Software model for studying the features of wireless connections in Flying Ad-Hoc Networks (FANETs)

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Abstract. Over the last decade, earlier named self-organizing mobile computer networks, MANET (Mobile Ad Hoc Network), including those based on unmanned aerial vehicles (UAV) – FANET (Flying Ad Hoc Network), have become widespread. In FANET, the UAV is connected to the network using wireless technology. Due to the constant dynamics of the nodes of such FANET, in this network, there are sometimes lost connections between the nodes. Modern wireless technologies such as WiFi, ZigBee, AirMAX, and others, have different technical characteristics that significantly affect the ability to build FANET. In the article developed a software model that allows you to study the statistical characteristics of mobile networks. The motion of each object (network node) is described using a quaternion model. The software model is developed in the Python programming language. The obtained software model for the given conditions allows us to estimate the basic statistical characteristics of FANET and to make recommendations to their construction and application.

1. Introduction
In recent years, the capabilities of computer networks have greatly increased. Networks developed rapidly and found applications in many areas of human life and activity. Computer networks have received new properties: mobility and self-organization. So there was Mobile Ad Hoc Network (MANET), in which network nodes can move on a plane. As a result of advances in new technologies, such as sensors, microprocessors, wireless communications, and network technologies, it has also become possible to implement networks using unmanned aerial vehicles (UAV). Such networks are called Flying Ad Hoc Network (FANET). In FANET, network nodes move in three-dimensional space. The use of several UAVs to create a network requires the coordination of their actions for the joint achievement of goals. This level of coordination requires the development of new network models.

2. Background
FANET is a non-drone measure (COM), which is self-organizing, like a UAV unit (figure 1). This measure is characterized by high mobility of the universities, a dynamically variable topology, clutter in the 3D space, interchangeable characteristics of the universities (the need for transmission, battery charge, and battery.). Interconnection between the higher education institution and the higher education institution will be denied by the higher-order through some industrial universities, which can be used for routing functions [10].
These features create a large number of additional difficulties in organizing network communication and require solving some problems [7], [8]:

– at the physical level: the study of radio wave propagation models and antenna structure are key development factors [1];

– MAC level: due to high mobility and large differences in distances between nodes, there are often problems with the quality of the communication channel. Changing the value of the packet transmission delay is another problem of the MAC layer in FANET. This is especially critical for real-time applications [11];

– network level: routing is one of the most difficult issues for FANET. Existing solutions may not meet all FANET requirements [10];

– transport level: the success of FANET projects is closely linked to the reliability of the communication architecture, and the creation of a reliable transport mechanism is important, especially in a highly dynamic environment [3], [9], [12].

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3. Communication in FANET

Modern wireless technologies such as WiFi, ZigBee, AirMAX, and others, have different technical characteristics that significantly affect the ability to build FANET.

Wi-Fi is a family of wireless network protocols, based on the IEEE 802.11 family of standards, which are commonly used for local area networking of devices and Internet access [5].

Zigbee is an IEEE 802.15.4-based specification for a suite of high-level communication protocols used to create personal area networks.

The main feature of ZigBee technology is that with low power consumption it supports not only simple network topologies (point-to-point, tree, and star), but also self-organizing and self-healing mesh topology with relaying and routing messages.

Unlike IEEE 802.11 protocols, were at a greater distance the subscribers can no longer hear each other, when using AirMax technology there are no errors due to the overlap of packets from multiple subscribers due to the use of TDMA technology. Its essence is as follows: the base station, working with the AirMax protocol, determines the order of operation of the devices connected to it by allocating to each subscriber its time interval (slot) for data transmission. Therefore, the occurrence of collisions is eliminated, and the quality of data reception and transmission is improved.

AirMax technology uses the MIMO antenna configuration to achieve high radio bandwidth.

The advantages of AirMax include the ability to scale the network. So, if when working on WiFi standards, the maximum number of simultaneous connections to the access point should not exceed 20-

![Figure 1. The general scheme of FANET [10].](image-url)
25, then AirMax provides simultaneous operation in the radio channel up to 120 devices. All AirMax devices run the AirOS operating system.

Of course, many other technologies can be used to build a FANET. Only those that the authors tested in physical experiments are mentioned here.

4. Mobility models
According to the classical theory of dynamics [2], we will consider the aircraft as a “solid”, which is a set of material points rigidly interconnected. When moving, the distance between the points and the center of mass does not change and the trajectory of the aircraft can be described as the trajectory of the center of mass.

The motion of any type of aircraft can be represented as a set of translational and rotational motion. In this study, we will consider only translational motion.

The position of the UAV can be represented by quaternion equations, which are a system of linear equations that do not degenerate and satisfy a single equation of communication. Representation of orthogonal coordinate transformations in the form of the product of quaternions allows us to perform modeling of arbitrary motion with lower computational costs [4].

The quaternion, in general, can be represented as an ordered system of four real numbers, or as a scalar and vector part [2]:

$$E = \begin{bmatrix} e_0 \\ e_1 \\ e_2 \\ e_3 \end{bmatrix} = e_0 + e_1 i + e_2 j + e_3 k = e_0 + e, \tag{1}$$

where $e$ is the vector part of the quaternion.

The vector part of the unit quaternion $e$ can be represented as:

$$e = e_1 i + e_2 j + e_3 k \tag{2}$$

where $i^2 = j^2 = k^2 = -1$.

A single quaternion can describe a single rotation in three-dimensional space around a certain axis. Rotation around the axis at an angle $\Theta$ specified by a single vector $\theta$ can be represented as:

Scalar part

$$e_0 = \cos \left( \frac{\Theta}{2} \right) \tag{3}$$

Vector part

$$e = \theta \sin \left( \frac{\Theta}{2} \right) \tag{4}$$

We introduce an inertial coordinate system $A(\mathbf{i}_1, \mathbf{i}_2, \mathbf{i}_3)$ (figure 2) and a connected coordinate system $O(\mathbf{e}_1, \mathbf{e}_2, \mathbf{e}_3)$, in which the origin coincides with the center of mass of the aircraft, the axis $\mathbf{e}_1$ is directed along the velocity vector at each point in the simulation time, $\mathbf{e}_2$ directed upward perpendicular to $\mathbf{e}_1$, the axis $\mathbf{e}_2$ complements the coordinate system to the right.

We introduce an additional basis $O(\mathbf{i}_1, \mathbf{i}_2, \mathbf{i}_3)$, the axes of which are parallel to the axes $A(\mathbf{i}_1, \mathbf{i}_2, \mathbf{i}_3)$, and the center is at a point $O$. Then the motion of the aircraft is determined by the motion of the point $O$ (the motion of the end of the vector $\mathbf{R}_0$ to the point $O'$), and the kinetic – the rotation of the basis $O(\mathbf{e}_1, \mathbf{e}_2, \mathbf{e}_3)$ relative to $O(\mathbf{i}_1, \mathbf{i}_2, \mathbf{i}_3)$.

The rotation of the basis can be set by some normalized quaternion of rotation $E$.

$$\mathbf{e}_k = E \circ \mathbf{e}_k \circ \mathbf{\bar{E}}, \quad k = 1,2,3. \tag{5}$$

where $E = \lambda_0 + \lambda_k$ – some normalized quaternion, $\mathbf{E}$ – quaternion, inverted to $E$, such that $E \circ \mathbf{\bar{E}} = 1$. 


In this case, the final position of the object can be given by the formula

$$\vec{R}(t) = \vec{R}_0 + E \circ \vec{r}(0) \circ \vec{E}$$  \hspace{1cm} (6)

Applying the quaternion representation of rotations, the position of the object in the system $A(\vec{i}_1, \vec{i}_2, \vec{i}_3)$ can be represented as (figure 2):

$$\vec{R} = \vec{R}_0 + E \circ \vec{r}^0 \circ \vec{E}$$  \hspace{1cm} (7)

where $\vec{r}^0 = \sum_{k=1}^{3} r_k \vec{i}_k$ determines the initial position of the object in the base $O(\vec{i}_1, \vec{i}_2, \vec{i}_3)$. Given the condition for the normalized quaternion

$$\vec{E} \circ \vec{E} = 1, \vec{E} \circ \vec{E} + E \circ \vec{E} = 0$$  \hspace{1cm} (8)

we obtain the UAV velocity vector in the basis $A(\vec{i}_1, \vec{i}_2, \vec{i}_3)$

$$\vec{V} = \vec{R}_o + \dot{\vec{r}} = \vec{V}_o + \vec{E} \circ \vec{r}^0 \circ \vec{E} + E \circ \vec{r}^0 \circ \vec{E} = \vec{V}_o + \vec{E} \circ \vec{E} + \vec{E} \circ \vec{r} - \vec{r}^0 \circ \vec{E} + \vec{E} \circ \vec{E}$$  \hspace{1cm} (9)

where $\vec{V}_o$ – the speed of the point $O$ in the system $A(\vec{i}_1, \vec{i}_2, \vec{i}_3)$, $E$ – the derivative of the quaternion time, which is calculated as:

$$\dot{E} = \lambda_0 + \sum_{k=1}^{3} \lambda_k \vec{i}_k$$  \hspace{1cm} (10)

The angular velocity vector of an object relative to the base $A(\vec{i}_1, \vec{i}_2, \vec{i}_3)$

$$\vec{\omega} = 2(\vec{E} \circ \vec{E})$$  \hspace{1cm} (11)

Therefore, according to the rules of multiplication of quaternion's

$$\vec{V} = \vec{V}_o + \vec{\omega} \times \vec{r}$$  \hspace{1cm} (12)

If the object rotates around a fixed axis $\vec{\xi}$ at an angle $\alpha$, then the quaternion of rotation, velocity, and angular velocity vector can be written as:

$$E = \cos \alpha + \vec{\xi} \sin \alpha \vec{\xi}; \quad \dot{E} = \frac{1}{2} \left(- \sin \alpha \vec{\xi} + \vec{\xi} \times \vec{\xi} \sin \alpha \right) \dot{\alpha} = \left(\vec{\xi} \times \vec{\xi} = 0 \right); \quad \vec{\omega} = 2\dot{E} \times \vec{E} = \vec{\xi} \dot{\alpha}. \hspace{1cm} (13)$$

Let us know the trajectory along which the object moves. Divide it into segments corresponding to time intervals $dt$ (fig. 3). We will interpolate the trajectory by quaternions. This interpolation is called spherical linear interpolation (SLERP) [6]. The SLERP results in a unit length quaternion. Therefore, the resulting trajectory can be described by the product of quaternion's
\[ E = E_0 \circ E_1 \circ \ldots \circ E_j \circ \ldots \circ E_N, j = 1, 2, \ldots N. \] (14)

SLERP interpolation is not easy enough and requires a lot of trigonometric operations. However, other forms of representation are no fewer complexes, and representations of rotations are unacceptable for linear interpolation in general. For example, interpolating the components of a matrix can yield a matrix that degenerates an object into a plane.

It should be noted that quaternion multiplication is noncommutative (when changing the order of factors, the result of quaternion multiplication is different).

5. Software model
For the general case, the mathematical model of the FANET network can be represented as:

\[ H(t) = f(S, F, Y, X, t) \] (15)

where \( H(t) \) – vector of network characteristics at the current time \( t \) \((t \geq 0)\), \( H = \{V, T, N, C, Z\} \).

Parameters – primary network data: \( S \) – structural, \( F \) – functional, \( Y \) – network load, \( X \) - environment.
Characteristics – secondary data: \( V \) – power, \( T \) – time, \( N \) – reliable, \( C \) – economic, \( Z \) – other.

Changing the structural and functional organization of the FANET network, due to the movement of UAV in space, leads to the improvement of some performance indicators and the deterioration of others, this significantly complicates the choice of the best option, as performance indicators are contradictory. It is impossible to simulate all parameters and characteristics of the network taking into account the movement.

Therefore, when creating a software model, some restrictions and assumptions were introduced:
– UAV performs only uniform rectilinear motion without maneuvers, modeled by formulas (11-14).

The height of each UAV during the experiment does not change;
– each UAV has a radio range, the size of which depends on the wireless communication technology being simulated (power, frequency range, etc.). The radio field of view is a layer in 3D space (in 2D space circle) the center of which is UAV. An example of modeling the radio visibility zones of two UAVs in 3-D space (in conventional units of radius) is given in figure 4;
– the connection between UAVs appears when the spheres intersect.

When modeling a large number of UAVs, the visualization of the intersection of spheres is complicated, so a simplified mode of 2-D visualization is provided (figure 5).

![Figure 4](image-url) Example of modeling the radio visibility zones of two UAVs in 3-D space.

![Figure 5](image-url) Simplified mode 2-D visualization of communication between UAVs.

The input data of the software model are:
– the number of UAVs to build a FANET;
– for each UAV the speed, direction (trajectory), and altitude of flight, the radius of a zone of radio visibility is set.
The software model allows you to calculate the following characteristics of FANET:
– connectivity or the average number of adjacent nodes in the radio range;
– network survivability or probability of information delivery to any existing node in the network;
– mortality of nodes (disappearance, exit from the zone of visibility of nodes for a certain period, average value).

6. Conclusions
Thus, the developed software model allows us to study the characteristics of connectivity and survivability of FANET for different wireless technologies.

The quaternion model of UAV motion allows us to solve the inverse problem, namely to optimize the trajectory of UAVs to maintain the connectivity and survivability of FANET.

In recent years, several experiments have been conducted to build UAV-based networks, which have confirmed the adequacy of the software model. Ubiquiti Networks equipment was used to build the network: the Ubiquiti Rocket M5 wireless access point and the Ubiquiti NanoStation M5 access point, which use the developed AirMax communication protocol. The appropriate equipment was chosen because of the availability on the market and the presence of some advantages of the AirMax standard over conventional WiFi in conditions where a large number of subscribers are far away from the base station.

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