5-9] the average transmission speed can be determined by the following formula:

$$S = \frac{G \cdot exp(-\frac{x \cdot V}{c \cdot L} G)}{G(1 + 2\frac{x \cdot V}{c \cdot L}) + exp(-\frac{x \cdot V}{c \cdot L} G)}, \quad (7)$$

where *x* – maximum distance between the repeater and the subscriber (that is, between MS), m; *c* – speed of signal propagation, m/s; *L* – packet length, bit; *V* – transmission speed, bps, and substituting.

Substituting the following output data: *V*=11 Mbps, *c*=3×108 m/s, *L*=1000 bps into expression (7), we will have the following graphs illustrating the dependence of *S* at the MS-MS channel level (Fig. 2).

Analysing the graphs in Fig. 2 (a), we can see that the average transmission speed decreases monotonically as the maximum distance between nodes x increases. This is due to the fact that when x increases, the vulnerability zone *a* increases, which causes an increase in the number of collisions during the organization of MA. Also, according to Fig. 2 (b), an increase in *x* leads to a decrease in the stability threshold *g* and the range of stable operation of the MA protocol. Thus, at *x*=300m (*a* = 0,011) *g* is approximately 9 ($S_{max} \approx 0{,}81$), at *x*= 500m (*a* = 0,0183) - $g \approx 6{,}8$ ($S_{max} \approx 0{,}76$) and at *x*= 1000m (*a* = 0,0366) - $g \approx 4{,}6$ ($S_{max} \approx 0{,}67$). According to Fig. 2 (c), the problem of increasing bandwidth at a given x (or, equivalently, increasing the maximum distance between MS *x* at a given *S*) can be solved by increasing the packet length *L*, but at the same time, the probability of the packet damage by interference and the time of packet delivery in the network are increased.

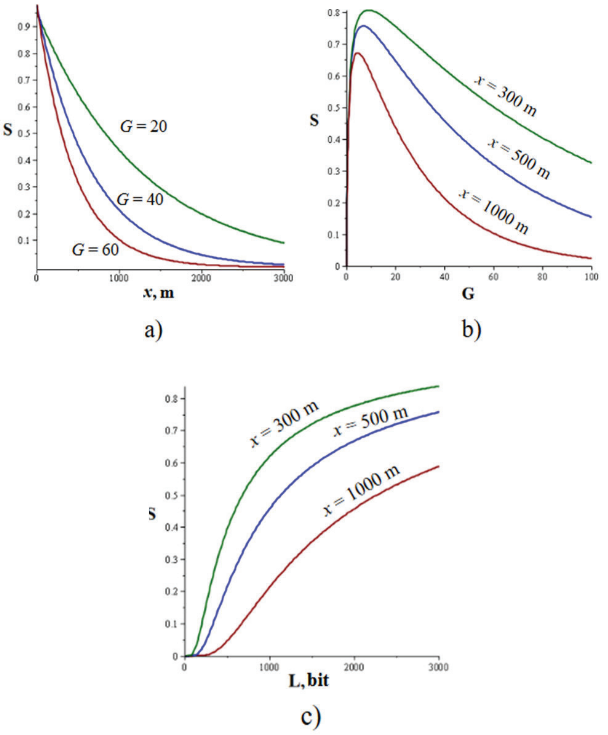


Fig. 2 - Graphs illustrating the dependence of the bandwidth of the MS-MS channel on: a) - the distance between nodes at different values of traffic intensity, b) - the traffic intensity at different values of distance between nodes, c) - the packet length at different values of distance between nodes (at G=40)

Therefore, the choice of the maximum distance between nodes (radius of MS radio coverage) x is determined by the minimum permissible value of the bandwidth of the MA protocol at the given V and L.

Organization of access to the channel resource of the UAV network is possible in several ways:

1. Organization of an n-frequency mono channel to which all subscribers are connected. In [5, 8], a 2-frequency mono channel is considered in detail. This method allows each of the packets transmitted by the subscriber to be relayed through a network of repeaters in all cells of the network. However, to avoid self-excitation of the chain of repeaters, each of them, after transmitting a packet, must have a period of insensitivity equal to $2a+1$, which significantly increases the transmission delay of each packet.

2. Because of the adaptive procedures of packet reservation and conflict resolution, it is possible to ensure the bandwidth of MA S not lower than 0,9 at a=0,01 in a fairly wide range of traffic G [5, 8]. Moreover, these procedures, in contrast to the usual CSMA, will allow quickly adapting to changes in incoming traffic caused by the mobility of MS and UAV.

Therefore, using, for example, the adaptive random MA protocol with redundancy (APR), the value of the average transmission speed in the MS-UAV and UAV-UAV channels can be determined as follows:

$$S = \frac{GN\,exp(-aG)}{1+G((N+b+a+\frac{1-exp(-aG)}{G})\,exp(-aG)+b+2a-\frac{1-exp(-aG)}{G})} \quad (8)$$

where N – block size of redundant packet; G – intensity of the arrival of blocks from N packets, b – duration of the reservation packet sent by the subscriber and the transmission permission packet sent in response by the repeater; r – duration of time from the arrival of the last conflicting packet.

Substituting the following output data: V=11 Mbps, c=3×108 m/s, L=1000 bit into expression (8), we will have the following graphs illustrating the dependence S of MS-UAV and UAV-UAV channels (Fig. 3).

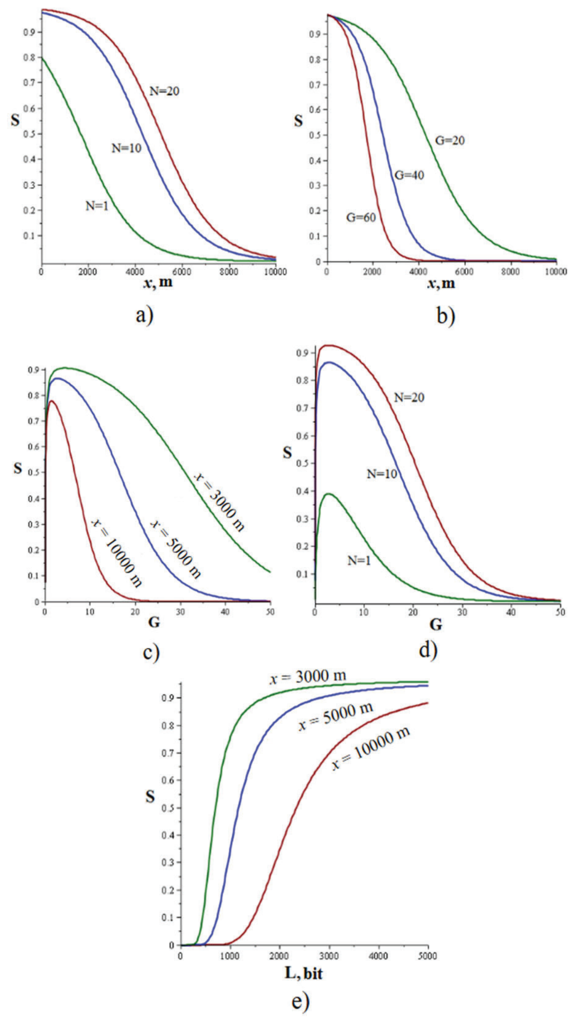


Fig. 3. Graphs illustrating the dependence of the bandwidth of the UAV-UAV (UAV-MS) channel on: a) - the distance between nodes at different values of the size of the redundancy block (at *G*=20), b) - the distance between nodes at different values of traffic intensity (at *G*=10), c) - the traffic intensity at different values of distance between nodes (at *N*=10), d) - the traffic intensity at different values of the size of the redundancy block (at *x*=5000 m), e) - the packet length at different values of distance between nodes (at *N*=10, *G*=20)

Analysing Fig. 3 (a), we can see that the application of block (*N*=10, *N*=20) redundancy makes it possible to significantly expand the maximum distance between UAV and MS (UAV and UAV) at a given bandwidth, in contrast to the usual flexible CSMA protocol (*N*= 1). Also, according to Fig. 3 (b, c, d, e), it can be seen that the APR protocol allows significantly expanding the range of possible traffic intensity and increase the stability of the UAV network when the input load changes.

Therefore, the analysis of the dependence of the bandwidth of MS-MS and UAV-UAV (MS-UAV) channels on system parameters allows determining the network connectivity at the channel level and estimate the maximum communication range at a given channel bandwidth. So, at a given level *S*, for example, 0.5, the maximum distance between MS should be no more than 500m with a packet traffic intensity of no more than 38, the maximum MS-UAV distance should be no more than 5000m with a traffic intensity of packet blocks (*N*=10) no more than 17, and the maximum UAV-UAV distance must be no more than 10,000m with a traffic intensity of packet blocks (*N*=30) no more than 10. Having determined the maximum vulnerability intervals in this way, it is possible to determine the necessary energy needed to implement a given MA protocol

However, the obtained above values of the communication range of the "node-node" pair do not make it possible to evaluate the geometry of the entire network (communication range with retransmission), which is determined by the amount of packet delay from end to end at the network level for a given type of traffic. The next subsection is devoted to the research of this issue.

3. Assessment of packet transmission delay in WEN channels

The organization of information interaction at the network level between any pair of network subscribers requires the availability of a data transmission route of a given quality (QoS). The quality criterion or route metric (for example, at transmitting voice traffic) can be the number of retransmissions or the amount of delay of the packet transmission from end to end through a network of intermediate relay nodes. In general, this amount will have the following form: $D = T_{pack} + \mathrm{T}_{acs} + T_{propa} + T_{proc} + \mathrm{T}_{buf}$, where T_{pack} – packetization time (packet formation at the sending node), which depends on the traffic type (the packet formation algorithm, for example, for voice - by the codec type); T_{acs} – average channel access delay time (for a random MA), which depends on the traffic intensity and channel capacity; T_{propa} – signal propagation time in the transmission medium (does not depend on the traffic type); T_{proc} – packet processing time in intermediate network nodes (depends on the traffic type); T_{buf} – delay time in the buffer of intermediate network nodes (depends on the traffic type, queuing discipline, prioritization of the traffic (service-level agreement)). For an IP packet with an average length of 576 bits and a coding rate of 64 kbps, the packetization time will be 9ms, which can be neglected for a rough estimate of the transmission delay. The packet processing time in intermediate network nodes will also be considered insignificant. Also, let's assume that uniform traffic is transmitted in the network, the FIFO discipline ("first in, first out") is applied at intermediate nodes, whereby the packet at the node is processed immediately without sending it to the queue, that is, the delay time in the buffer can be neglected.

Then the average packet transmission delay time on the MS-MS link will have the following simplified form:

$$D_1 = \left(\frac{G}{S} - 1\right)(X + (1 + a)P_I) + 1 + a \quad (9)$$

where P_I – probability of a free state of the radio channel; X – average delay time before retransmission, normalized on T ($X \gg T$).

Assuming that $P_I = \frac{1}{G(1+2a)+exp(-aG)}$, $a = \frac{x_1 \cdot V}{c \cdot L}$ and and taking into account (7), we have:

$$D_1 = \frac{G\left(1+2\frac{x_1 \cdot V}{c \cdot L}\right)}{exp(-\frac{x_1 \cdot V}{c \cdot L}G)}\left(X + \frac{1+\frac{x_1 \cdot V}{c \cdot L}}{G(1+2\frac{x_1 \cdot V}{c \cdot L})+exp(-\frac{x_1 \cdot V}{c \cdot L}G)}\right) + 1 + \frac{x_1 \cdot V}{c \cdot L} \quad (10)$$

In turn, the average packet transmission delay time on the UAV-UAV link (MS-UAV) will have the following form:

$$D_2 = \frac{1}{N}\left(\left(\frac{1}{P} - 1\right)(X + (b + a + r)P_I) + N + a\right) \quad (11)$$

where $P = \frac{exp(-aG)}{1+GB}$ - probability of successful transmission of a block of packets; $P_I = \frac{1}{1+GB}$ - probability of a free state of the radio channel.

Substituting the following output data: *V*=11 Mbps, *c*=3×108 m/s, *L*=1000 bit, *b*=0,1, *X*=2 into expressions (10), (11), we will have the following graphs illustrating the dependence of the average transmission delay of one MS-MS link (at *x*=500 m) and one UAV-MS link (UAV-UAV) (at *x*=3000 m, *N*=10,20,30) on traffic intensity (Fig. 4).

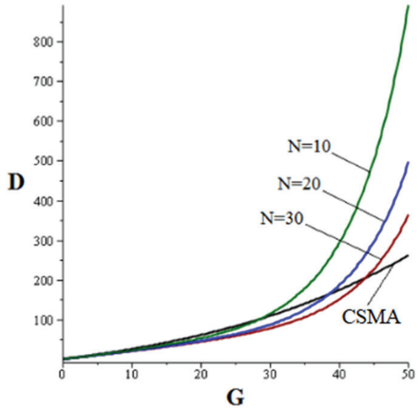


Fig. 4. Graphs illustrating the dependence of the average transmission delay of one MS-MS link (at x=1000 m) and one UAV-UAV (UAV-MS) link (at x=5000 m, N=5,10,15) on traffic intensity

Analysing Fig. 4, we can see that when the traffic intensity is less than 30, the network link using UAV has a shorter delay time than the MS-MS link, whereby the limit value of the traffic intensity is greater, the larger the size of the packets' block in the ARP protocol. It should also be noted that with the same transmission delay, the UAV link has a six-fold gain in a distance. Therefore, in order to minimize the delay when transmitting information over long distances, it is more appropriate to transmit information through the UAV network and over short distances - through the MS network. Then, there is a practical interest in determining the limiting number of retransmissions through the MS, at which it is necessary to switch to the UAV network, about what speech will go further.

If we consider that the route of information transmission consists of *M* links, then the total delay of the "end-to-end" packet for the MS network and the UAV network will be, respectively:

$$D_1' = D_1 \cdot M, D_2' = D_2 \cdot M \qquad (12)$$

Suppose that the average load of one MS-MS link is G_1=20, and the load of one UAV-UAV link – G_2=50, then the dependence of the transmission delay on the number of route links will have the following form (Fig. 5).

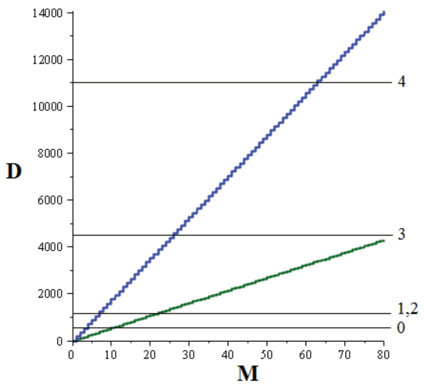


Fig. 5. Graphs illustrating the dependence of average end-to-end packet transmission delay through MS network (1) and through UAV network (2) with indication of QoS levels (ITU-T Y.1541)

Analysing Fig. 5, we can see that at twice the load, the transmission delay on one UAV link is three times greater than the transmission delay on one MS link. Therefore, if the number of links in the MS network route is more than 3, it is more appropriate to transmit information through the UAV network, otherwise through the MS network. Also, the obtained graph allows estimating the maximum distance of "end-to-end" information transmission (geometry of the entire network) with retransmission through intermediate nodes. It is limited by the requirements for the amount of transmission delay for a particular type of traffic. In Fig. 7, horizontal lines show the QoS quality levels for IP networks according to ITU-T Y.1541.

Of course, the obtained data are purely hypothetical, since as the number of retransmissions in the route increases, the channel bandwidth decreases significantly due to the high probability of packet loss.

4. Calculation of the connectivity duration taking into account the mobility of subscribers

WEN subscribers cannot constantly be in the radio visibility zone of each other and the UAV coverage zone due to their mobility. So, there is a practical interest in calculating the connectivity duration between them, during which they can exchange information (build a route and transmit some amount of information).

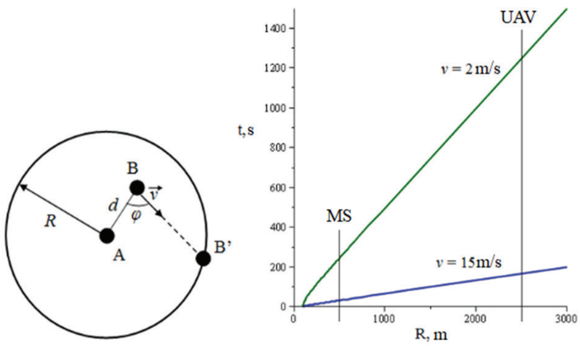
WEN provide any (by direction and speed) movement of nodes. In practice, if we are talking about "pedestrian-pedestrian" mobile communication, the direction of movement in the city changes following its development plan (most often turns at 90), and the speed does not exceed 2 m/s. Cars, considering the restricted speeds in the city, move at a maximum speed of up to 16 m/s.

4.1. Calculation for the case of direct radio visibility between nodes

Consider the movement of node *B* with respect to node *A*, located initially at a distance *d* from it, with speed *v* at an angle *φ* (Fig. 6, a). Let us assume that the connectivity duration *(t)* is the period of time until node *B* is at point *B′*, which is limited by the radius of radio visibility *R*. Then, using the trigonometry apparatus, we will get:

$$t = \frac{d\cos\phi + \sqrt{R^2 - d^2\sin^2\phi}}{v} \quad (13)$$

For the initial data d = 100m, v_1 = 2 m/s, v_2 = 15 m/s and φ = 90°, we obtain the results shown in Fig. 6, b. According to these data, it follows that the duration of MS-MS communication (*R* = 500 m) can be no more than 2-3 minutes for pedestrians and no more than 0.5 minutes for cars, and in the case of UAV-MS (*R* = 2500 m) will be approximately 20-25 minutes for pedestrians and about 6-7 minutes for cars. Therefore, the effectiveness of the use of UAVs is obvious. By controlling the UAV position in space, it is possible to achieve even greater values of the duration of subscriber connectivity.



a) b)

Fig. 6. The model a) and the calculation results of connectivity duration b)

4.2. Calculation in case of retransmission through an intermediate node

Consider a model in which node *A* can communicate with node *C* only by relaying a signal through node *B*. Node *C* is outside the radio visibility of node *A*, while *C* is in the visibility zone of *B*. For simplification, we will consider that the radio visibility radius *R* is the same for all nodes.

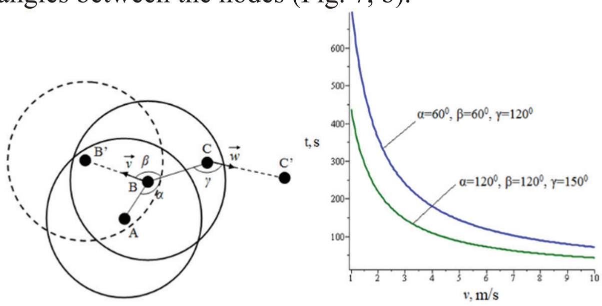
Node *A* builds a route to *C* for communication, and some time *τ* is spent on this. Since *B* and *C* move relative to each other (and relative to *A* with speeds *v* and *w*, respectively) (Fig. 7, a) and, for example, diverge, then there is a relative probability that during the time *t* of establishing a route from *A* to *C*, the repeater *B* and end node *C* will diverge so much that the transmission of messages from *A* to *C* will be impossible. Let's calculate this time.

We will assume that the connectivity duration *(t)* is the period of time until the node *C* is out of sight of the repeater, i.e. at the point *C′*. Then, using the formulas of geometry and kinematics of the material point, we get:

$$t = \frac{\sqrt{AB^2 + AC^2 - 2AB\cdot AC\cdot\cos(\alpha+\beta+\gamma)}}{v*} \quad (14)$$

where v^* - relative speed of nodes B and C, the value of which is determined by the directions and values of the vectors $\vec{v}$ and $\vec{w}$.

By setting the distance between nodes *AB*=200m and *AC*=600m, we will obtain the dependence of the connectivity duration with one retransmission on the relative speed of the nodes for different values of the angles between the nodes (Fig. 7, b).



a) b)

Fig. 7. The model (a) and the calculation results of connectivity duration with one retransmission (b)

Analysing Fig. 7, we can see that the values of the connectivity duration with one retransmission lie within the same limits as in the previous case (without retransmission) and are determined by the placement of nodes and the direction and value of their movement speed.

Now consider the behaviour of a WEN fragment of 4 nodes. In the initial state, nodes (*B*, *C*, *D*) are within radio visibility of node *A* (Fig. 8, a).

Information can be exchanged with them. But due to mobility (the vectors of movement of the nodes are shown relative to *A*), the network topology changes, and after some time, node *B* leaves the visibility zone of *A*. Communication with it for node *A* is interrupted for some time (Fig. 8, b). This continues until *B* is within radio visibility zone of node *C*, which in turn will act as a repeater for node *A*. Note that during this period of time nodes can change direction and speed of movement.

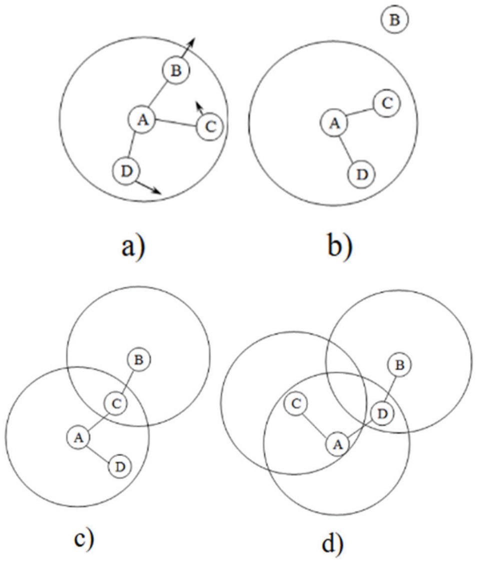


Fig. 8. Ensuring connectivity when moving nodes

Now the communication between A and B is carried out through repeater *C* in two hops (Fig. 8, c). A situation is possible when node *C* can no longer serve as a repeater (for example, the battery is discharged). In this case, the routing algorithm, adapting to the new conditions, creates another route - through repeater *D* (Fig. 8, d). In this case, we can talk about the possibility of communication between nodes *A* and *B* through *D*.

If we display the above-mentioned sequence of events on the diagram (Fig. 9), we will clearly see a disturbance of connectivity between nodes *A* and *B* at intervals *i-j* та *k-l*.

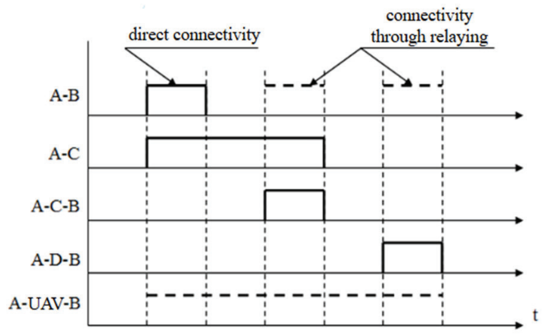


Fig. 9. Connectivity intervals

When transmitting long messages, this can lead to information loss (without taking special measures). Such measures can be:

1. Splitting messages into packets and sending packets only after confirmation of connectivity and a forecast to support it within the time of sending one packet. To guarantee transmission, the sending node must have (or provide for) the possibility of "expanding" the coverage area due to increasing the transmitter power or changing the antenna radiation pattern [2-5], that is, node A "does not let go" of B during the transmission of at least one packet.

2.Providing for the availability of "reserve routes" that are automatically included (soft hand-off) when the main one is interrupted.

3.Using of architectural or algorithmic changes, including those that violate the principle of a peer-to-peer network, that is, the use of a UAV network as additional aerial repeater-node.

5. Modelling the movement of network nodes

Using the mathematical model discussed in subsection 4.1, we will simulate the movement of nodes under different scenarios and compare the duration of connectivity between WEN nodes under different mobility scenarios. The following mobility scenarios are offered to simulate the movement of nodes:

1) "same directions" or "march" ($\phi = const, v = const$). According to this scenario, all nodes within the radio visibility zone R move in a straight line and parallel to each other in the same direction with the same speed, as shown in Fig. 10, a.

2) "random directions" or "incoherent" ($\phi = const, v = const$). According to this scenario, all nodes within the radio visibility zone R move in a straight line in different random directions with the same speed, as shown in Fig. 10, b.

3) "random wandering in the field" ($\phi = var$, $L = const, v = const$). According to this scenario,

all nodes within the radio visibility zone R move at the same speed along a broken trajectory, randomly changing their direction through each constant step, as shown in Fig. 10, c.

4) "random wandering in the city" ($\phi = var(0^0, 90^0, 180^0, 270^0)$, $L = const, v = const$). According to this scenario, all nodes within the radio visibility zone R move at the same speed along perpendicular straight lines (streets) and randomly change their direction at each intersection through each constant step $l << R$, as shown in Fig. 10, d.

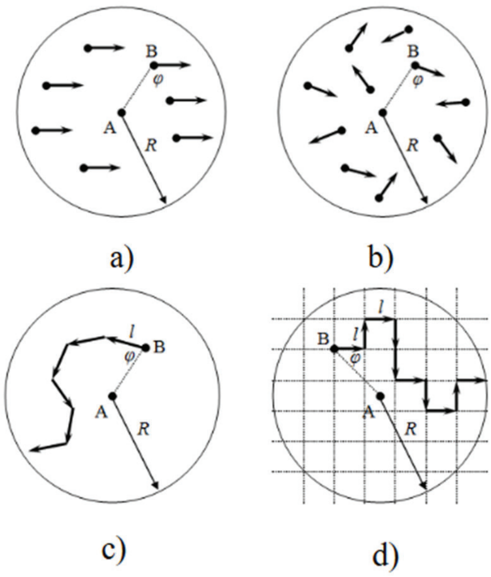


Fig. 10. Movement trajectories of WEN nodes depending on the mobility scenario: a) - "march", b) - "incoherent", c) - "random wandering in the field", d) - "random wandering in the city"

The coordinates of all nodes are set randomly within the radio visibility zone R of a given fixed node (for example, UAV). The number of nodes for each coverage zone radius is proportional to its area, that is, R_2. Let's calculate the average time that a node reaches the limit of the radio visibility zone, depending on its radius at different speeds and movement scenarios. The simulation was performed in the MAPLE 14 software environment. The simulation results are shown in Fig. 11, a, b.

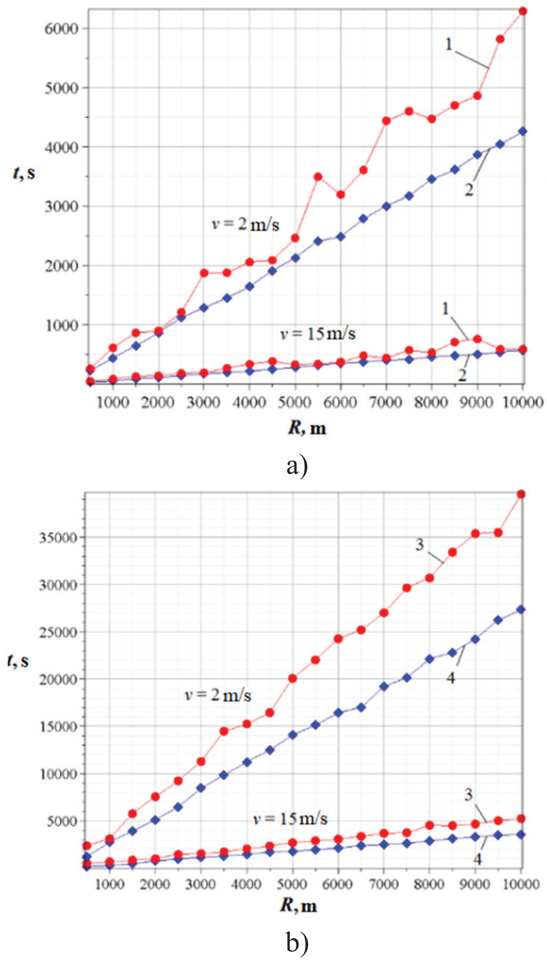


Fig. 11. Dependence of the average time for a MS to reach the limit of the coverage area on its radius at different speeds and movement scenarios: 1 – "march" (a), 2 – "incoherent" (a), 3 – "random wandering in the field" (b), 4 - "random wandering in the city" (b)

Analysing Fig. 11 (a, b), we can see that the duration of connectivity *(t)* is directly proportional to the size of the coverage area *(R)* and inversely proportional to the speed of node movement *(v)*. The type (scenario) of node mobility also affects the duration of connectivity. The largest values of the duration of connectivity (with the same R and v) correspond to the scenario "random wandering in the field" (curve 3), the second largest - "random wandering in the city" (curve 4), the third largest - "march" (curve 1), the smallest - the "incoherent" scenario (curve 2). Thus, in the case of a UAV (R=5000m), the average duration of connection with pedestrians (v=2m/s) will be 20000, 14000, 2463, 2130 seconds, respectively, with cars (v=15m/s) – 2686, 1900, 327, 286 seconds. Knowing these data, it is possible to determine the frequency of working out a new UAV position.

Conclusions

The maximum communication range (of the VHF range) is limited by the curvature of the earth's surface and the heights of the suspension of the transmitting and receiving antenna. So, considering refraction, the maximum length of the MS-MS radio line can be 7-10 km, and the UAV-MS - more than 130 km with a UAV barrage height of more than 1 km. In addition, the maximum range of radio communication is limited by the energy of the radio line, at which the signal-to-noise ratio at the reception point is not less than a specified value to ensure a given bit error rate (BER) at a given type of modulation (corresponding transmission rate). Thus, when using typical 802.11a/b/g equipment, the maximum length of the MS-MS radio line does not exceed 1000 m (at a transmission speed of 1 Mbps), and with the real topography of the area - no more than 630 m (for a large city).

The maximum range of "node-node" communication is also determined by the effectiveness of the multiple access protocol to the shared channel resource. When the length of the radio line increases, the number of collisions, during the organization of MA, increases, and therefore the bandwidth decreases, and the transmission delay increases. Therefore, the maximum communication range can be determined by the limit value of bandwidth at a given transmission speed, data packet size and traffic intensity. Thus, at S=0.5, the maximum length of the MS-MS radio line should be no more than 500 m (for CSMA), UAV-MS - no more than 5000 m (for APR, N=10) and UAV-UAV - no more than 10000 m (for APR, N=30).

For transmitting information at greater distances than the range of a direct connection, it is essential to use the retransmission (switching) mechanism of packets through intermediate nodes. The maximum communication range in this case is determined by the specified end-to-end transmission delay to ensure the required QoS. Thus, for real-time applications (VoIP, video conferencing, etc.), the number of UAV network retransmissions should not exceed 6, and for applications not critical to delay (short transactions, data arrays, streaming video, etc.) may be several dozen at a given traffic intensity. It is also shown that with twice the traffic intensity, the average UAV-UAV link transmission delay is three times higher than the MS-MS link average transmission delay. Therefore, if the number of links in the route of the MS network is more than 3, it is more appropriate to transmit information through the UAV network if there is coverage of the last.

Based on analytical mathematical models, the connectivity duration of WEN mobile nodes (MS and UAV) in direct radio visibility conditions and considering retransmission was investigated. It is shown that the duration of connectivity is directly proportional to the size of the coverage zone and inversely proportional to the movement speed of nodes. The nature (scenario) of node mobility also affects the duration of connectivity. The simulation of the nodes' movement was carried out under 4 scenarios: "march", "incoherent", "random wandering in the field" and "random wandering in the city". The largest values of the connectivity duration correspond to the third scenario, and the smallest - to the second (with a fixed radius of the coverage area and the movement speed of nodes). Thus, the average connectivity duration of the UAV-pedestrian connection in the event of an "incoherent" will be about 36 minutes, and the UAV-car connection - about 5 minutes.

The obtained results can be used for further research on the problems of operational positioning of sensors.

References

1. O. Lysenko, S. Valuiskyi, P. Kirchu, and A. Romaniuk, “Optimal control of Telecommunication Aeroplatform in the area of emergency”, *Information and Telecommunication Sciences*, no. 1, pp. 14–20, 2013.

2. S. Valuiskyi, A. Lysenko, T. Pryshchepa, and S. Chumachenko, “The problem of finding a rational topology of wireless sensor networks using UAVs”, *2015 Second International Scientific-Practical Conference Problems of Infocommunications Science and Technology (PIC S&T)*, 2015.

3. O. Lysenko, V. Romaniuk, O. Tachinina, and S. Valuiskyi, “The problems of control in wireless sensor and mobile ad-hoc networks”, *Integrated Computer Technologies in Mechanical Engineering*, pp. 385–402, 2020.

4. M. Zhu, F. Liu, Z. Cai, and M. Xu, “Maintaining connectivity of Manets through multiple unmanned aerial vehicles”, *Mathematical Problems in Engineering*, vol. 2015, pp. 1–14, 2015.

5. S. Bunin and A. Voiter, Computer networks with packet radio communication. K.: *Tehnika*, 1989.

6. L. Kleinrock, Queuing Theory. M.: *Mashinostroenie*, 1979.

7. L. Kleinrock and F. Tobagi, “Packet switching in radio channels: Part I--carrier sense multiple-

access modes and their throughput-delay characteristics”, *IEEE Transactions on Communications*, vol. 23, no. 12, pp. 1400–1416, 1975.

8. M. Ilchenko, S. Bunin, and A. Vojter, Packet-switched cellular radio networks. K.: *Naukova dumka*, 2003.
9. L. Kleinrock, Computing networks with queues. M: *Mir*, 1979.

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Програма оцінки зв’язності вузлів безпроводових епізодичних мереж при умові застосування БПЛА

Проблематика. На основі аналітичних математичних моделей було досліджено тривалість зв’язності мобільних абонентів (вузлів) (МА) безпроводової епізодичної мережі (БЕМ, що складається із МА та БПЛА) в умовах прямої радіо видимості та з урахуванням ретрансляції.

Мета дослідження. Метою роботи є пошук методологічних підходів до забезпечення зв’язності вузлів БСМ, що є необхідною умовою отримання інформації від БСМ в умовах відсутності комунікаційної інфраструктури.

Методика реалізації. Метод оперативного обчислення координат проміжних пунктів маршруту передбачає встановлення квазімобільного режиму руху сенсорів та послідовне використання алгоритмів розв'язання навігаційної задачі, задачі кластеризації та задачі пошуку траєкторії обльоту пунктів збору інформації з кластерів мобільних сенсорів, що сформувалися на момент початку збору інформації.

Результати дослідження. Показано, що тривалість зв’язності прямо пропорційна розміру зони покриття та обернено пропорційна швидкості переміщення вузлів. На величину тривалості зв’язності також впливає характер (сценарій) мобільності вузлів. Було виконано моделювання переміщення вузлів за 4-ма сценаріями: «марш», «різнобій», «випадкову блукання в полі» та «випадкове блукання в місті». Найбільші значення тривалості зв’язності відповідають третьому сценарію, а найменші – другому (при фіксованому радіусі зони покриття та швидкості переміщення вузлів). Так середня тривалість зв’язності з’єднання «БПЛА-пішохід» на випадок «різнобою» становитиме порядку 36 хвилин, а з’єднання «БПЛА-автомобіль» порядку 5 хвилин..

Висновки. Отримані в результаті дослідження системні та функціональні параметри мереж ляжуть в основу вихідних даних і обмежень математичної моделі, а також дадуть змогу на етапі планування визначити початкове розміщення мережі БПЛА.

Ключові слова: *бездротова епізодична мережа; безпілотний літальний апарат; зв’язність вузлів.*