Swarm of Public Unmanned Aerial Vehicles as a Queuing Network

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Abstract. Unmanned aerial vehicles which are used to build flying ubiquitous sensor networks are viewed as a queuing system and their swarm — as a queuing network. It is proved that a sufficiently large number of UAVs swarm can be considered as a network of Jackson. The distribution of the lengths of the shortest paths for the UAVs swarms with a cube and a sphere is determined.

Keywords: Public flying ubiquitous sensor network · Unmanned Aerial Vehicle · The queuing system · The queuing network · The length of the shortest path

1 Introduction

One of the most attractive areas of the networks and communication systems has recently been Flying Ad Hoc Networks (FANET) [1–3]. Initially used mainly for military purposes, UAVs are currently used in civilian applications [4,5]. By analogy with the division of terrestrial in the Ad Hoc network [6,7] and ubiquitous or wireless sensor networks [8,9] in the field of Ad Hoc networks there were flying ubiquitous sensor network FUSN [10]. Widespread public unmanned aerial vehicles and related networking features FUSN enable to identify a new class of public communications networks FUSN-P (Public) [11]. One of the main features of FUSN-P is that the UAV is operated usually by nonprofessional users, so that it requires the simplest handling of them during operation. For this purpose, in [11] in the FUSN-P it was proposed to use the UAV flight for the data collection from the sensor fields on a given route. Simultaneous use of multiple UAVs leads both to creation of a swarm and to the possibility of considering it as a swarm of the queuing network. Notable works of UAV swarms as a part of FANET usually pursued the target of cooperation the UAV opportunities for solving military tasks, for search of the target, etc. [12–14]. We believe that the wide spread of public unmanned aerial vehicles enables to consider a separate UAV as a queuing system [10] and a swarm as a queuing network.

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2 UAV as a Queuing System

Let sensory nodes FUSN-P which are considered, for example, for the head [15], are located on the UAV, which perform the flight of the sensor field territory (terrestrial network USN) and collect the data from the terrestrial-based sensor nodes. While servicing a plurality of nodes, the UAV can be seen as a queuing system, the input of which receives the entity (terrestrial sensor nodes in the service area) which can expect the service within the time of their stay in the area of accessibility. The entities (nodes) that have not been serviced during this time are denial of the service. The flow rate is dependent on the radius of the service area, the density of nodes and the speed of the UAV. To serve the UAV terrestrial sensor assembly some time is spent and the node should be in the area of accessibility during the period of service (Fig. 1).

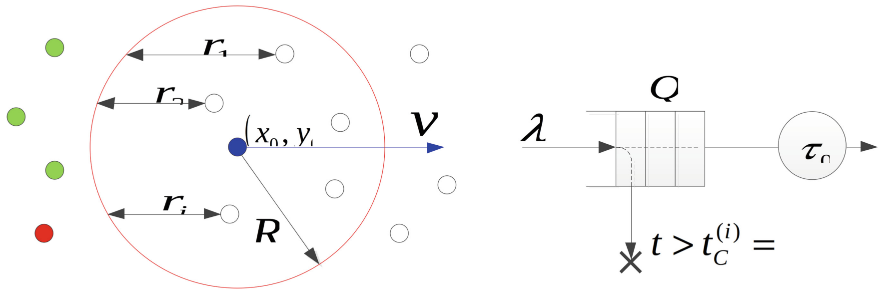

Fig. 1. UAV as a queuing system.

If the coordinates of the terrestrial nodes are accidental, the entry system receives the random flow of the entities. The properties of this flow are determined by the properties of the sensor field (publishing sites on the surface), the radius of the service drones and its speed. We will make the following assumptions:

- the sensory field is a Poisson field;
- the UAV is believed to move in a straight line at a constant velocity v;
- the zone service is a circle with a radius R.

Define the distribution function for the incoming flow entities. For this purpose we will examine the service area of the UAV at time 0 and at time t. During t the entities (nodes) which are found in the area that is defined by a shift of the UAV service area for time t will go in the system. According to the properties of the Poisson field, the probability of presence of n points (nodes) in a certain area is determined by the Poisson distribution and depends only on the field area. The probability of presence of z entities (nodes) in the field S is

$$p_z = \frac{a^z}{z!} e^{-a} \tag{1}$$

where a = p * S; p - is the number of points (nodes) in a unit area; S - is the field area.

$$p_z(t) = \frac{(p \cdot S(t))^z}{z!} e^{-p \cdot S(t)} \tag{2}$$

The field area can be defined as

$$S(t) = 2R \cdot vt \tag{3}$$

The flow rate, i.e. the average number of entities per unit of time is equal to

$$\gamma = p \cdot 2R \cdot vt \tag{4}$$

The distribution of the time interval between the entities We will consider the random variable T as the time interval between two successive events in the stream and will find its distribution function.

$$F(t) = P(T < t) \tag{5}$$

Then the probability that z entities will go to the time section of the length t is

$$P(T \geq t) = 1 - F(t) \tag{6}$$

Therefore, the probability can be calculated by the formula

$$P(T \geq t) = p_0(t) = e^{-p \cdot 2 \cdot R \cdot vt} \tag{7}$$

Considering this fact, the distribution function of the time interval between the entities is

$$F(t) = 1 - e^{-p \cdot 2 \cdot R \cdot vt} \tag{8}$$

Thus, the elementary flow will enter the system, the time intervals between the entities, which are distributed exponentially with a mean.

$$\bar{a} = \frac{1}{\rho \cdot 2R \cdot v} \tag{9}$$

3 Swarm of UAV-P as a Queuing Network

Taking into consideration the above mentioned facts, the flow of entities (messages), which arrives at the node of each of the UAV has the properties of a simple entity flow. Beside the flow of messages from a particular terrestrial sensor field, the viewed nodes receive the traffic flows from other nodes on the network.

Further we will assume that the output flow of messages from i node with probability r_{ij} is an input to the node j. With probability $1 - \sum_{j=1}^{n} r_{ij}$ the entities will leave the node i and will be sent to the external environment, i.e., to the gateway, Fig. 2.

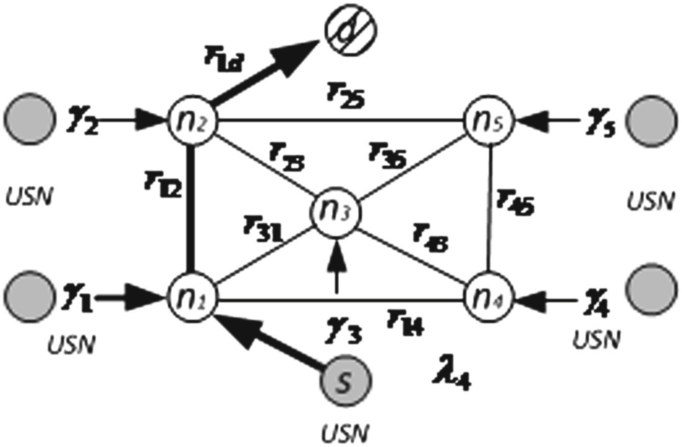

Fig. 2. Model of data delivery route between the source (s) and receiver (t).

In the general case, the service time of the messages on the route segment t consists of two main components: the time of sending the message on channel τ and the time-out state of the channel readinessψ, which are generally random.

Changing of the channel status is a random process that occurs under the influence of many independent factors (events), such as the entry and stepping out of communication range due to the random deviations from the desired path of movement, the effect of interference from transmitters located on the other elements of the system and others. It is expected that with a sufficiently large number of independent events the channel readiness intervals will have the distribution which is close to exponential distribution, therefore, the state of waiting time readiness ψ will also have the similar distribution.

If the time distribution of the message sending through the communication channel τ is close to an exponential one, then the assumption of exponential distribution of service time t is quite possible.

If we strengthen the above mentioned conditions of the network by the assumption of exponential service time of messages in the nodes, these conditions will coincide with the conditions of the network Jackson [16].

$$\overline{T} = \sum_{j=1}^{M} \frac{\lambda_j}{\gamma} T_j, \tag{10}$$

where M - is the number of channels in the network; n - is the number of network nodes; T_j - is the delay in the j-th channel; $\gamma = \sum_{i=1}^{n} \gamma_i$ - is the total traffic network; λ - is the total traffic served in the j-th channel.- is the delay in the j-th channel;

The value

$$T_j = \frac{1}{\mu_j - \lambda_j}, \tag{11}$$

where $\mu_j = \frac{1}{t_j}$ - is the service rate in the j-th channel.

Delivery time for a particular route network θ_k can be estimated by using the properties of the Jackson network. It is known that each node of the network can be considered as independent QS M/M/1, and the whole route — as a series of independent QS M/M/1, Fig. 3.

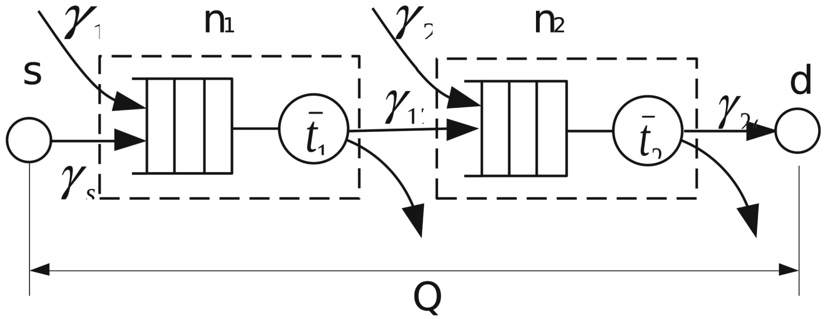

Fig. 3. Model of data delivery route between the source (s) and receiver (t).

The distribution function of time to deliver a message in this system can be described by Erlang distribution.

In case of equality of all $\lambda_i = \lambda$, and $\mu_i = \mu$ with the average value $m \cdot t$, which is the average time to deliver a message on the route $\theta_k = m_k \cdot t$ where m_k is the number of channels in the k-route (Fig. 4).

$$S(x, m) = \frac{m \cdot \mu \cdot (m \cdot \mu \cdot x)^{m-1}}{(m-1)!} e^{-m \cdot \mu \cdot x} \tag{12}$$

The order m, in this case, corresponds to the number of transits (hops), assuming that the message transmission (service) for each of them is equal.

The more accurate approximation of the viewed network as the Jackson network is, the more n there are and the nearer service time of distribution blitz to exponential distribution is. With a relatively small number of n nodes and a small number of routes network the properties can significantly differ from the properties of the Jackson network. In this case, the route pattern can be described as a multiphase system G/G/1. Getting of the distribution function of delivery time, in this case, can be very difficult. However, an approximate estimate of the average delivery time to the j channel route is possible, as it is shown in [16]

$$\widetilde{T}_j \approx \frac{\rho_j \cdot \bar{t}_j}{2(1-\rho_j)} \left(\frac{\sigma_{a_j}^2 + \sigma_{t_j}^2}{\bar{t}_j{}^2} \right) \left(\frac{\bar{t}_j{}^2 + \sigma_{t_j}^2}{a_j{}^2 + \sigma_{t_j}^2} \right) \tag{13}$$

Where $p_j = \lambda_j \bar{t}_j$; $\sigma_{a_j}^2$ - dispersion of intervals between messages; $\sigma_{t_j}^2$ - dispersion of service time in j channel; $\bar{t}_j$ - Service time in j channel; $a_j = \frac{1}{\lambda_j}$ - the mean value of the interval between messages in j channel.

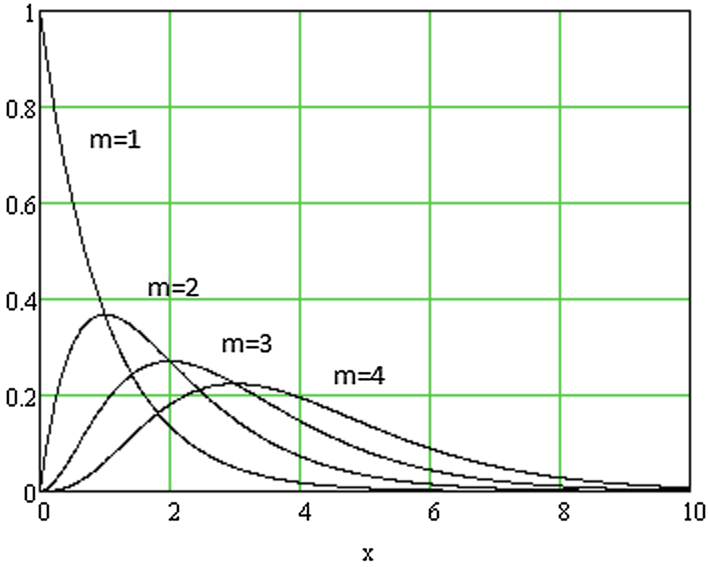

Fig. 4. The probability density of the delivery time on the route of m length = 1,2,3,4 hops.

Then the delivery time on the route will be equal to

$$\theta_k = \sum_{j=1}^{m_k} \widetilde{T}_j \tag{14}$$

where m_k is the number of channels in the k route.

It should be noted that the more accurate the estimate of the mean delivery time on the route 4 and 5 is, the higher the intensity of the message flow is λ_j and the smaller relation between the service time in the channel and time of messages receipt on the input of each channel.

It is obvious that one of the determining factors of the delivery time is the number of "hops" (channels) in the route m. This number depends on the used methods of routing. It is logical to assume that the route of the minimum length (with a minimum number of "hops") is chosen. Figure 5 shows the implementation of the random distribution of nodes in the space which is defined by a cube $200 \times 200 \times 200$ m (a) and by an equal volume of a sphere (b).

Figure 6 shows the distribution of the lengths of the shortest paths in the network which is formed by nodes that are arranged in a cube, with a communication node radius of 50 m.

This distribution was obtained by simulation. The shortest route was chosen by the criterion of a minimum number of hops. The average path length was 4.47 hop. For comparison, the same figure shows a Poisson distribution with a mean of 4.47. The connectivity probability was 0.98.

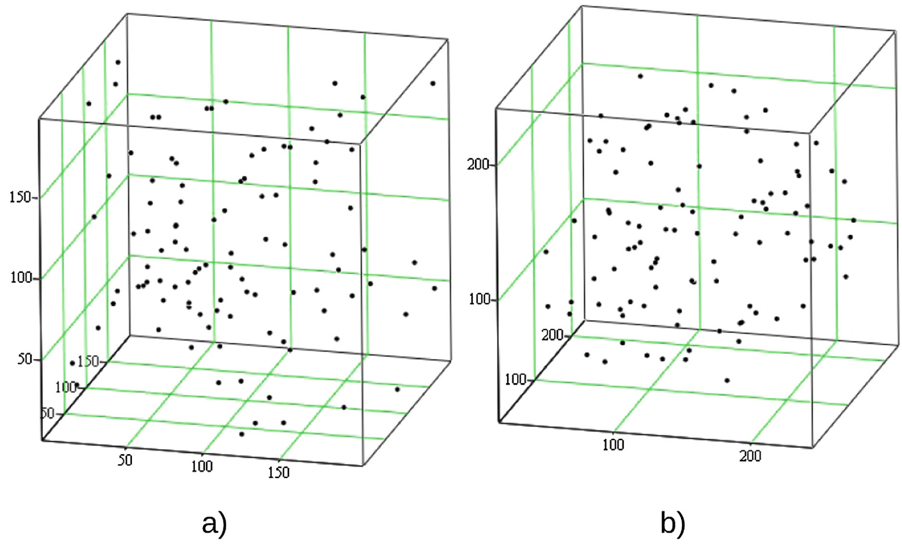

Fig. 5. Random placement of 100 nodes in the cube $200 \times 200 \times 200$ m (a) and in the sphere of equal volume (b) 14.

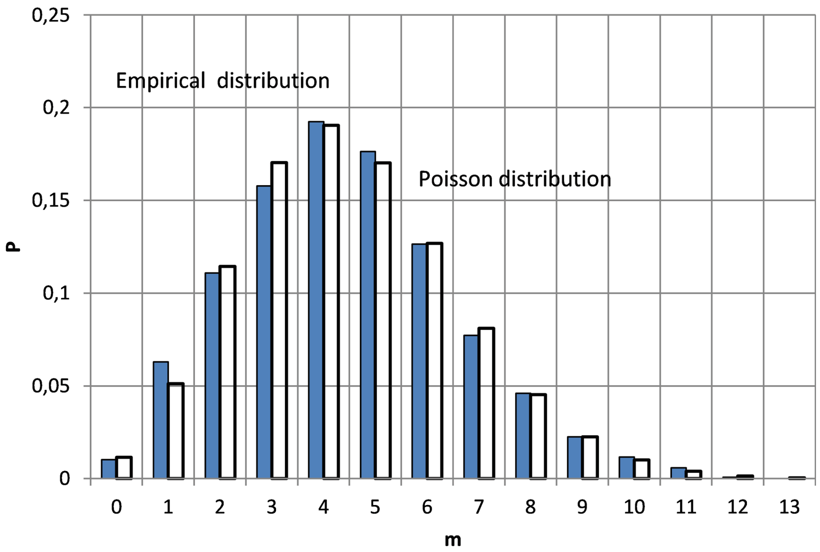

Fig. 6. Distribution of the lengths of the shortest paths in the network of 100 nodes in the cube $200 \times 200 \times 200$ m.

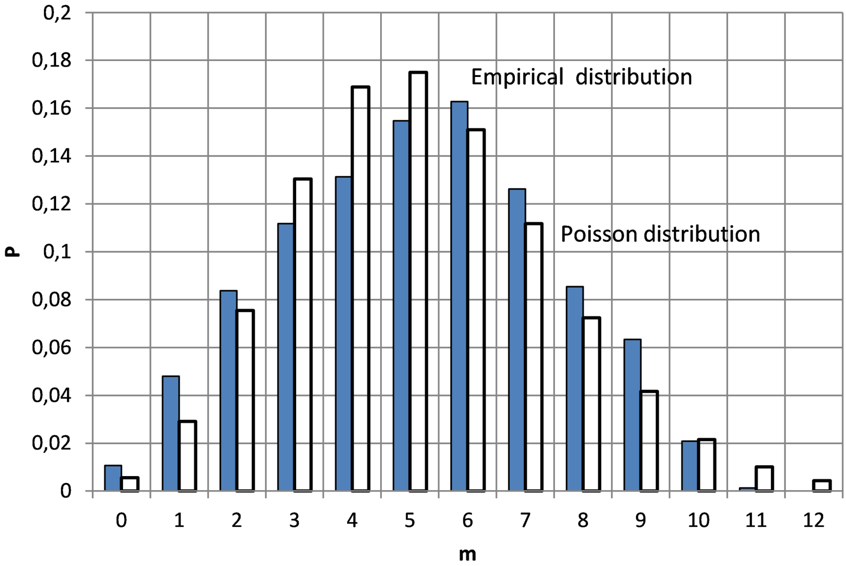

Fig. 7. The distribution of the lengths of the shortest paths in the network of 100 nodes in an equal volume area.

Figure 7 shows the distribution of the lengths of the shortest paths in the network with a random arrangement of 100 nodes in the area with a communication network node radius of 50 m.

The average path length was 5.18 hop. For comparison, the same figure also shows a Poisson distribution with a mean of 5.18. In this case, the network connectivity was 0.94.

The connectivity probability can be defined as the probability of falling into the sphere of a given radius of at least one node.

Out of the properties of the Poisson field, this probability is

$$P_{\geq 1} = 1 - e^{-a} \tag{15}$$

Where a - is the expected number of points in the field.

$$a = V \cdot \rho \tag{16}$$

where $V = \frac{4}{3}\pi \cdot x^3$ is the sphere volume of radius x; p - is the sphere volume of radius x;

Then the dependence of the probability density and connectivity of the network node communication radius is equal to

$$P = 1 - e^{-\frac{4}{3}\pi \cdot x^3 \cdot \rho} \tag{17}$$

For the simulated network, starting from (17), it is equal to 0.999. The values of connectivity which are obtained from the simulation results are within the error due to the finite size of the sample. It should be noted that the expression (17) gives the probability of connectivity for the unlimited Poisson field. In this case, the field is limited with a certain volume. In the case of restrictions, "edge effect" takes place which considers that the probability of connectivity for the nodes near the border is less than for the nodes that are closer to the center of considered limiting volume of the figure. This is obvious when considering a node which is located strictly at the boundary field.

The adjacent to it node can be located within the area. If the boundary is the plane, the extent to which communication with the neighboring node is possible is less than half for the site located near the center of the examined area (if the communication range is smaller than the area of the node). In this regard, it should be expected that the assessment of the connection probability (17) is the upper bound. Also the closer to the probability the value of the connected network will be (17), the larger the ratio of bounding shape to its surface area is. It is obvious that by increasing of the geometric dimensions the ratio will increase. As it is seen from the given figures in the case of considering the limited space of a cube, the length of the shortest path is well described by a Poisson distribution. In the case when the space is limited by a sphere, the distribution of the lengths of the shortest paths differs from the Poisson distribution to a greater extent. The average lengths of the shortest path (in the race) in the cases of cube and sphere are expected to vary.

4 Conclusion

1. While the organization of interaction with UAVs USN nodes to collect data under the certain conditions, the network connections between the UAV can be seen as a queuing network.
2. When a sufficiently large number of nodes which are located on the UAV model, the network Jackson can be used. In this case, the delivery time of data between the sources and receiver will obey the law of Erlang.
3. With a relatively small number of UAV to estimate the time of the data delivery it is possible to use familiar approximate estimates for systems G/G/1.
4. The number of "hops" in the shortest route between the nodes of the UAV is distributed according to the law which is close to the Poisson law that enables to estimate the length of the routes and the delay of the data delivery.

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