STGM: A Spatiotemporally Correlated Group Mobility Model for Flying Ad Hoc Networks

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Abstract. Flying Ad hoc Network (FANET) is a special type of Mobile Ad hoc Network (MANET) consisting of a swarm of Unmanned Aerial Vehicles (UAVs), and simulation is the dominant method for its research. Mobility models that generate the trajectories of UAVs in a flying session are the foundation for constructing a realistic simulation environment. However, existing mobility models targeting general MANETs are not adaptable to FANET, as the mobility patterns of UAVs are fundamentally different from general mobile nodes on the ground. In this paper, we propose a group mobility model called STGM (*S*patio*T*emporally correlated *G*roup *M*obility model) for UAVs in a FANET. The distinct feature of STGM is that both the temporal property on the trajectory of a UAV itself and the spatial correlation across multiple UAVs that fly as a coordinated group are taken into account. In addition, the collision-free distribution of UAVs are maintained in STGM. Built on top of mathematical principles, STGM provides a parameterized framework. By adjusting its parameters, it is able to provide UAV trajectories covering different application scenarios. We validate the effectiveness of STGM with a set of important metrics, and the results show that STGM is a suitable and configurable mobility model, which will facilitate FANET research at upper layers.

Keywords: Mobility model · Flying Ad Hoc Network · Simulation

1 Introduction

Small Unmanned Aerial Vehicles (UAVs) are becoming widely applicable in recent years due to their versatility, flexibility and ease of re-deployment. These small UAVs equipped with various sensors and wireless communication modules can be connected to form Flying Ad hoc Networks (FANETs) [1]. FANETs are increasingly used for civil applications, such as monitoring, surveillance, search and rescue [2].

However, compared to traditional Mobile Ad hoc Networks (MANETs), FANETs are facing some unique challenges caused by their high mobility. For example, the topology of a FANET may change frequently, raising problems for the design and analysis of routing protocols. To overcome these problems,

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we need better understanding on the mobility of FANET nodes. Field testings, although realistic, are very costly, and the observed results are only applicable to the specific settings. In contrast, simulations using mobility models are considered to be a low-cost alternative, and their results can be applicable to more generalized situations [3].

As an abstraction of node movements, a mobility model describes the moving patterns of the node (including the change of its position, velocity, etc.). It can serve as an input to FANET simulation by producing trajectories for UAV nodes in a flying session, or waypoints of UAV nodes at specific times. Therefore, it is the foundation for other FANET research at upper layers, such as network connectivity analysis, network performance evaluation and the design of reliable routing protocols.

Although mobility models have been extensively studied for general mobile ad hoc networks (MANETs), existing models are not very adaptable to the domain of FANETs, as mobility patterns of UAVs are fundamentally different from general mobile nodes on the ground. Thus MANET models may not truthfully emulate FANETs. This limitation suggests an urgent need to comprehensively investigate FANET mobility models for the development of high-quality simulation environments, which will facilitate the research on other FANET problems.

The aim of this paper is to propose a mobility model for FANETs that capture their unique features. The rest of this paper is organized as follows. In Sect. 2, we give a brief description of related works. In Sect. 3, we propose the STGM mobility model. In Sect. 4, we justify the model with experimental results. Finally, we draw conclusions in Sect. 5.

2 Related Work

Mobility models have been extensively studied for MANETs [3], but mobility models targeting FANETs are relatively new and scarce. In [4], a survey on mobility models for airborne networks is presented. The mobility models for aerial vehicles can be classified into two categories: traditional MANET models adapted to aerial ad hoc networks and new models developed for aerial ad hoc networks. The first category includes the pure random models which do not consider any additional constraints. The well-known models among them include Random Way Point (RWP) and Random Direction (RD) model [3]. But the movement of UAV nodes obeys some kinematic and dynamic constraints, e.g., they tend not to make sharp turns or sudden stops. Disregarding these constraints will introduce unrealistic trajectories of UAVs. The very few existing mobility models for aerial vehicles are different from traditional MANET models in that the former capture smooth aerial turns which is caused by kinematic and dynamic constraints. In [5], the Smooth Turn (ST) mobility model is presented. ST perpendicularity ensures the smoothness of the trajectories. It is also an entity model, and it does not take group motion into consideration. The basic Gauss Markov (GM) mobility model [6] and Enhanced Gauss Markov (EGM) mobility model [7] can produce UAV trajectories for more general FANET scenarios, and the waypoints on each trajectory exhibit good temporal correlations that are common in reality. But these Markov models are still entity models, lacking the ability to capture spatial correlations among the UAVs in a group. As for group models, a widely used group model for traditional MANETs is Reference Point Group Mobility Model (RPGM) [3], and a number of its variants have been proposed as well, like Column mobility model, Pursue mobility model, Nomadic mobility model, etc. Up to now, group models targeting FANETs are very scarce. In [8], A pheromone model is proposed for addressing the requirements of ad hoc networks of UAVs cooperating to achieve a common mission. However, this model is not network-friendly, because its pheromone logic pushes the UAVs away from each other, leading to the break of node links.

3 Spatiotemporally Correlated Group Mobility Model

3.1 Overview of the Model

There are three aspects to be considered in our modeling framework. First, a UAV node in the real world cannot move in a random trajectory because of kinematic and dynamic constraints, so the temporal property of the trajectory reflecting these constraints should be considered in our model. Second, the UAVs in a FANET usually form a group or multiple groups, and the UAVs in the same group are moving coordinately. More specifically, there is a logical center in this group, which dictates the motion properties of the entire group, such as location, speed, direction, etc. All UAV nodes in this group should follow the motion of this logical center in a large degree, with some necessary randomness allowed. Third, the UAVs should maintain collision-free distribution during flying session. Hence, this property should also be kept in our model.

Based on above analysis, we propose a **S**patio **T**emporally correlated **G**roup **M**obility model, called STGM. The whole process of STGM can be decomposed into two phases. In the first phase, we propose a *correlated Gauss Markov model* to generate a trajectory (which is a series of waypoints along consecutive time slots) for each UAV in a group. We choose Gauss Markov process for modeling because it is much better at producing a temporally correlated sequence of elements than many other models, e.g., random ones. To capture the spatial correlations among the trajectories of different UAV nodes, we introduce important changes to the basic Gauss Markov model. Besides, since we should avoid collisions among UAVs in the whole flying session, the waypoints in these trajectories should be examined and adjusted to avoid collisions between UAVs when it is necessary. We perform this task in the second phase of the STGM model. Figure 1 illustrates the framework of STGM, and more detailed description about these two phases is given below.

3.2 Phase #1: Generation of Velocities and Waypoints

In UAV simulation, the trajectory of each UAV node can be approximated as a sequence of waypoints at discrete times. If we know the original waypoint and

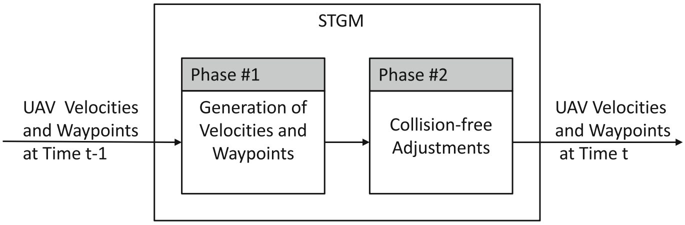

Fig. 1. Overview of STGM process

the velocity of each node at every time slot, we can calculate its waypoints for all time slots. For example, supposing at time t, UAV node i is at waypoint $WP_i(t)$, and its velocity at t is $\mathbf{V}_i(t)$, then its waypoint at time $t+\delta$ can be calculated as $WP_i(t+\delta) = WP_i(t) + \mathbf{V}_i(t) * \delta$. Since the velocity of a UAV consists of its speed and direction, our task is to derive a mathematical formula for each of the two aspects. In our framework, we adopt Gauss Markov process for modeling temporal properties of each trajectory, and take the direction and speed of the logical center as references for modeling spatial correlations between different trajectories. With these considerations, the speed and direction of each node are calculated by the following equations respectively.

$$S_i(t) = (1-\beta)S_i^{gm}(t) + \beta S_l(t) \tag{1}$$

$$D_i(t) = (1-\beta)D_i^{gm}(t) + \beta D_l(t) \tag{2}$$

In the equations, $S_i(t)$ and $D_i(t)$ are the speed and direction of a UAV node i at time t respectively. $S_i^{gm}(t)$ and $D_i^{gm}(t)$ is the basic Gauss Markov process for each node itself. $S_l(t)$ and $D_l(t)$ represents the logical center's speed and direction at time t respectively. The parameter $\beta \in [0,1]$ is a coefficient reflecting the correlation of each UAV node with the logical center on their movements. When $\beta = 0$, the UAV nodes have nothing to do with the logical center, indicating that the UAVs are not flying as a group. When $\beta = 1$, the UAV has the strongest correlation with the logical center. In fact, it will follow the moving of the logical center strictly in this case.

The basic Gauss Markov equations for speed $S_i^{gm}(t)$ and direction $D_i^{gm}(t)$ are given as follows:

$$S_i^{gm}(t) = \alpha S_i^{gm}(t-1) + (1-\alpha)\overline{S}_i^{gm} + \sqrt{1-\alpha^2}s(t-1) \tag{3}$$

$$D_i^{gm}(t) = \alpha D_i^{gm}(t-1) + (1-\alpha)\overline{D}_i^{gm} + \sqrt{1-\alpha^2}d(t-1) \tag{4}$$

$\overline{S}_i^{gm}$ and $\overline{D}_i^{gm}$ are constants representing the mean value of the speed and direction of node i respectively; $s(t-1)$ and $d(t-1)$ are random variables from Gaussian distribution. Parameter α reflects the degree of randomness in the Gauss Markov process, varying in the range $[0,1]$. When $\alpha = 0$, the model is memory-less, and the trajectory for each UAV node will be totally random, without any temporal correlation along its waypoints. In contrast, when $\alpha = 1$, the UAV speed and direction keep unchanged throughout the flying session. In other words, it is flying along a straight line with a constant speed.

In Eq. (1) and (2), the speed $S_l(t)$ and direction $D_l(t)$ of the logical center play their roles in affecting the speed and direction of a UAV node. In this way, the motion of the logical center decides the motion of the entire group. In the context of simulation, $S_l(t)$ and $D_l(t)$ can be provided as input vectors given by the following equations.

$$S_l(t) = \mathbf{VG}(t) \tag{5}$$

$$D_l(t) = \mathbf{DG}(t) \tag{6}$$

VG and **DG** are group motion vectors, which are two sequences of speed and direction values respectively at different times. The values of **VG** and **DG** are generated by path planning strategy according to specific demands.

It can be seen that by setting the two parameters α and β with different values respectively, we are able to control the degrees of temporal and spatial correlations for the trajectories of the UAV nodes.

3.3 Phase #2: Collision-Free Adjustments

As mentioned in Sect. 3.1, UAVs should avoid collisions in the flying session, which was not taken into account in Phase #1. In this phase, we adjust the original waypoints to ensure that the UAV nodes always keep a safe distance with each other. Note that each waypoint should be moved as little as possible to respect the spatiotemporal properties derived from Phase #1. These adjustments are performed in two steps. The first step is to identify the UAV nodes which are not in safe distance with at least one other UAV in the same group. In case any node violates this condition, the second step is invoked to perform an adjustment algorithm on the waypoint of this node. This algorithm is based on the following assumptions: (1) The global activity space of all UAVs is known. (2) The initial distribution of UAV group is collision-free. (3) Collisions during the interval between t and $t+1$ is not considered, i.e., collisions are only examined at the start of each time slot. With these assumptions, Algorithm 1 gives the process of the waypoint adjustments.

Note that in Algorithm 1, the *threshold* is the safe distance between UAVs, an empirical value that is set as *ten meters* in this paper. Figure 2 illustrates an instance of the adjustment algorithm. Assuming the node under consideration is i, and its waypoint at time $t-1$ is $WP_i(t-1)$, then it will reach the position indicated by $WP_i(t)$ calculated in the first phase at time t. Since i is in danger of collision with another node j, we need to conduct adjustment for i. We start from the current position $WP_i(t)$, and find the nearest safe point around $WP_i(t)$, as indicated by $WP_i'(t)$ in Fig. 2. This point also preserves its spatiotemporal property as much as possible. This procedure will be applied to all the other UAV nodes in this group in a sorted order. Eventually, the adjusted waypoints $WP'(t)$ are obtained.

Algorithm 1. Collision-free Adjustment Algorithm

Input:

Waypoints $WP(t)$ of all nodes calculated in Phase #1.

Output:

Collision-free waypoints $WP'(t)$

1: Sorting UAV nodes in descending order of their distances to the logical center.
2: Picking a node i from the node set in sorted order.
3: If existing a node j, with $Distance(WP_i(t), WP_j(t)) < threshold$, then i is in the unsafe area of j, goto step 4; otherwise goto step 5.
4: Searching the nearest safe waypoint $WP_i'(t)$ around $WP_i(t)$ for i, such that it is not in the unsafe area of j and any other nodes.
5: If all the nodes have been processed then take step 6, otherwise go to step 2.
6: **return** $WP'(t)$.

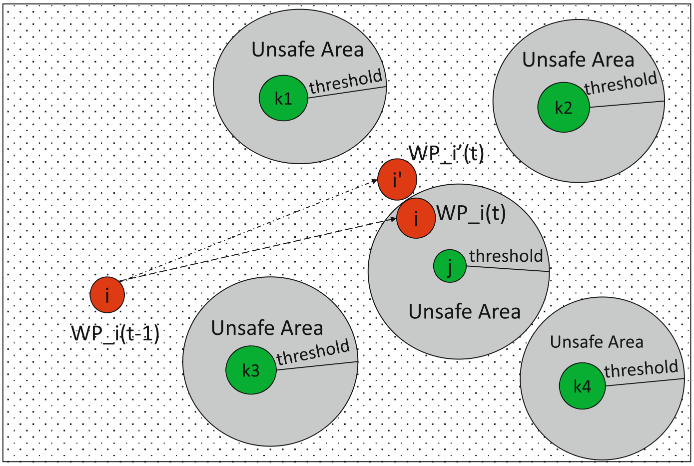

Fig. 2. An instance of collision-free adjustment

4 Simulation Results and Analysis

4.1 Metrics and Experimental Setup

To validate STGM model is flexible and suitable, we use some protocol-independent metrics, such as Spatial Correlation, Temporal Correlation and Path Availability. These metrics are defined in [9]. The BonnMotion [10] is taken to generate mobility scenarios and analyze the performance of the mobility model with above metrics. It has been widely used for studying the characteristics of mobile ad hoc networks. BonnMotion is an open-source software, thus we can implement our proposed STGM model with it and make comparisons with other models. The major simulation parameters set in BonnMotion are described in Table 1.

Table 1. Major simulation parameters

Simulation parameter	Value
Simulation area length	1000 m
Simulation area width	1000 m
Min speed	5 m/s
Max speed	15 m/s
α	[0∼1]
β	[0∼1]
Number of simulated nodes	30
Simulation Time	600 s

4.2 Results And Analysis

With the above experimental setup, we perform two sets of experiments. The first one is to validate whether STGM can capture the flying characteristics of a FANET across a wide variety of application scenarios. The second one is to compare with a few other mobility models described in the related work to show that STGM outperforms existing mobility models. We perform five independent experiments for each evaluated metric. The illustrated results below are averaged.

As described earlier, STGM should exhibit spatial and temporal correlations for a UAV swarm in the FANET. As the two parameters α and β in the STGM formulas are designed to control the degrees of temporal and spatial correlations for different scenarios, we first evaluate STGM by adjusting the α parameter to reveal the configurable temporal correlation. For this experiment, we set β to 0.5. Figure 3 shows the various values of average temporal correlation by tuning parameter values $\alpha = [0, 0.25, 0.5, 0.75, 1]$. It can be observed that the temporal correlation is low when α is small, and the temporal correlation gets large when α is being increased. Obviously, the temporal correlation is captured, and can be adjusted using the α paramter in STGM. Thus, for application scenarios where the UAVs are required to fly with sharp turnarounds, we will see low temporal correlation among waypoints for individual UAVs. This scenario can be simulated with STGM by setting α with a small value. In contrast, for situations where UAVs are flying in a very predictable trajectory, their high temporal correlation can be satisfied by setting α with a large value. In summary, by adjusting the α parameter, STGM can cover various application scenarios with different requirements on temporal correlation.

Figure 4 shows that the variation of spatial correlation can be controlled by the β parameter (α is set to 0.5 in this experiment). Obviously, the spatial correlation in STGM gets stronger with the increase of β. Therefore, to meet demands on spatial correlation for different application scenarios, we can simply adjusting the β parameter. For example, in search and rescue scenarios, relative low spatial correlation is required to enable larger coverage on scanned areas.

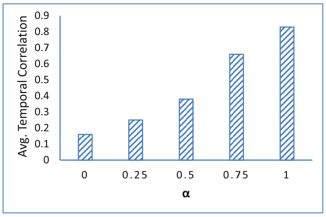

Fig. 3. Temporal correlation

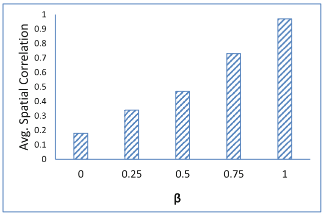

Fig. 4. Spatial correlation

In this case, we can set a relative small value for β. On the other hand, in a patrol scenario, where UAV swarms are flying in a more regular path, these UAVs will exhibit strong spatial correlation with each other. In such situation, the requirement can be satisfied by setting a large value for β.

Apart from revealing mobility characteristics of STGM itself using the above metrics, there is still a need to check whether STGM can simulate the dynamic of FANETs. We use path availability metric to make it. Figure 5 shows the path availability over different value pair of α and β. From Fig. 5, the fluctuation of path availability indicates that FANET is a dynamic and unstable network, especially when the value pair of α and β is small. In other words, the smaller value pair of α and β leads to the more randomness of UAV nodes. As a result, FANET is more unsteady in this situation. Another observation is that the dynamic degree of FANET in STGM is controllable. When we want to simulate a relative steady FANET, we can set α and β with relatively large values. In contrast, by setting the α and β with small values, an unsteady FANET scenario can be obtained. It validates that STGM is able to simulate different dynamics of FANETs according to the demands of specific application scenarios. This will enable researchers to construct various simulation environments for evaluating their routing protocols.

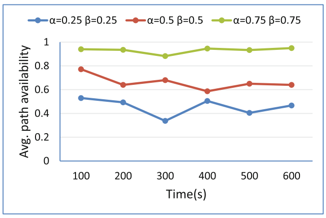

Fig. 5. Path availability

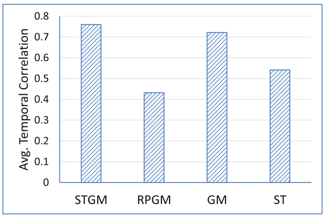

Fig. 6. Temporal correlation of different mobility models

From the above experiments and analysis, we can see that STGM model provides a flexible framework to satisfy different requirements of FANETs.

Next, we perform a set of experiments to compare with existing models to show that our model is more suitable for FANET research.

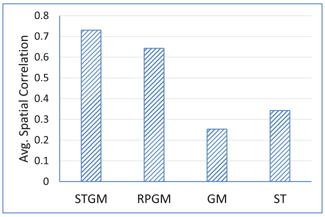

Fig. 7. Spatial correlation of different mobility models

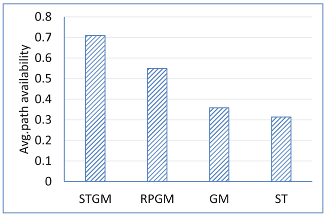

Fig. 8. Path availability of different mobility models

Figure 6 shows STGM and GM model have the higher temporal correlation than RPGM and ST. The reason is that STGM and GM guarantee temporal correlation by Gauss Markov process. The temporal correlation in Gauss Morkov formula is inherent. While RPGM and ST generate their movement by randomly selecting speed and direction, which can not ensure steady temporal correlation. ST has higher temporal correlation than RPGM. This is because ST ensure relative smooth trajectories by adjusting head direction. It is beneficial to obtain temporal correlation.

Figure 7 shows that group mobility models (STGM and RPGM) have higher spatial correlation than the entity models. This is because the entity models do not take spatial correlation into account. For the two group models, the correlation of STGM is higher than RPGM. The reason is that RPGM was proposed for the movement of human populations using the RWP model, where the kinematic and dynamic constraints are not modeled.

Figure 8 presents the average path availability among different mobility models. Obviously, the group mobility model have higher path availability than the entity models. The reason resides in this observation is that the movement of each node in group models is correlated with other nodes. This property is beneficial to obtain higher path availability. Besides, another observation is that STGM is more stable than RPGM. This is because STGM takes both spatial correlation and temporal correlation into account. Whereas, the RPGM generates trajectories by RWP entity model which is a pure random mobility model. In addition, the dynamic of STGM is controllable. Thus, STGM is superior than RPGM for FANETs research.

5 Conclusion

Mobility model serves as the foundation for constructing a realistic simulation environment for FANET research. However, the existing mobility models are mainly developed for MANETs, which may not truthfully emulate FANETs. In this paper, we propose a spatiotemporally correlated group mobility model (STGM) for FANETs. The distinct feature of STGM is that both the temporal correlation on the mobility of a specific UAV itself and the spatial correlation across multiple UAVs that fly as a coordinated group are taken into account.

Moreover, it maintains a safe distribution during the whole process. The experimental results show that STGM not only meets the expectation of the FANET scenarios, but also performs better than existing models. It suggests that STGM can provide a foundation that will facilitate FANET research at upper layers.

In the future, we plan to investigate the performance of routing protocols in FANET using the proposed STGM model in this paper, and develop an effective routing protocol that meets the requirements posed by FANET accordingly.

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