The Global In-Flight Internet

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Abstract—**In this paper, the concept of a new form of mobile network formed in the sky is introduced, where the mobile routers are simply the commercial aircraft. This implementation aims to eliminate two main problems arising from the current in-flight broadband implementation. The first problem is the resource management issue that may arise from the rapid increase of in-flight broadband Internet use in the near future. This could consequently limit current satellite resources, and bandwidth. The other issue is the inherent problem associated with Internet use over satellite, such as the degraded performance of delay sensitive applications due to the long propagation delay of a satellite link. A system model for data access, stable clustering of aircraft, and efficient routing schemes are introduced, which are suitable for the aeronautical mobility model. Link stability is predicted by a novel approach using Doppler shift subjected to control packets to dynamically form stable clustering and routing protocols. Another aim of this paper is to show that relative velocity between nodes is adequate as a stability metric, dominating relative distance, and this becomes evident in the simulations presented. An outline of how the new system could potentially interact with the traditional Internet using Mobile IP is also briefly discussed.**

Index Terms—**Aeronautical ad hoc network, aeronautical routing, aircraft communication, clustering methods, link stability, network mobility.**

I. INTRODUCTION

THE year 2004 was an exciting year as far as in-flight broadband Internet access was concerned, as the first commercial flight to have this technology was officially launched by Lufthansa on their Munich—Los Angeles flight using the Connexion by Boeing service [1]. Implementation of this service has continued and more airlines have begun offering it, and many more airlines will implement it in the near future. As this technology continues to have widespread implementation, more and more people will begin to utilize its service. However, it is unlikely that resources for such services will also continue to grow at the same rate. It will thus become essential to utilize resources effectively. Currently, the main communications resource used for such a service is the geostationary (GEO) satellite system. Although the use of this resource is quite effective today, in the near future due to the increase of the exploitation of these technologies, satellite resources may become limited. In such a scenario, new methods of communication can be integrated into the existing architecture. An extended model for such a system could incorporate other means of data retrieval and access such as aircraft to aircraft via ad hoc networking, and direct communication with ground stations in addition to the traditional method of satellite usage. Furthermore, this could solve other inherent problems associated with satellite communication that causes problems for delay sensitive Internet applications due to the propagation delay of the satellite link. Additionally, it will allow aircraft to effectively share their on-board cached data and Internet access and reduce the in-flight Internet usage cost.

There have been recent studies in aeronautical satellite communication, where the communication is limited to satellite [2]–[4]. An extended system model was proposed in [5], which simulated a routing scenario between the aircraft, satellites and Internet gateways, where the idea of direct communication to ground stations was envisaged.

In this paper, the network architecture is extended to include multihop ad hoc networking between aircraft, in addition to direct communication with ground stations and satellite usage, forming a new breed of network called the aeronautical ad hoc network (AANET). AANET is a new ad hoc network between commercial aircraft in the sky for the purpose of sharing of data and Internet access. Fig. 1 illustrates the concept of AANET. In AANET, an aircraft can initially download data from the Internet either directly from the ground or via satellite. The data can then be cached and shared with other aircraft in the proximity by dynamically establishing single or multihop paths to the requesting aircraft, using ad hoc networking principles. AANET system may be implemented and widely deployed much faster and with less investment due to the requirement of less infrastructure involved compared with satellite and ground station methods. AANET's fundamental changes may easily be implemented in hardware and software inside the aircraft and the cost could be far less than launching new satellites and deployment of ground station antennas in conventional methods. These advantages are in addition to the AANET delay and data rate benefits and the lowering of the satellite traffic load.

However, the feasibility of AANET also has to be justified. First, there needs to be an adequate number of aircraft in the sky at any given time in order for ad hoc networking among aircraft to be possible. According to the National Air Traffic Controllers Association [6], there are on average 5000 aircraft in the sky above the United States at any one time. Data were collected to verify this using the Flight Explorer Personal Edition [7] in April 2005. These indicated that density varied depending on time and day from as few as 600 commercial aircraft to over 5000 across United States' sky. The figure for the European sky is 25,000 per day, and this figure is predicted to be doubled by year 2010 [8]. Globally these figures would naturally grow to tens of thousands more. Furthermore, any aircraft should be within range of at least one other aircraft in order for a link to be established and multihop routing to prove practical. If the line-of-sight (LOS) distance (with regard to earth's curvature)

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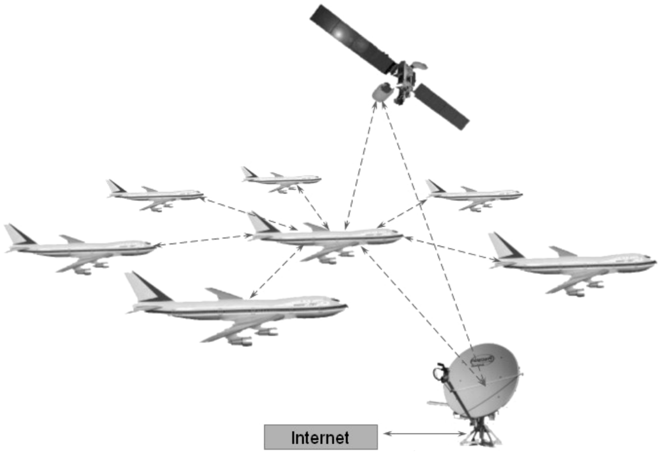

Fig. 1. The AANET topology.

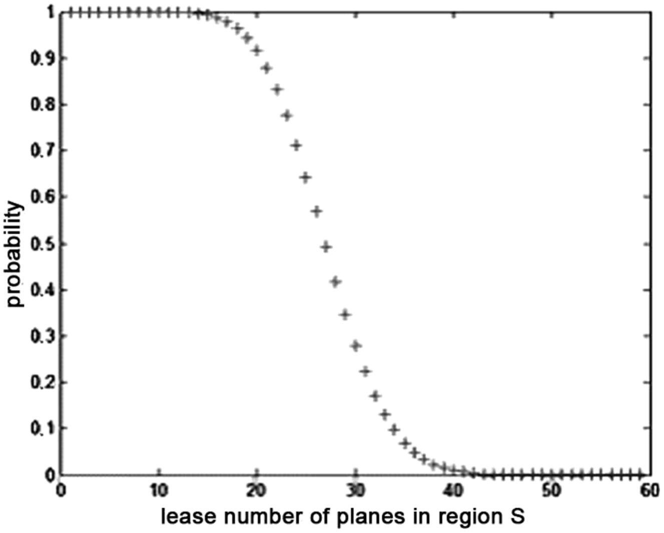

Fig. 2. Probability of finding at least n aircraft in region S.

is considered, the approximate geometrical area of the *communication zone* S is calculated using $S = \pi(2Rh + h^2)$, where R is the radius of the Earth, and h is the altitude of the aircraft. Taking a lower aircraft density of 700 aircraft across U.S. and using the Poisson distribution, the probability of the number of aircraft n in the region S can be worked out using $p(n, S) = ((\lambda S)^n/n!)e^{-\lambda S}$, where $\mathrm{R} = 6378$ km, $h = 9$ km (average cruise altitude of most commercial and general aviation aircraft is between 8 km to 11 km), and $\lambda \approx 7.6 \times 10^{-5}$ aircraft/km^2. Fig. 2 shows the probability of finding at least n aircraft in area S at any one time for the United States. From this figure, it can be seen that having at least two aircraft or even up to a dozen aircraft within range is close to 100%, thus meeting the second rule for the feasibility of AANET.

Routing in AANET is the other important aspect of the system as it is essential to establish suitable routes efficiently for data access between aircraft. Due to the large-scale nature of the proposed AANET, it may be inefficient to have a flat hierarchical structure for routing. Hence, a model for clustering of aircraft is presented to produce a scalable system to perform satisfactorily in a large global network of aircraft. Clustering could also provide an efficient framework for quality-of-service (QoS) support [9]. The other issue that would affect the routing approach is the high speed of the aircraft. It is important that paths formed between aircraft for data access are not frequently broken due to communicating aircraft moving out of range of each other. Thus, the routing scheme should take into account stability or link duration of paths dynamically. The routing scheme must be able to find stable routes for data transfers, and the clustering scheme must ensure that member aircraft of clusters do not frequently leave their associated clusters, a condition often known as *link down*. Although there have been proposed mobility-aware and stable-driven routing and clustering approaches, they may not work effectively in the AANET mobility model as outlined in the next section. A new stability metric is hence used to dynamically form both stable clusters and multihop paths in the AANET using proposed clustering and routing algorithms suitable for AANET. Stability is reflected in maximizing the period of cluster memberships and increased path or link duration between aircraft.

The routing method presented for AANET is for obtaining data rather than transmitting it. Demanding Internet applications, such as web browsing and file transfer protocol (FTP) are based on the idea of retrieving data from other servers. The principle of the proposed routing is based on requesting data with an identifier *id* where one or more aircraft are able to provide the data to the requesting node. The remainder of this paper is structured as follows. Section II presents related works on existing clustering and routing schemes. Section III presents the data access model and proposed clustering and routing schemes, followed by simulations of the proposed clustering and routing in Section IV. Section V concludes the paper.

II. RELATED WORKS

Link stability is an important issue in AANET. It is also a general concern in Mobile Ad hoc Networks (MANETs) and has been a major metric treated in recent work [10]–[12]. To form stable links in AANET, some form of stability metric must be considered during routing and cluster formation in order to maintain a stable overall system for data access.

In recent years, there have been many different routing protocols proposed for MANET, some proactive [13]–[16], on-demand [17]–[19] and hybrid approaches [20], [21], and some location-based routing schemes [22]–[24]. These routing protocols, however, do not ensure the stability of routes with regard to link duration. A path found using such protocols may break quickly as none of these routing schemes take into account mobility characteristics during route discovery. The associativity-based routing (ABR) protocol [25] takes stability of paths into account, however, the stability metric used in ABR may not be highly effective in AANET due to the target's mobility characteristics. In ABR, each node sends and receives beacons or "ticks" to and from its neighbors which signify the period of its presence within the range of its neighbors. The longer a node spends time within range of its corresponding neighbors, the more "ticks" received from it, and hence the higher its "associativity" with respect to its neighbors, which characterize its relative stability. The associativity ticks in ABR effectively present nodes that have been within range for a considerable period of time as stable. Although this mechanism may be useful in mobility models that are discrete in nature (e.g., with pause times), it may not work very well with incessant fast mobile entities such as the aircraft in AANET. In ABR, a node must remain within range of its neighbor for a considerable period of time before it receives sufficient associativity ticks, signifying the stability of the node with respect to its neighbor. However, in the AANET, such nodes are often those that may soon be leaving the transmission range (hence resulting in unstable routes or cluster members). Even when a stable node is present, there is a delay before ABR recognizes this stability (when the stable node's associativity ticks increase due to its prolonged presence). This can be inefficient in AANET since stable nodes may be required for routing as soon as they become available.

With regard to forming stable clusters, [26] presents a method to adopt redundant backbone nodes, so that when the primary backbone node is destroyed or moves out of the range of the cluster head, a new backbone node is selected out of these redundant nodes. The stability lies in the fact that cluster heads are at least two hops away, and a node gives up its backbone (cluster head) position only when a cluster head moves near it, unlike the lowest ID (LID) [27] algorithm in which the cluster heads give up their cluster head positions when a node with a lower ID is heard. Since this condition does not arise in AANET, this approach may not provide an adequate solution to choosing members that remain within the range of the cluster head for a sufficient period of time (i.e., membership stability).

A distributed clustering algorithm called MOBIC [28] takes mobility metrics into account for cluster formation. However, MOBIC may not work well in the aeronautical ad hoc network as MOBIC uses the ratio of the power of successive control messages to determine the velocity of neighbors for stability. In the aeronautical model, power of messages can be quite problematic, as there may be attenuation caused to power of signals due to atmospheric attenuation such as rain [29]. Additionally, MOBIC requires two messages to be received from each neighbor, increasing control overhead, and computation time, before estimating the stability of the neighbor. Furthermore, since in the AANET clustering model cluster heads are predetermined in a backbone network, the need for dynamic cluster head election as performed by MOBIC is avoided. Hence, MOBIC may not be very suitable for the AANET mobility model. Accordingly, new clustering and routing schemes are proposed that work effectively in AANET, presented in Section III.

III. AANET Data Access Network and Routing Model

In this section, the overall data access network and routing model of the AANET is presented.

A. Data Access Overview

There are several methods of accessing data in the proposed model. These include 1) the traditional method of Internet access via the (GEO) satellite system, as used currently by Connexion By Boeing [1]; 2) directly through the ground segment Internet via Ground Internet Gateways (GIG); and 3) through other aircraft using the proposed AANET. The nature of data, their local availability, the location of nodes, and other factors may affect the ideal method of data retrieval. The flowchart for data access is shown in Figs. 3–5.

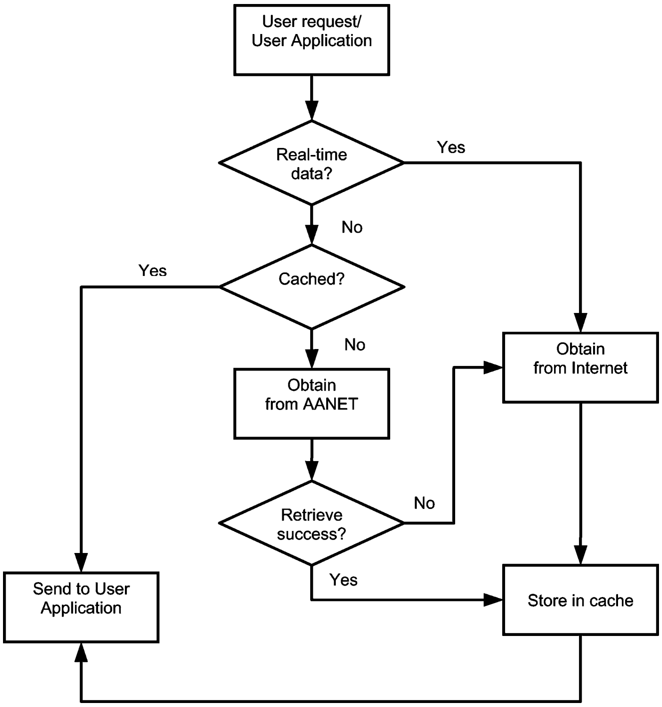

Fig. 3. Overall system flowchart for data access.

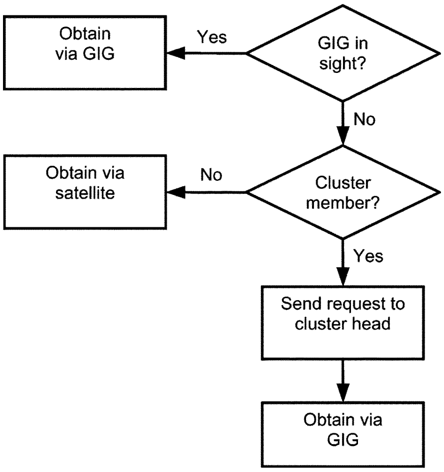

Fig. 4. Obtain from Internet state flowchart.

Storable data retrieved from the Internet are usually stored in an on-board cache, which can then be shared with other users in the same aircraft and other aircraft using the AANET. Data sharing may also be used in the style of swarming protocols as in [30]. In all cases, it is assumed that if the data cannot be obtained from the Internet, the request is automatically ignored.

B. Increasing Link Stability in AANET

Due to the high ground speeds of aircraft, there needs to be an efficient method for constructing both routes and clusters which are stable when formed. With this in mind, the other aim of this paper is to show that relative velocity alone is sufficient in providing stable clusters and paths dynamically. The use of Global

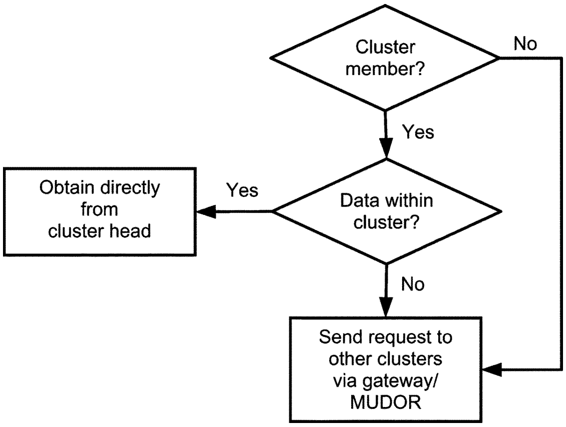

Fig. 5. Obtain from AANET state flowchart.

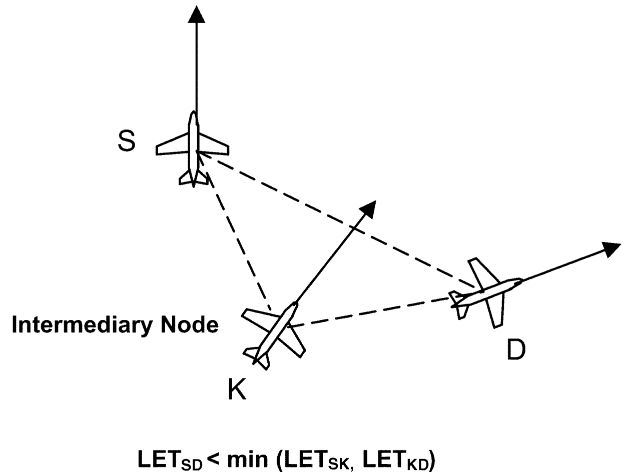

Fig. 6. Route established using intermediary nodes.

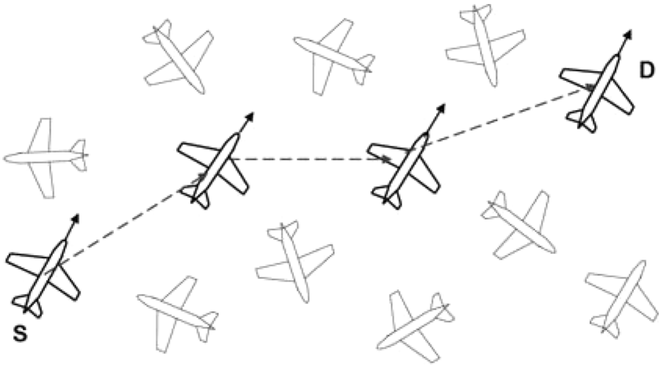

Fig. 7. A path formed from nodes having similar velocity.

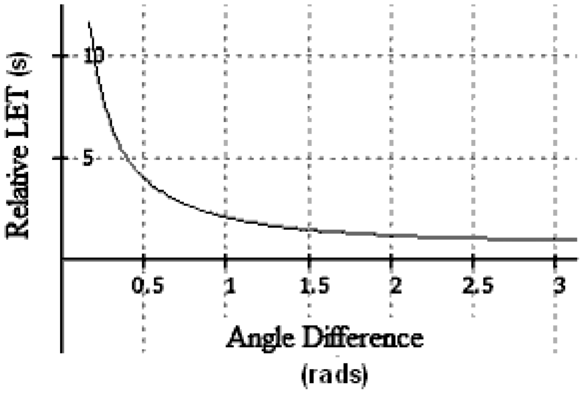

Fig. 8. Effect of relative velocity on link duration.

Positioning System (GPS) to estimate the link expiration time (LET) is also shown as an alternative approach. This requires the knowledge of both velocity and relative position of nodes. LET is related to the duration that a link can be maintained between two mobile nodes [31]. If we consider two mobile nodes i and j that have a transmission or LOS range of r, speeds v_i and v_j, directions θ_i and θ_j, and coordinates (x_i, y_i) and (x_i, y_i), respectively, the LET is predicted by

$$\begin{aligned}\mathrm{LET} &= \frac{-(ab+cd)+\sqrt{(a^2+c^2)r^2-(ad-bc)^2}}{a^2+c^2}\\ a &= v_i\cos\theta_i - v_j\cos\theta_j\\ b &= x_i - x_j\\ c &= v_i\sin\theta_i - v_j\sin\theta_j\\ d &= y_i - y_j \end{aligned}\tag{1}$$

For multihop routing, the path expiration time (PET) will be limited by the link with the smallest LET (bottleneck link) on such a path; i.e., $\mathrm{PET} = \min\{\mathrm{LET}_1, \mathrm{LET}_2, \mathrm{LET}_3, \ldots, \mathrm{LET}_m\}$ for a path with m links. Additionally, to increase path duration, the least number of hops may not be the best way to form stable paths. Even if a destination node is within range, it may not necessarily be the best way to route to it by a direct (one-hop) link. A direct single-hop link may have a shorter link duration than a path formed with "redundant" *intermediary nodes*. Primarily this is related to the relative velocity of nodes on the path. This is illustrated in Fig. 6.

Generally, if a path is selected from nodes that have velocities very close to each other, the path has a longer duration and hence is more stable. A simple scenario is illustrated in Fig. 7.

To demonstrate the significance of velocity on LET or link duration, consider two nodes at an initial position of (0,0) having equal speeds v (magnitude) and transmission range r, and where the first node is moving horizontally, while the other node moves at a direction θ. The LET will be given as

$$\mathrm{LET} = k \cdot \sqrt{2(1-\cos\theta)}/(1-\cos\theta) \tag{2}$$

where $k = r/2v$, which is a constant for nodes moving at constant speed with no pause time and no acceleration (resembling the aeronautical mobility model). Fig. 8 shows the relative LET in relation to the angle difference (velocity direction) for the case where $k = 1$. From the figure, it is clear that considering nodes having direction difference of less than 0.5 radians would dramatically increase the link duration of the link. In fact, it can be argued that the relative velocity of the nodes is more significant than their relative distances from each other when considering link duration (stability). LET considers relative position and velocity of nodes, however, as it will be seen in the simulations of Section IV, relative velocity proves adequate for selecting stable nodes for routing. Effectively, in order to increase

Fig. 9. Group mobility in aeronautical systems.

path stability, intermediary nodes can be used to decrease the relative velocity of respective nodes on the path.

The use of intermediary nodes greatly affects the proposed routing methodology, as nondisjoint paths to the same destination are also considered, and not necessarily the "shortest" path is chosen. Our nondisjoint mobility-aware routing algorithm is described in Section III-E.

C. Using Doppler Shift as a Stability Metric

There are two ways to find the relative velocity of neighbor nodes: using GPS and power [28], [31], [32], and Doppler shift of received packets [5]. The power version may not be suitable because radio signals are often attenuated by atmosphere and rain, particularly the higher frequency signals used for broadband communications [29]. The power and GPS method can effectively be bypassed, by utilizing the Doppler shift of control packets received from neighboring nodes to calculate the relative velocity. Each (radio transmitted) packet received is subject to a Doppler shift [5], [29] which depends on the relative motion of the transmitting aircraft to the receiving aircraft. The Doppler shift is the apparent change in the frequency of transmitted electromagnetic signals due to the relative motion of the transmitter and receiver [33]. The use of the Doppler factor in routing was first introduced in [5], for use between a mobile node (aircraft) and static nodes (satellites and ground stations). However, the nature of the relative Doppler factor changes here, as all nodes are mobile.

The relationship between the velocity and the Doppler shift is $v = c(f/f_0 - 1)$, where v is the relative velocity of nodes, c is the speed of light, f is the expected frequency, and f_0 is the observed frequency. Also, v is negative if the aircraft are approaching each other and positive if they are receding from each other. A generalization can be made that aircraft approaching each other form links *twice* as stable as those formed when they are receding from each other, using the following analogy. To map LET to velocity and Doppler shift, the maximum possible LET is considered for directly approaching and receding nodes, respectively. For approaching, the maximum LET can be obtained when the aircraft are at their maximum communication range, and are directly heading towards each other. In the case where the aircraft are directly receding from each other, they must have just gone past each other, and this corresponds to half of the LET of direct approach from maximum range. Thus, the general approach is to estimate LET to be *generally longer* (as much as twice as long) if the aircraft are approaching than if they are receding. The cost metric proposed for link and route selection is the $Doppler\ Value$ (cost) given by

$$\begin{aligned} Doppler\ Value &= -\,v(\text{if } v \text{ is negative. i.e., approaching}) \\ &= 2v(\text{if } v \text{ is positive. i.e., receding}). \end{aligned}$$

In practice, the Doppler shift of the received packet is used to work out the Doppler Value as follows:

$$\begin{aligned} Doppler\ Value &= -\,c(f/f_0 - 1)\cdots\cdots \\ &\qquad \left(if\frac{f}{f_0} < 1\right)\cdots approaching \\ Doppler\ Value &= +\,2c(f/f_0 - 1)\cdots\cdots \\ &\qquad \left(if\frac{f}{f_0} > 1\right)\cdots receding \end{aligned}$$

The smaller the Doppler Value, the higher the relative stability of the link formed. In the multihop scenario, the stability of path relies on the bottleneck highest cost link which limits the stability of the path. This information is carried in the forwarding route request packet, and is updated when there is a new maximum Doppler Value along the path (a bottleneck value) during packet forwarding. Section III-E outlines the detailed method of how this is used in the proposed reactive routing algorithm.

D. Clustering of Nodes

Clusters of aircraft originating from the same source and heading in the same general direction (not necessarily destination) could be ideal for sharing data. Fig. 9 shows an actual aircraft scenario over the north eastern oceans of North America taken using the Flight Explorer [7]. These aircraft are most likely all headed for the European continent. They may not all be going to the exact destination but they all have velocities very close to each other.

Furthermore, it can be considered that most passengers on these flights will be accessing very similar information on travel, accommodation, and destination information which are to a high degree common. The clustering should thus consider both the region and relative velocity of nodes in that region. Fig. 10 shows a possible scenario for global clustering of aircraft using regional clusters.

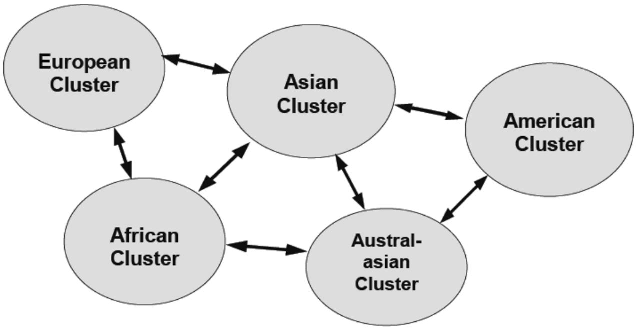

Fig. 10. Global regional clusters of commercial aircraft.

Furthermore, in additional to the major continental clusters, it is possible to form a very stable mobile backbone network

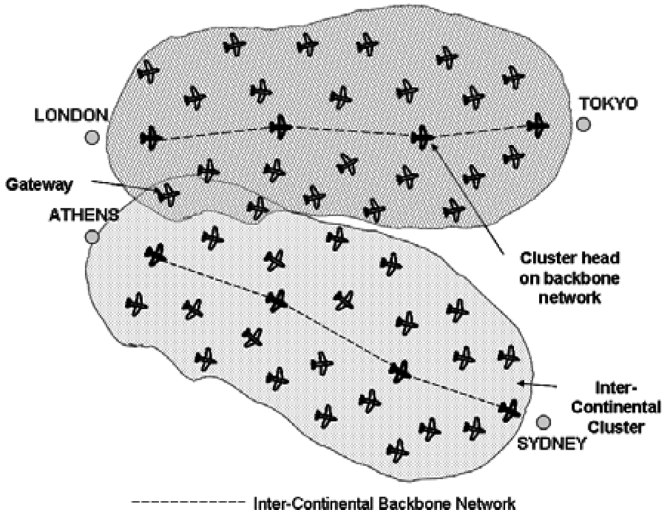

Fig. 11. Clusters and backbone networks.

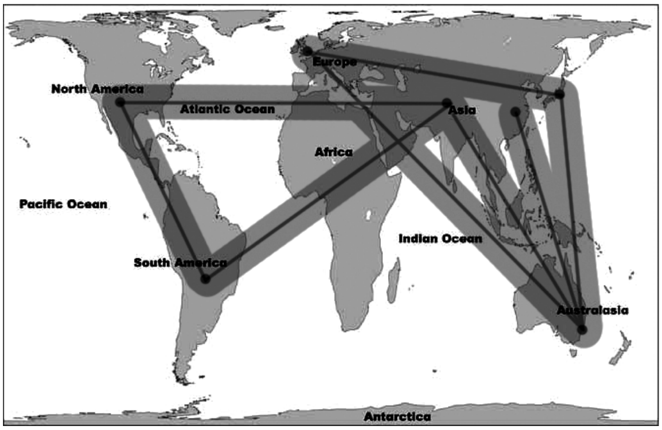

Fig. 12. Major ICB networks.

(MBN), as in Fig. 11. The backbone network is formed under the following criteria.

1) There has to be at least one Ground Internet Gateway (GIG) on the ground by which an aircraft on the backbone network can directly communicate with.
2) Each aircraft on the backbone network must be able to communicate with its next and previous backbone aircraft (on the same backbone).

The above criteria ensure that there is a direct connection to the ground segment Internet, and that there is a nonbreaking route from the beginning to the end of the backbone network. The backbone is ideally formed by selecting aircraft going from a single source airport to a single destination airport on another continent to form the intercontinental backbone (ICB). This kind of backbone forms the most stable backbone as all aircraft on this backbone path have relative velocities close to zero. The significance of this was demonstrated in Section III-B. Around each backbone an intercontinental cluster (ICC) of aircraft can be formed, with a diameter of two hops as an initial proposition. Fig. 12 shows major ICB networks that can be formed. The backbone aircraft act as *cluster heads* and are responsible for managing and providing data to their corresponding cluster members. The aircraft on the same backbone have a common *cluster id*, broadcasted in beacons.

The clustering algorithm used to form clusters around the predefined cluster heads is termed *Doppler velocity clustering* (DVC), and works in the following manner. The cluster heads (Fig. 11) periodically send beacons. Each node not part of the backbone network also sends beacons. The cluster head checks the Doppler shift of the beacons coming from neighbors and decides which neighbors can join (based on the Doppler Value) if they are not already members of the cluster. It will then send a *Join Accept* message to the corresponding node. The node can then choose to become a member of this new cluster. The node also checks the Doppler shift of beacons and *Join Accept* messages coming from the cluster heads of different backbone networks and decides the best cluster(s) to join. The node can join several clusters from which it received a *Join Accept* message, and act as a gateway between the clusters (shown in Fig. 11) for intercluster communication. It will also inform each cluster head about the clusters it is a member of; hence the cluster heads readily know their gateway nodes and the neighboring clusters they have access to. There can be a maximum number of n nodes that can join a cluster, defined by the cluster head. The cluster head will send a *Join Accept* message to the top smallest Doppler Value nodes it receives beacons from until it fills up its cluster with a maximum of n members. If there are several gateways to the same neighboring cluster, the cluster head will choose the most stable one (according to the Doppler Value) for intercluster communication. If the periodic beacons are not heard by either the cluster head or the member for a period of time, the member is considered to have left the cluster (link down) and is removed from the *members list* at the cluster head. Likewise, the member dissociates itself from the cluster and informs its other associated cluster(s) about this dissociation.

When data are updated on the backbone network, a local broadcast of the data *identifier* is performed by the cluster head to its corresponding cluster members. Hence, all member nodes of a cluster have knowledge of the data they possess or can retrieve. Hence, when a request for data is received from outside the cluster (intercluster request) the gateway node (i.e., the first node of the destined cluster which receives the request) can reply and forward the data accordingly. The proposed clustering scheme also reduces node density per cluster in physically node-dense areas, since nodes within the same geographical area do not necessarily belong to the same cluster. Consequently, geographically overlapping, however, independent mobile clusters would result. Accordingly, the cluster heads may act as mobile routers for the network mobility (NEMO) basic support implementation [34]. They can manage their corresponding mobile network (clusters), and connect it to the ground segment Internet via the GIG.

E. Multipath Doppler Routing (MUDOR)

The multipath doppler routing (MUDOR) is a reactive routing protocol that allows a remote cluster or aircraft to establish multihop routes to other data providing clusters or aircraft. This can be for intercluster communication where no direct gateways exist to neighboring clusters or for remote and sparse areas where clusters cannot be formed as nodes are not within the range of the cluster heads, and also for nodes which could not become members of any potential clusters as the clusters' size had reached its maximum capacity. Again, much like the clustering algorithm, MUDOR is based on stability of nodes using the Doppler shift of control messages. Furthermore, unlike all previous traditional reactive routing algorithms that work on disjoint path discovery by dropping identical consecutive request packets received from different nodes, MUDOR takes advantage of nondisjoint path discovery and uses it to select more stable Intermediary Nodes to form more stable paths not possible using disjoint path discovery. Route request (RREQ) packet forwarding is also limited by only forwarding *better cost* packets. There is also a maximum hopcount field in the RREQ packet header which is decremented each time the packet is forwarded. This prevents extended broadcasting throughout the entire network. The MUDOR algorithm is as follows.

Requesting Node:

Broadcast RREQ to all LOS single-hop (neighbor) nodes requesting for *id* representing the requested data.

Receiving Node (**Request-forwarding**):

```
If $\mathrm{PDV} > \mathrm{PHDV}$
        $\mathrm{PHDV} = \mathrm{PDV}$
End if
If $\mathrm{PHDV} < \mathrm{BDVSF}$
        $\mathrm{BDVSF} = \mathrm{PHDV}$
Else
        Drop RREQ
If RREQ not dropped and Node has id
        Produce RREP
Else
        Rebroadcast RREQ: $(\mathrm{hopcount} = \mathrm{hopcount} - 1)$
End if
```

Receiving Node (**Reply-forwarding**):

```
If $\mathrm{PDV} > \mathrm{PHDV}$
        $\mathrm{PHDV} = \mathrm{PDV}$
End if
If Receiving Node is Requesting Node
        Store RREP in table
Else
        Forward RREP to previous node
End if
```

Requesting Node:

Receive all replies. Arrange them in a routing table based on smallest cost (using PHDV of each packet). Select the first path as the primary path for routing. In case of path failure, choose the second path in the table. Hence, this is the multipath mechanism adopted by MUDOR.

The Packet's Doppler Value (PDV) is the cost related to the Doppler shift subjected to the whole packet as it travels from the previous node to the current node. The Packet Header Doppler Value (PHDV) is the *bottleneck* Doppler Value so far on the path. The PHDV is updated at each node, and also on the return (reply) path as part of the route reply (RREP) packet. The other is the minimum Doppler Value for the same identical RREQ stored at each (receiving) node, termed Best Doppler Value So Far (BDVSF). This is used as a discriminator for identical RREQ packets. Only RREQ packets that provide a smaller Doppler Value are forwarded, otherwise they are discarded.

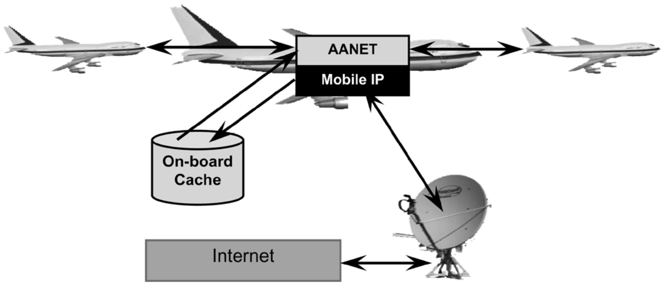

Fig. 13. AANET and Mobile IP interaction.

In addition, each node adds its own address to the packet cache addresses, like the dynamic source routing (DSR) protocol [17] before forwarding the packet. This assists in the nondisjoint path discovery, and allows the requesting node (source node) to choose the most stable path for retrieving data.

F. Mobile IP With AANET

The retrieval of information via the GIG may potentially use traditional methods and Mobile IPv6 and the extended NEMO basic support protocol [34]. Thus, it is proposed to have a composite layered approach, as shown in Fig. 13. The AANET protocol layer deals with communication between aircraft, while the Mobile IP layer is used for direct communication with the ground segment Internet. When sharable data (such as web pages, multimedia files) are downloaded onto the aircraft via the Mobile IP layer, they are cached on-board and tagged with their unique data identifier. The data may then be used by the AANET layer to share with other aircraft. The data retrieved via satellite may also be cached on the same on-board cache.

IV. SIMULATION OF CLUSTERING AND MULTIHOP ROUTING FOR INCREASING LINK DURATION

All the following simulations were developed in Java. In these simulations, the stability for both clusters and routes is investigated.

A. Clustering Formation Simulation

In this simulation, a scenario with one cluster head and 5000 nodes scattered around an area of 9,000,000 km^2 is used. The cluster radius is 300 km. The maximum cluster membership is changed for each simulation. Speed of all nodes is set to 840 km/h in a linear, direct path, with no pause time. Nodes move for a simulated period equivalent to six hours. This effectively simulates a typical flight journey in the aeronautical mobility model. Three schemes are simulated.

Scheme 1—Choose closest nodes as cluster members.

Scheme 2—Simulates the DVC algorithm.

Scheme 3—Choose nodes with latest LET as members.

In each of the schemes, nodes which are within range of the cluster head are chosen as cluster members based on the cost metric until the maximum cluster membership is reached. The cost metric for Scheme 1 is distance, for Scheme 2 is the Doppler Value, and for Scheme 3 is the inverse of LET. After the cluster members are chosen, at some stage some of the members may leave the cluster head's range (link down). In such a case, the

TABLE I
Results for Max Node Membership of Five

Scheme	Link Up	Link Down
1	18	13
2	5	0
3	5	0

TABLE II
Results for Max Node Membership of Ten

Scheme	Link Up	Link Down
1	46	36
2	15	5
3	15	5

TABLE III
Results for Max Node Membership of 20

Scheme	Link Up	Link Down
1	102	82
2	35	15
3	35	15

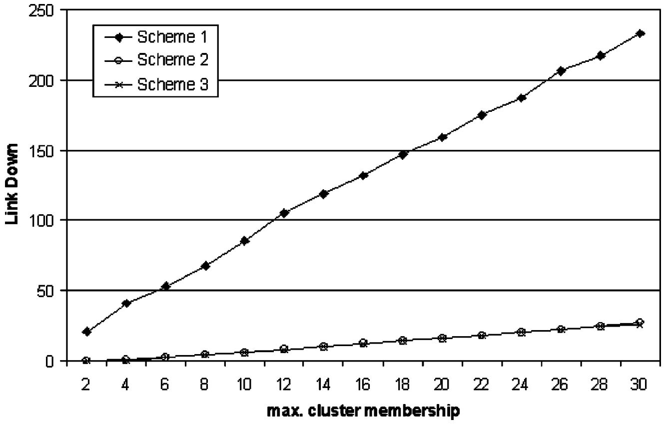

Fig. 14. Link down versus maximum cluster membership.

algorithm is repeated to add new members to make up for lost members. Nodes which are already members of the cluster, remain as members until they leave the cluster head's range.

Tables I–III demonstrate the link up (node joining cluster) and link down (node leaving cluster) for this simulation. Fig. 14 demonstrates the effect of maximum node membership on link down. The performances of Schemes 2 and 3 are extremely close (almost correlating) in this case.

Figs. 15 and 16 show the effect of node membership with variable range (in km). The results show that having smaller cluster memberships decreases the chance of link down (as fewer, but more stable nodes are selected for the cluster). The most noticeable characteristic of these results is the strong correlation between Scheme 2 (DVC) and Scheme 3 (latest LET), which implies that the velocity metric alone is sufficient for forming stable clusters. In this scenario, it can be seen that a range of 250 km and over is quite satisfactory for optimum performance.

B. Multihop Simulation

In the following simulations, we investigate the effect and significance of velocity on multihop path stability reflected in the number of handoffs (link breakages) at the end of each simulation. We simulate three schemes that choose different metrics to select stable nodes for routing, and repeat the procedure when the node leaves the range of the requesting node. The schemes are as follows.

D—Simulates shortest path (using DSR).

V—Simulates the MUDOR routing protocol.

VD—Select node with the latest LET as defined in (1).

In all schemes, there is a node which requests for some data. There exist certain percentages of aircraft (nodes) that can provide this data to the requesting node (defined by "percentage of nodes having data") scattered throughout the simulated area. The request is broadcasted to nodes within range, and in turn these nodes rebroadcast the request according to the criteria of each scheme. Several paths may be found that could provide the required data. In each scheme, the smallest cost path is chosen. The breaking of a path corresponds to a handoff and the corresponding algorithm reinitiates to select a new path. The shortest path metric for the shortest path algorithm (D) is distance. VD follows the same algorithm as MUDOR (V) but instead of the Doppler Value it uses the inverse of LET as the cost metric. In this simulation, a scenario of linear mobile nodes of various densities in a bounded area resembling 9,000,000 km^2 is used. Each node moves in a linear set direction (initial position and direction are chosen randomly) and continues to move in the same

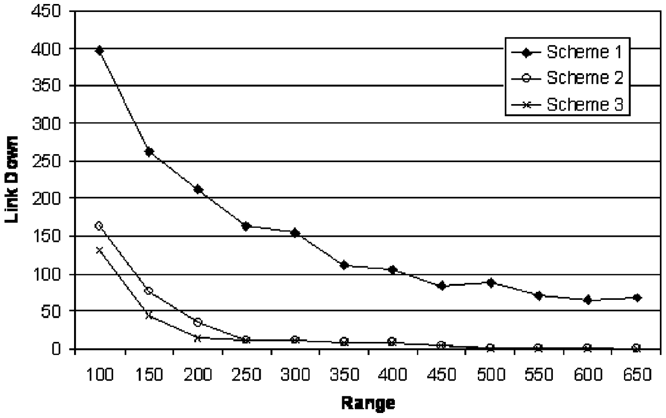

Fig. 15. Maximum cluster membership of 15.

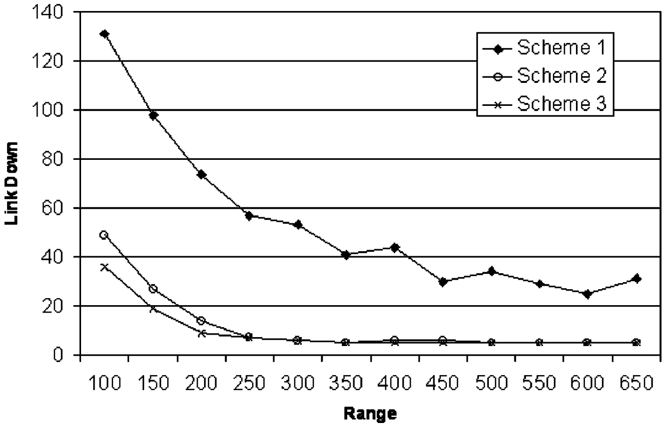

Fig. 16. Maximum cluster membership of five.

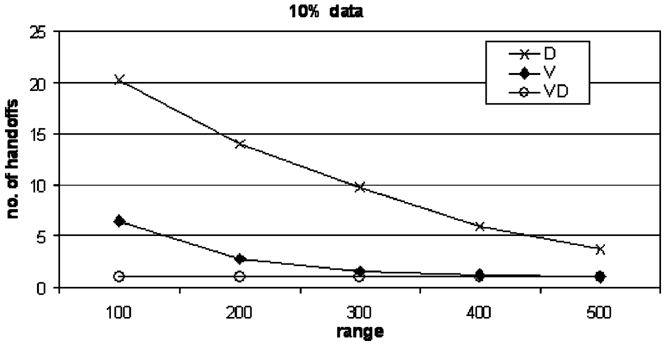

Fig. 17. Variable range for node density of 5000 and 10% data nodes.

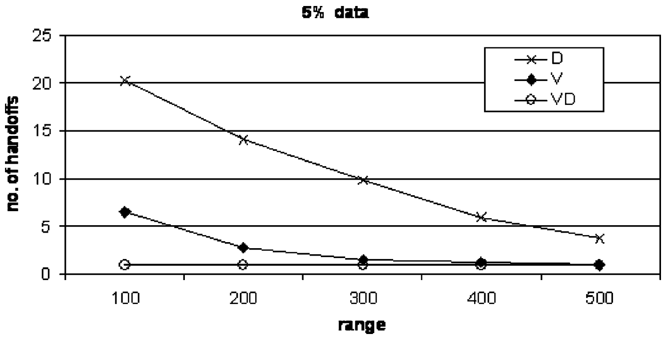

Fig. 18. Variable range, variable node density (500–6000), and 5% data nodes.

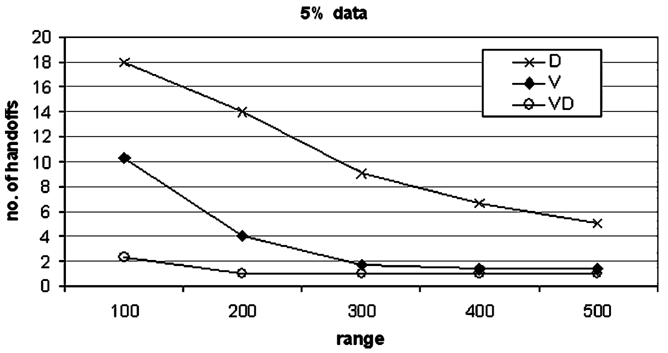

Fig. 19. Variable range for node density of 5000, 5% data nodes.

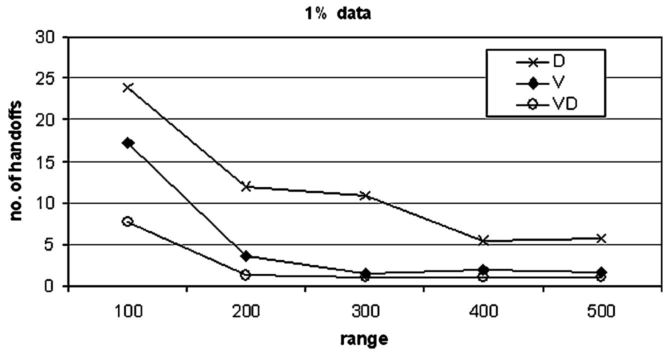

Fig. 20. Effect of velocity and LET on link stability for 1% data nodes.

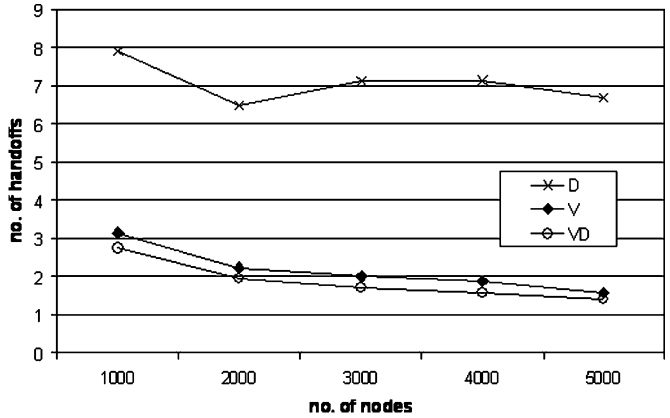

Fig. 21. The effect of node density on number of handoffs with 350 km range.

direction and with the same speed for the entire simulation period. The speed of all nodes is set to 840 km/h. Flight journeys are 3 hours and 50 minutes long. Maximum hopcount is set to 10. The primary aim is to investigate the link stability corresponding to the number of handoffs in different scenarios when aircraft density, range, and the percentage of aircraft having required data is varied. Figs. 17–20 show the number of handoffs with respect to range, considering variable percentage of aircraft having the requested data.

In this simulation, it can be seen that both MUDOR (V) and the LET scheme (VD) outperform the shortest path (D) scheme with respect to stability of routes. Also it can be seen from the above figures that for a range of 300 km and above, V and VD perform quite similarly. Velocity alone (using the Doppler Value) thus can be a very effective metric for determining the stability of links on a path for these ranges and this can simply be found using the Doppler shift of control messages as used in MUDOR. Fig. 21 shows the effect of increasing node density on number of handoffs.

Node density is increased in order to provide more optional nodes for routing. Effectively when node density increases, the probability of finding more stable neighbors also increases which results in fewer handoffs.

V. CONCLUSION

In this paper, we introduced the concept of the AANET, which may provide an effective approach for data access among commercial aircraft in order to mitigate problems associated with the current in-flight Internet access. We also proposed clustering and routing schemes that could effectively work in this new type of high-speed mobile network. The proposed schemes were simulated and the results suggest their effectiveness in the targeted network in regards to obtaining stable paths which break less frequently and also stable clusters where cluster members leave their clusters less frequently. The proposed schemes utilize the relative velocity of nodes using the Doppler shift subjected to control messages, so that stable nodes with small relative velocities can be chosen to construct stable clusters and paths in the proposed AANET. Furthermore, the stable clusters formed using the proposed clustering algorithm are ideal for the NEMO [34] implementation, where a mobile cluster is analogous to a mobile network. The demonstrated group mobility of aircraft moving together to common regions can also be used for this purpose. We have tried to reduce complexity as much as possible and provided a basic framework for the new type of network. It is believed that the concepts introduced in this paper would provide a ground work for future research in this type of network, which can be a very exciting application of ad hoc networking.

REFERENCES

[1] Connexion by Boeing. [Online]. Available: http://www.connexionby-boeing.com

[2] M. Holzbock *et al.*, "Evolution of aeronautical communications for personal and multimedia services," *IEEE Commun. Mag.*, vol. 41, no. 7, pp. 36–43, Jul. 2003.

[3] O. Ercetin, M. O. Ball, and L. Tassiulas, "Modeling study for evaluation of aeronautical broadband data requirements over satellite networks," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 41, no. 1, pp. 36–370, Jan. 2005.

[4] E. Lutz *et al.*, "Development and future applications of satellite communications," in *Proc. IEEE PIMRC*, Barcelona, Spain, Sep. 2004, pp. 2342–2346.

[5] E. Sakhaee and A. Jamalipour, "Aerouter—A graphical simulation tool for routing in aeronautical systems," in *Proc. IEEE WCNC*, New Orleans, LA, Mar. 2005, pp. 2506–2511.

[6] National Air Traffic Controllers Association (NATCA). [Online]. Available: http://www.natca.org/mediacenter/bythenumbers.msp

[7] Flight Explorer Personal Edition 5.0 [Online]. Available: http://www.flightexplorer.com.

[8] TV Link Europe [Online]. Available: http://www.tvlink.org/vnr.cfm?vidID=126.

[9] G. Aggelou, *Mobile Ad Hoc Networks: From Wireless LANs to 4G Networks*, 1st ed. New York: McGraw-Hill Professional, 2004, p. 122.

[10] S. Cho and J. P. Hayes, "Impact of mobility on connection stability in ad hoc networks," in *Proc. IEEE WCNC*, New Orleans, LA, Mar. 2005, pp. 1650–1656.

[11] F. Bai, N. Sadagapan, B. Krishnamachari, and A. Helmy, "Modeling path duration distributions in MANETs and their impact on reactive routing protocols," *IEEE J. Sel. Areas Commun.*, vol. 22, no. 7, pp. 1357–1373, Sep. 2004.

[12] N. Sadagopan, F. Bai, B. Krishnamachari, and A. Helmy, "PATHS: Analysis of path duration statistics and their impact on reactive MANET routing protocols," in *Proc. MOBIHOC*, Annapolis, MD, Jun. 2003, pp. 245–256.

[13] C. E. Perkins and P. Bhagwat, "Highly dynamic destination-sequenced distance-vector routing (DSDV) for mobile computers," in *Proc. ACM SIGCOMM*, London, U.K., Sep. 1994, pp. 234–244.

[14] S. Murthy and J. J. Garcia-Luna-Aceves, "An efficient routing protocol for wireless networks," *ACM Mobile Networks and App. J. (Special Issue on Routing in Mobile Communication Networks)*, pp. 183–197, Oct. 1996.

[15] T. Clausen *et al.*, "Optimized link state routing protocol," RFC 3626, Oct. 2003, .

[16] R. Ogier, M. Lewis, and F. Templin, Topology dissemination based on reverse path forwarding (TBRPF) RFC 3684, Feb. 2004.

[17] D. Johnson and D. Maltz, "Dynamic source routing in ad hoc wireless networks," in *Mobile Computing*, T. Imielinski and H. Korth, Eds. Norwell, MA: Kluwer, 1996, ch. 5, pp. 153–181.

[18] C. E. Perkins and E. M. Royer, "Ad hoc on-demand distance vector routing," in *Proc. IEEE WMCSA*, New Orleans, LA, Feb. 1999, pp. 90–100.

[19] V. D. Park and M. S. Corson, "A highly adaptive distributed routing algorithm for mobile wireless networks," in *Proc. IEEE INFOCOM*, Kobe, Japan, Apr. 1997, pp. 1405–1413.

[20] Z. Haas and M. Pearlman, "The performance of query control schemes for the zone routing protocol," *IEEE/ACM Trans. Netw.*, vol. 9, no. 4, pp. 427–438, 2001.

[21] C. Santivanez, R. Ramanathan, and I. Stavrakakis, "Making link-state routing scale for ad hoc networks," in *Proc. ACM MOBIHOC*, Long Beach, CA, Oct. 2001, pp. 22–32.

[22] Y. Ko and N. H. Vaidya, "Location-aided routing (LAR) in mobile ad hoc networks," in *Proc. IEEE/ACM MOBICOM*, Dallas, TX, Oct. 1998, pp. 66–75.

[23] S. Basagni, I. Chlamtac, V. R. Syrotiuk, and B. A. Woodward, "A distance routing effect algorithm for mobility (DREAM)," in *Proc. IEEE/ACM MOBICOM*, Dallas, TX, Oct. 1998, pp. 76–84.

[24] B. Karp and H. T. Kung, "GPSR: Greedy perimeter stateless routing for wireless networks," in *Proc. IEEE/ACM MOBICOM*, Boston, MA, Aug. 2000, pp. 243–254.

[25] C.-K. Toh, "Associativity-based routing for ad-hoc mobile networks," *J. Wireless Pers. Commun.*, vol. 4, no. 2, pp. 1–36, 1997.

[26] K. Xu and M. Gerla, "A heterogeneous routing protocol based on a new stable clustering scheme," in *Proc. MILCOM*, Anaheim, CA, Oct. 2002, pp. 838–843.

[27] C. R. Lin and M. Gerla, "Adaptive clustering for mobile wireless networks," *IEEE J. Sel. Areas Commun.*, vol. 15, no. 7, pp. 1265–1275, Sep. 1997.

[28] P. Basu, N. Khan, and T. D. C. Little, "A mobility based metric for clustering in mobile ad hoc networks," in *Proc. IEEE ICDCSW*, Apr. 2001, pp. 413–418.

[29] M. Holzbock, M. Werner, A. Jahn, and E. Lutz, "Future broadband communications for airliners," in *Proc. EMPS*, London, U.K., Sep. 2000, pp. 221–226.

[30] A. Nandan, S. Das, G. Pau, M. Gerla, and M. Y. Sanadidi, "Co-operative downloading in vehicular ad-hoc wireless networks," in *Proc. WONS*, St. Moritz, Switzerland, Jan. 2005, pp. 32–41.

[31] W. Su, S. J. Lee, and M. Gerla, "Mobility prediction and routing in ad hoc wireless networks," *Int. J. Netw. Manage.*, vol. 11, no. 1, pp. 3–30, Jan. 2001.

[32] P. Agrawal, D. K. Anvekar, and B. Narendran, "Optimal prioritization of handovers in mobile cellular networks," in *Proc. IEEE PIMRC*, The Hague, The Netherlands, Sep. 1994, pp. 1393–1398.

[33] D. Halliday, R. Resnick, and J. Walker, *Fundamentals of Physics*, 4th ed. New York: Wiley, 1993.

[34] V. Devarapalli, R. Wakikawa, A. Petrescu, and P. Thubert, Network mobility basic support protocol IETF, RFC 3963, Jan. 2005.

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