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Link availability estimation based reliable routing for aeronautical ad hoc networks

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ABSTRACT

The aeronautical ad hoc network (AANET) is an application of the mobile ad hoc networking technology to aeronautical communications. As the airliners move at a very high speed, one critical issue for improving the performance of AANET is to select reliable route that can address the frequent link breakage problem induced by the unpredicted network topology changes. In this paper, we focus on developing a link availability estimation based reliable routing protocol which considers the unpredicted network topology change problem to improve the performance of AANET. The link availability indicates the probability that a link will be continuously available for a given period of time. We first propose a novel Semi-Markov Smooth mobility model to mimic the behavior of the airliners in the sky. On the basis of the mobility model, we obtain the probability density function of the relative speed of two nodes, and further derive the expectation of the link lifetime. The accuracy of our analysis is validated by comparing the analytical results with that obtained by means of simulations. Moreover, we define the link availability factor and use it as the path selection metric to design a reliable routing protocol for AANET. Simulation results show that a gain in performance can be obtained by our protocol compared with the traditional routing strategy.

1. Introduction

Recently, there has been a clear trend towards the application of the ad hoc networking technology [1] in the civil aviation communication system, and then a novel research field of aeronautical ad hoc networks (AANET) [2–5] has arisen. AANET has recently gained significant attention, as it can set up a mobile ad hoc network among the free flight airliners, and thus provide a multi-hop communication link among the airliners and the ground base nodes. Therefore, the airliners which are far away from the ground base node can access the Internet with a multi-hop fashion. Through this way, the passengers can access the Internet with low latency and cheap charges.

As the airliners move at a very high speed in AANET, typically 700 km/h to 1000 km/h [6], the network topology will change frequently and unpredictably. Consequently, the multi-hop communication links will be broken frequently, thus decreasing the performance of AANET. Therefore, in order to improve the performance of AANET, one crucial challenge is to develop effective routing schemes which can select reliable paths that last as long as possible. Most of the existing routing schemes [7–12] are based on the idea of shortest paths, such as Ad-hoc On-demand Distance Vector (AODV) routing [7] and Dynamic Source Routing (DSR) [8]. That is, they use the number of hops in routes as the path selection metric. However, as the nodes in

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AANET move frequently, the shortest path may be broken immediately after it has been established. In such a case, rediscovering routes will induce high message overheads. Therefore, the shortest path-based routing schemes are inapplicable to AANET.

In order to select more reliable paths, there have been considerable attempts to present algorithms [13–19] to choose the optimal set of routes. Sakhaee et al. [6] proposed clustering and routing schemes to obtain stable and optimal routes for AANET. They took into account the relative velocity of nodes and the link duration of paths dynamically, and then chose the optimal routes through calculating the Doppler frequency shift. Gu et al. [13] also estimated the relative velocity between arbitrary two mobile nodes with Doppler frequency shift. Then they integrated the relative velocity and expected queuing delay as the route selection metric. Lee et al. [15] considered traffic load of nodes which can lead to network congestion and create bottlenecks as the main path selection metric. Cheng et al. [17] suggest discovering long lifetime routes algorithm to improve the performance of transport layer protocols. Senthilkumar and Somasundaram [18] took power constraint along with QoS constraints into consideration, and then predicted the stability of Link Expiry Time (LET) to select multiple optimal paths. Li et al. [19] propose a scoped flooding and mobility prediction based RGR protocol. This protocol takes advantage of the location information, speed, direction and timestamp of nodes to assess the real-time status of the next hop node. So the nodes have the ability to decide whether to send data packets through the reactive route or switch to GGF immediately. Simulation results have validated the effectiveness of these routing schemes by comparing with the traditional shortest path-based routing protocols. However, these schemes fail to provide a universal analytical model to mimic the mobile trace of the nodes in AANET. In particular, the Doppler frequency shift method does not take into account the actual mobile trace of the mobile nodes.

In order to address the above problems, considerable efforts [20–27] have been paid to model the smooth movement of mobile nodes and then calculate the link lifetime between arbitrary two mobile nodes. The Random Waypoint (RWP) model [20] was a significant work to estimate the unpredictable movements of the nodes in mobile ad hoc networks. However, Yoon et al. [21], Bettstetter et al. [22], and Blough et al. [23] pointed out the defects of the RWP model respectively. Yoon presented that the speed of nodes in RWP model continuously decreases as the simulation progresses, while the next two works showed that RWP model has non-uniform spatial node distribution at steady state, and thus the closed-form expression of this distribution could not be obtained. Therefore, further and deep analytical studies of this model have not been done. In addition to the above defects, the random mobility models may have unrealistic move behaviors, such as sudden stop, sudden acceleration, and sudden sharp turn, etc. These behaviors are not in accordance with the physical law of motion.

To address the unrealistic move behaviors, Li et al. [24] propose a Markov swarm mobility model for modeling time-dependent changes in the network topology induced by coordinated movements of mobile nodes in mobile ad hoc networks. The network topology of a mobile ad hoc network can be controlled through adjustment of the collaboration degree. Liang and Haas [25] have proposed a Gauss-Markov (GM) mobility model. In this model, the future location of a mobile node is predicted by the probability density function of its current location. The probability density function is calculated by the Gauss-Markov model. Zhao et al. [26,27] also proposed a novel Semi-Markov Smooth (SMS) model to accurately mimic the behavior of the mobile nodes that allow the physical law of smooth motion. In this model, there are four major movement phases for the mobile nodes, i.e., speed up phase, middle smooth phase, slow down phase, and pause phase, respectively. Based on this model, Wang et al. [28] and Nayebi and Sarbazi-Azad [29] studied the link lifetime among the mobile nodes. This work has motivated and guided research efforts on analyzing the link availability for routing metrics in mobile ad hoc networks.

On the basis of the link lifetime estimation, some works [30–33] adopted the predicted link availability as routing metric to develop reliable routing schemes. Here, link availability means the probability that a link will be continuously available from time t_0 to time $(t_0 + t)$. This metric can be used by a node to select more reliable neighbors to form a more stable route than the shortest path metric. In [30], Han et al. employed a probabilistic and statistical computing method to evaluate the link availability among the mobile nodes. This work was based on the random walk mobility model [34]. Afterwards, they developed a link availability prediction-based reliable routing protocol for mobile ad hoc networks. In addition, Jiang et al. [31–33] also proposed a novel routing protocol based on a reasonable estimation of the link availability.

Although a number of simulation results have validated the effectiveness of the above link availability prediction schemes and routing schemes, there still exist several critical limitations. First of all, all these link availability prediction schemes were designed for modeling the nodes mobility in mobile ad hoc networks where the nodes move at a very slow speed. Therefore, these schemes cannot be applied to accurately model the mobile behavior of the nodes in high speed AANET. Secondly, most of these works only considered four major movement phases for the mobile nodes. However, these phases cannot accurately model the behavior of the mobile nodes in AANET.

In this paper, we primarily introduce a novel Semi-Markov Smooth model to mimic the behavior of mobile nodes in AANET. This model can accurately reflect the mobile trace of the airliners in the sky. Then, we present a mathematical model to analyze the link lifetime. The accuracy of the proposed model is evaluated through simulations. Afterwards, we present a mathematical method to estimate the probability that a link being continuously available for a given time duration. This probability is referred to as the link availability. And we utilize the link availability as the path selection metric to design reliable routing protocol for improving the performance of AANET. Finally, we validate the effectiveness of our routing protocol by comparing the simulation results with the AODV protocol.