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ANALYSIS OF MATHEMATICAL MODELS OF MOBILITY OF COMMUNICATION SYSTEMS OF SPECIAL PURPOSE RADIO COMMUNICATION SYSTEMS

The object of research is the military radio communication system. One of the problems in improving the effectiveness of military radio communication systems is the correct description of the movement process in them. Efficient routing protocols are only possible if reliable information on network topology for network nodes is available. Thus, with this information, packets can be forwarded correctly between the sender and the recipient. Given that the mobility of individual nodes is insignificant in special wireless networks, nodes in the network show the mobility properties of a group of nodes. This observation is directly related to the very existence of military wireless networks with the ability to organize themselves, that is, to support group cooperation and group activities. In this work the problem of analysis (decomposition) of the mobility models of military radio communication networks with the possibility of self-organization is solved. The classification of mobility patterns, the description of individual mobility models and the analysis of various aspects currently available, as well as those properties lacking in the attempt to simulate the movement of individual nodes, have been carried out. During the research, the analysis of random, semi-deterministic and deterministic models was carried out. The advantages and disadvantages of the above models have been identified.

In the course of the research, the authors of the work used the main principles of the theory of mass service, the theory of automation, the theory of complex technical systems, as well as general scientific methods of knowledge, namely analysis and synthesis.

The research results will be useful in:

– synthesis of mathematical models of node mobility;

– evaluation of the effectiveness of the science-based tool for assessing the mobility of nodes;

– validation of recommendations to improve the efficiency of mobile radio networks;

– analysis of the radio-electronic situation during the conduct of military operations (operations);

– creating advanced technologies to improve the efficiency of mobile radio networks.

Keywords: *routing protocols, mobility models, Ad Hoc Networks, data transmission systems.*

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1. Introduction

According to the experience of local wars and armed conflicts in recent decades, during operations (combat operations), radio communication devices are usually the basis of any military and weapons control system, as well as communication and information transmission systems. It happens because of the high dynamics of hostilities, long range and the ability to work in motion [1, 2].

Currently, work is occurring to implement data transmission systems using networks with the possibility of self-organization (Ad Hoc Networks).

In the classic version of building wireless networks, where all clients connect to the router and data is transmitted only through it. In a decentralized network, each of these devices can move in different directions, breaking and establishing new connections with neighboring devices as a result of the move.

The main tasks of networks with the ability to self-organize data transmission are:

– construction of fault-tolerant network infrastructure;
– increasing the use of radio frequency resources;
– ensuring the network adaptation to the action of external factors;
– reducing the cost of deployment and operation of the network in comparison with the classical construction principles.

A self-organizing decentralized network consists of routers and mobile devices that are interconnected and act as a client and router.

Effective operation of routing protocols is possible only if there is reliable information about the network topology for network nodes. Thus, with this information, packets can be forwarded correctly between sender and recipient.

Given that the mobility of individual nodes is insignificant in special purpose wireless networks as nodes in the network demonstrate the mobility of the nodes group. This observation is directly related to the very existence of military wireless networks with the possibility of self-organization, i. e. to support group cooperation and group activities.

Thus, *the object* of *research* is the military radio communication system.

And the analysis (decomposition) of the mobility models of military radio communication networks with the possibility of self-organization should be considered as *the aim of research*.

Therefore, it is important to analyze (decompose) models of mobility of military radio communication networks with the possibility of self-organization.

2. Methods of research

The analysis of scientific works [1–3] is carried out, that the known scientific researches are generally directed on modeling of only a separate parameter of the network nodes mobility.

The papers [4–6] analyzed the influence of mobility on the efficiency of mobile radio communication networks. It is noted that to increase the efficiency of mobile radio networks, it is advisable to use a correct mathematical apparatus.

However, the issues of synthesis of the generalized model of network node mobility remain little studied and require further research.

During the research, the authors used the main provisions of the queuing theory, automation theory, theory of complex technical systems, theory of information transfer and general scientific methods of cognition, namely analysis and synthesis.

3. Research results and discussion

The mobility model should try to simulate the movements of real mobile nodes. Changes in speed and direction must occur at reasonable intervals.

Mobility models could mainly divide into two types:

– object mobility model;
– model of group mobility.

Object mobility models are the mobile nodes whose movements do not depend on each other. Examples of object mobility models [2, 3]: mobility model of boundless simulation zone, Gauss-Markov mobility model, probabilistic version of mobile random walk model and others.

Mobility models are classified into three patterns as deterministic (highly predictable random motion), semi-deterministic (not so predictable random motion), and random (Fig. 1).

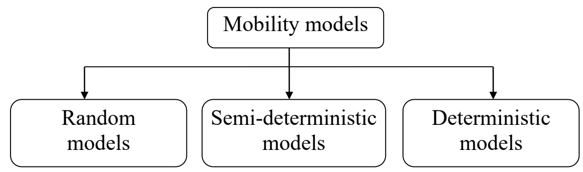

Fig. 1. Classification of mobility models

Determined mobility models describe the most predictable type of movement and are the simplest of all mobility models. For example, if the mobile nodes moved in a straight line (according to a deterministic model), the deviation of the direction vectors associated with any two positions would be zero, because the mobile nodes continue to move in the same direction.

A scenario that may resemble a model of deterministic mobility is cars moving in an urban traffic area where the speed of cars is limited, as well as the direction in which cars can move [3, 4]. A semi-deterministic model of mobility for example can be considered, the movement of military equipment in one general direction according to the purpose of the combat mission. In this case, the combat equipment of each combat vehicle, the path which it must follow is not specified, but they move in a general direction (in the direction of the front). Despite the fact that individual combat vehicles do not have a specific direction, it is possible to see the general scheme of the column. Such an example of mobility is called a «column model» [4].

In this case, the deviations between the vectors in the direction of the two positions can range from –90 to +90° depending on the width of the column, as shown by the deviation φ in Fig. 2.

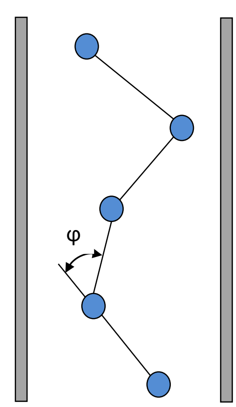

Fig. 2. Movement of the node corresponding to the column model

Models with random mobility where network nodes move in a random direction and speed (Fig. 3). This movement is completely uncontrolled, so the future movement here is completely independent of the past movement, and therefore, there are no restrictions imposed on the maximum deviation that the nodes can take for their next movement. And this coincidence in the choice of the next direction vector makes this type of motion completely unpredictable.

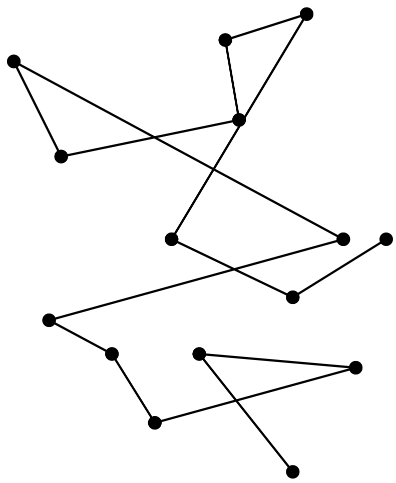

Fig. 3. Node motion in a model with random mobility

Based on their specific characteristics of node mobility, it is possible to categorize mobility models (Fig. 4). For some mobility models, the movement of a mobile node is likely to be influenced by its movement history. This type of mobility model will be called a «time-dependent mobility model». In some mobility scenarios, mobile nodes tend to travel relative to their previous location. Such models can be called «a model of mobility with spatial dependence». The model of mobility with geographical restriction, where the movement of nodes is limited by streets, highways or obstacles, can be attributed to the models of geographical restriction.

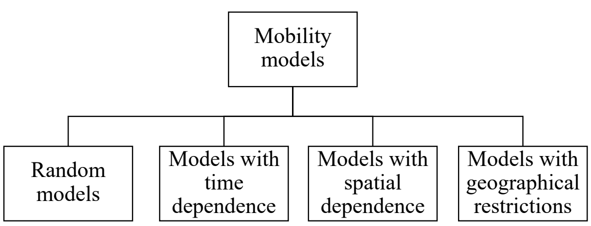

Fig. 4. Classification of mobility models

In models of mobility on an arbitrary basis, mobile nodes move randomly and freely, without restrictions. Thus, the destination, speed and direction are chosen randomly and independently of other nodes. This model is used in many simulation studies [5]. In NS-2, the implementation of this mobility model is as follows: during the start of the simulation, each mobile node randomly selects one place in the simulation field as a destination. It then moves to this destination with a constant speed, selected evenly and randomly [0, $V_{\max}$], where the parameter $V_{\max}$ is the maximum allowable speed for each mobile node. The speed and direction of the node are selected independently of the other nodes. After reaching the destination, the node stops for the duration specified by the parameter «pause time». If T_{pause}=0, it leads to constant mobility. At the end of this duration, it again selects another random destination in the simulation field and moves to it. The whole process is repeated again and again until the simulation is complete. For example, the movement of the node is shown in Fig. 5 [6, 7].

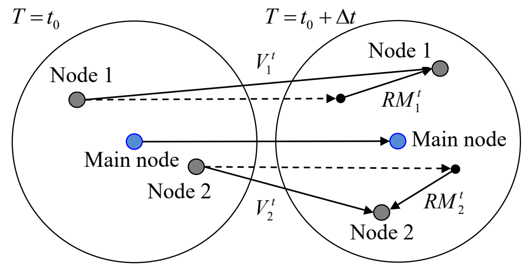

Fig. 5. Node motion in the RPGM model in terms of time

In the random waypoint model, $V_{\max}$ and T_{pause} are the key parameters that determine the mobility behavior of nodes. If $V_{\max}$ is small and T_{pause} is long, the special network topology becomes relatively stable. Otherwise, if the node moves fast ($V_{\max}$ is large) and T_{pause} is small, the network topology will be very dynamic. By changing these two parameters, especially the $V_{\max}$ parameter, the random waypoint model can generate different mobility scenarios with different levels of nodal speed.

The measure of the relative velocity between node i and j at time t is equal to:

$$RS(i,j,t)=\left|V_i(t)-V_j(t)\right|, \quad (1)$$

where $V_i(t)$ is the velocity of the i-th node at time t, and $V_j(t)$ is the velocity of the j-th node at time t.

Thus, the mobility index M is calculated as a measure of the relative velocity averaged over all pairs of nodes i over all time:

$$\bar{M}=\frac{1}{|i,j|}\sum_{i=1}^{N}\sum_{j=i+1}^{N}\frac{1}{T}\int_0^T RS(i,j,t)\,\mathrm{d}t, \quad (2)$$

where $|i, j|$ is the number of a single pair of nodes (i, j), N is the total number of nodes and T is the total time of simulation.

Using this mobility indicator, it is possible to roughly measure the level of nodal speed and differentiate different mobility scenarios based on the level of mobility.

Similarly, determine the average relative velocity of another mobility metric. Experiments show that the average relative velocity increases linearly and monotonically with the maximum allowable velocity [7].

The limitations of the random waypoint model and its variants are designed to simulate the movement of mobile nodes in a simplified way. Due to their ease of implementation and analysis, they are widely used.

However, they may not adequately capture certain mobility characteristics in some realistic scenarios, including time dependence, spatial dependence and geographical constraint.

The mobility of the node may be limited by the physical laws of acceleration, velocity and speed of the direction change. Therefore, the speed of the mobile node may depend on its previous speed. Thus, the speeds of one node at different time intervals are «correlated». As a result, various mobility models, which take into account time dependence, are proposed.

The Gauss-Markov mobility model was first introduced in [8] and is widely used. This model assumes that the velocity of the mobile node is correlated with time and is modeled as a stochastic Gauss-Markov process. In the field of two-dimensional modeling, the stochastic Gauss-Markov process can be represented by the following equations:

$$\overline{V_t} = \overline{\alpha} \circ \overline{V_{t-1}} + \left(1-\overline{\alpha}\right) \circ \sqrt{1-\overline{\alpha^2}} \circ \overline{W_{t-1}}, \quad (3)$$

where $V_t = [v_t^x, v_t^y]^T$ and $V_{t-1} = [v_{t-1}^x, v_{t-1}^y]^T$ is the speed in time t and $t-1$. $W_t = [w_{t-1}^x, w_{t-1}^y]$ is an uncorrelated random Gaussian process with mean and variance σ^2 and $\overline{\alpha} = [\alpha^x, \alpha^y]^T$, $\overline{v} = [v^x, v^y]$, $\overline{\sigma} = [\sigma^x, \sigma^y]^T$ are the vectors representing memory level, asymptotic mean and asymptotic standard deviation, respectively.

For simplicity, it is possible to write equation (3) in a two-dimensional field as follows:

$$v_t^y = \alpha v_{i-1}^y + \left(1-\alpha\right) v^y + \sigma^y \sqrt{1-\alpha^2 w_{t-1}^y}, \quad (4)$$

$$v_t^x = \alpha v_{i-1}^x + \left(1-\alpha\right) v^x + \sigma^x \sqrt{1-\alpha^2 w_{t-1}^x}. \quad (5)$$

When the node is going to move outside the simulation field and the direction of movement is forced to rotate 180 degrees.

Thus, the nodes remain within the simulation field. The speed of the node V_t at time t depends on the speed of the node V_{t-1} at time $t-1$. Therefore, the Gauss-Markov model is a time-dependent model of mobility, while the degree of dependence is determined by the memory level parameter α. The parameter α reflects the randomness of the Gauss-Markov process. By setting this parameter, the model is able to duplicate different types of mobility behavior in different scenarios. So if the parameter $\alpha=0$ then the model and the equations will look like [9]:

$$v_t^x = v^x + \sigma^x w_{t-1}^x, \quad (6)$$

$$v_t^y = v^y + \sigma^y w_{t-1}^y, \quad (7)$$

where v_t^x and v_t^y is the velocity of the node in the time interval t is determined only by the fixed velocity $\overline{v} = [v^x, v^y]^T$, but the Gaussian random variable $W_t = [w_{t-1}^x, w_{t-1}^y]^T$. Based on expressions (6) and (7) it is a model of random motion of the nodes.

At $\alpha=1$, the model has strict memory and node velocity in time t, the same velocity as node velocity in time $t-1$, there is the equation:

$$v_t^x = w_{t-1}^x, \quad (8)$$

$$v_t^y = w_{t-1}^y. \quad (9)$$

If the Gauss-Markov model has memory $0<\alpha<1$, then the speed of the node in the current time t will depend on the speed $V_{t-1} = [v_{t-1}^x, v_{t-1}^y]^T$ and the new Gaussian random variable $W_t = [w_{t-1}^x, w_{t-1}^y]^T$. The randomness level is regulated by the memory level parameter α. Thus, while increasing the speed of the node is affected by its previous speed, otherwise the speed of the node will be affected by the Gauss random variable [10, 11].

The above models do not cover many realistic mobility scenarios. Moreover, in some MANET tasks, including disaster relief and the battlefield, there is teamwork between nodes, and nodes are likely to monitor the group's main node. Therefore, the mobility of the mobile node may be affected by other neighboring nodes. Because the velocities of different nodes are «correlated» in space, let's call this characteristic the spatial dependence of velocity.

Given the fact that mobile nodes in MANET tend to coordinate their movement, a model of the reference points group mobility (RPGM) is proposed [11].

In the RPGM model, each group has a center that is the logical center or the main node of the group. Thus, each group consists of one leader and several members. The movement of the group leader determines the mobile behavior of the whole group. The movement of the group leader at time t can be represented by a motion vector V_{group}^t. It not only determines the movement of the group leader, but also provides a general trend of the whole group. Each member of this group has some degree of deviation from the general vector of the group movement.

The movement of group members is significantly influenced by the movement of the group leader. For each node, mobility is determined by a reference point that monitors group movement. After this predetermined reference point, each mobile node can be randomly placed in the neighborhood.

Formally, the vector of motion of the member i at time t, V_{group}^t can thus be described as [12, 13]:

$$V_i^t = V_{group}^t + RM_i^t, \quad (10)$$

where the motion vector RM_i^t is a random vector deflected by a group member from its own reference point. The vector RM_i^t is an independent equally distributed random process, the length of which is uniformly distributed in $[0, r_{\max}]$, and the direction of which is uniformly distributed in the interval $[0, 2\varpi]$, where $r_{\max}$ is the maximum allowable deviation of the distance.

The model is able to represent different mobility scenarios, where [13]:

– the whole field is divided into several neighboring regions, each region is exclusively occupied by one group, one such example is communication on the battlefield;

– in the second model, different groups with different tasks travel on the same field overlapping, a good example of overcoming natural disasters;

– in the third model, this scenario simulates the behavior of mobility at the conference, the territory is also divided into several regions and some groups are allowed to travel between regions.

As part of the mobility vector, an extension of the RPGM model is proposed. In this context, the authors note that many realistic mobility scenarios can be modeled and generated using this framework by correctly selecting control points along the desired path of the main node of the group.

If these control points can reflect motion behavior in realistic scenarios, the model provides a general and flexible basis for description and modeling. However, in practice, generating these checkpoints is not a trivial task. In the RPGM model, the vector indirectly determines how much the movement of group members deviates from their leader. Therefore, it is not possible to generate different mobility scenarios with different levels of spatial dependence by simply adjusting the model parameters. To solve this problem, a modified version of the RPGM model is proposed.

The movement can be described as [14, 15]:

$$\left|V_{member}(t)\right| = \left|V_{leader}(t)\right| + \text{random}(\ ) \cdot SDR \cdot \text{max\_speed}, \quad (11)$$

$$\theta_{member}(t) = \theta_{leader}(t) + \text{random}(\ ) \cdot ADR \cdot \text{max\_angle}, \quad (12)$$

where $0 < SDR$, $1 < ADR$, SDR is the coefficient of velocity deviation, ADR is the coefficient of deviation of the angle. SDR and ADR are used to control the deviation of the speed (magnitude and direction) of group members from the speed of the leader. By simply adjusting these two parameters, it is possible to create different mobility scenarios.

The Manhattan mobility model is a popular model of geographical constraint that let's use in our modeling. One easy way to integrate geographic constraints into a mobility model is to restrict node movement to map paths. The map is predefined in the simulation field and uses a random graph to simulate a city map [16].

Initially, the nodes are placed randomly on the edges of the graph. Then for each node, the point is selected randomly and the node moves to this point through the shortest path along the edges. Upon arrival, the node is paused for a pause T_{pause} and again selects a new destination for the next movement. This procedure is repeated until the end of the simulation. Unlike the random point vector model, where nodes can move freely, mobile nodes in this model allow to travel only by paths. In the model, the movement of the mobile node is also limited to the path in the simulation field.

The limitations of this research include the fact that to verify the adequacy and reliability of modeling results, it is necessary to have statistical results of practical research (experiments).

Areas of further research will focus on the development of a methodology for the operational management of interference protection of intelligent military radio systems.

4. Conclusions

The classification of mobility models, the description of separate mobility models and the analysis of various aspects available today, and also those properties which are lacking at attempt to model movement of separate knots are carried out. Description of modern models of group mobility, including the most modern trends in modeling group mobility of nodes. Also, given military networks, it is appropriate to conclude that, given the movement of a single node, there is still a need to have a model that can broadly cover the movement of group node movements.

Mobility modeling is evolving faster for group node traffic, a natural consequence of the fact that such behavior is more relevant than individual for transport routing, resource management and mobility management.

Despite the fact that today there are models that better combine some properties of human movement, they are still lack in modeling some parameters:

– delay or collision time;
– the ability to change the movement in real time due to new parameters that appear during the movement.

The results of the research will be useful in:

– the synthesis of the node mobility mathematical models;
– substantiation of recommendations for improving the efficiency of mobile radio networks;
– analysis of the radio electronic situation during hostilities (operations);
– while creating promising technologies to increase the efficiency of mobile radio networks.

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