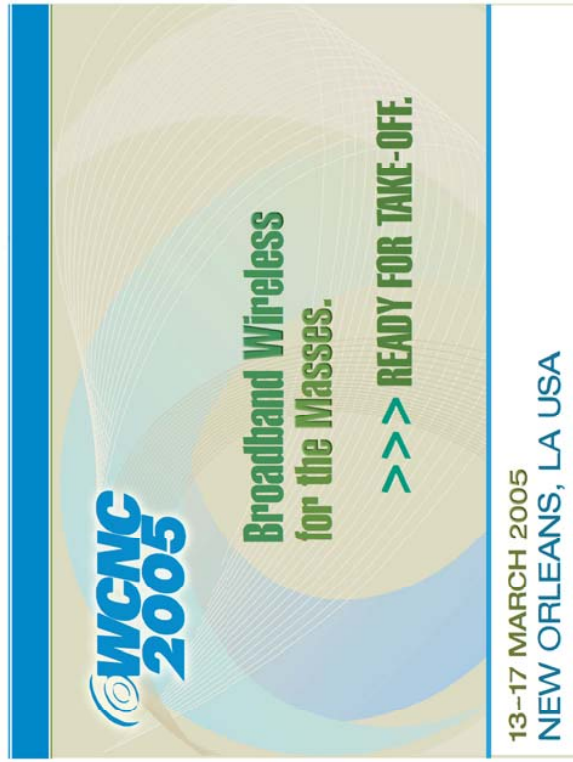


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AerouterTM - A Graphical Simulation Tool for Routing in Aeronautical Systems

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Abstract—The enormous growth and demand of in-flight Internet access has driven the need for producing effective simulation tools in order to effectively identify best resources such as satellites and gateways for routing in these large-scale systems. In this paper we will introduce a simple simulation tool called Aerouter, which can assist in identifying best satellites and gateways for routing in aeronautical applications. The proposed simulation tool will include new routing techniques as well as taking Doppler and atmospheric attenuations into account in its automatic calculations. Preliminary results illustrate the effectiveness and usefulness of Aerouter for future in-flight Internet access networks.

Index Terms —*In-flight Internet Access, aeronautical routing, routing tools, simulation tools*

I. INTRODUCTION

In recent years, there has been much advancement in providing consumers with mobile Internet technologies, spanning not only single user systems in the case of cellular technologies, but also taking us higher into the sky in the case of in-flight broadband Internet, as offered by Connexion by Boeing [1], and similar high speeds by Tenzing [2]. However there are inherent issues associated with this kind of system such as rain and atmospheric attenuation (with the use of much higher frequency bands such as the *Ku* and *Ka*), increased handoffs, and changing network topologies.

In most cases it is desirable to visually analyze such systems, and be able to change parameters in real-time whilst observing the effects of these changes. This will further simplify the task of management of these systems. Hence complexity is dramatically reduced for those responsible for managing resources in aeronautical systems. Thus, a user-friendly tool for effectively analyzing routing in aeronautical applications is essential in this fast growing industry. Resource selection is an important task for airline companies and choosing the right resources is vital when considering the high costs, and hence there is little room for errors. Leasing satellite services in particular is not cheap and there is great importance in choosing the right satellites for optimized

solutions for in-flight Internet access. By having a tool which can identify best satellites and gateways for routing in a flight route, an airline company could make better resource selections that best meet their needs. It is also a useful and effective method of selecting optimum paths that can provide the best and most cost effective Internet experience for on-board Internet users.

We have implemented the AerouterTM System, which is a simple tool that can be used for simulating such systems. AerouterTM System provides an effective way to graphically demonstrate how an aircraft routes to different satellites and gateways as it travels from its source to destination in real-time. In AerouterTM parameters can also be altered in real-time via user-input, allowing the users to see the effect of changes in these parameters, visually.

In this paper, we introduce many of the features of AerouterTM and how it can be used for simulating aeronautical routing. We will also introduce the idea of using the Doppler shift caused by high speed mobile systems such as the airplane and thresholds in producing more efficient routing, and prove their effectiveness using simple AerouterTM simulations.

II. BACKGROUND

A. Current State-of-the-Art Inflight Broadband Internet

During the past two to three years, we have seen leading airline companies begin to expand the horizons of Internet access by introducing broadband Internet inside airplanes. The technology's main basis is the use of geostationary satellite systems, and also the use of the higher frequency *Ku* band (12-18 GHz) [3, 4], which allows the possibility of achieving high speed data transfers. However, there are inherent problems with such a model, such as lag or transmission delay in using geostationary earth orbit (GEO) satellites due to their long distance (36000 km) from the earth and the atmospheric attenuation caused by using the higher frequency bands [3]. Despite these minor setbacks, in-flight Internet has been around for a few years now, and recently Lufthansa has taken the lead by being the first to commercially introduce broadband Internet on their flights using the Connexion by Boeing service [1]. Many other major airlines have signed definite agreements with Connexion by Boeing to install these technologies [1], and

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although it was initially estimated that this market would grow to around \$70 billion over the next 10 years [5], more recently this has been reduced due to the decline in air travel market, to a more revised figure of 2.5 billion by 2007, by the Northern Sky Research in October 2001 [6]. Tenzing associated with Airbus also provides solid speeds with its Swift64 services, which are expected to reach data rates of up to 432 Kbps with the use of Inmarsat 4s, and Inmarsat's Broadband Global Area Network (BGAN) planned for launch in 2005, and expected to begin services by 2006 [2, 7, 8].

B. Existing Simulation Tools

Simulation tools for satellite telecommunications systems have been developed, yet there are minor set-backs such as the need to supplement mobile systems, which rapidly change their position and hence have a changing network topology. Several simulation tools are in existence including Matlab [9], OPNET [10], and NS2 [11]. Although widely used, these simulation tools are very generic and sophisticated for non-technical people, and the need to develop a dedicated simulation software for routing in aeronautical applications is required to visually analyze their routing in real-time, supplemented by a simplified and effective interactive functionality that allows customization of routing preferences according to Quality of Service (QoS) and cost parameters. There are also several parameters, which are inherent in mobile systems, specifically linear fast-moving mobile systems such as the airplane. In order to cater for these parameters, a specialized routing simulator is required for such systems. This simulator should ideally be user-friendly and acceptable to both technical and non-technical people, who are concerned both with the commercial and technical side of aeronautical systems.

III. THE AEROUTER™ SYSTEM

The Aerouter™ System is developed in order to offer simplicity in finding better ways of routing in aeronautical and similar fast-moving linear mobile systems. Parameters can be inputted into the system in real-time and their effects visually analyzed. A standalone command based Aerouter Optimizer supplements Aerouter™ and outputs routing information onto a file, which can effectively be used to graph results, and find optimal parameters. Real information such as satellite and gateway positions and routing parameters can be inputted into this system. Furthermore, new routing parameters are introduced into this system to make aeronautical routing as efficient as possible, with high quality of service, and least number of handoffs. These parameters will be discussed throughout this paper.

The Aerouter™ system consists of two main calculative blocks: The first one finds paths and their costs, and the other block does the routing decision (choosing the best path for routing).

The Graphical User Interface (GUI) of the Aerouter™ consists of three parts: Part 1 takes user input of parameters, such as speed of airplane, threshold, time, and Doppler parameters. Part 2 consists of the graphical representation of the system, and how an aircraft (or mobile system) is moving

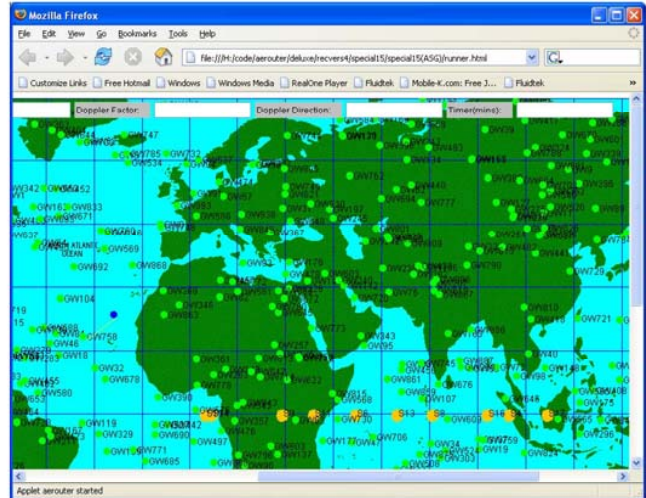


Figure 1. The Aerouter™ GUI.

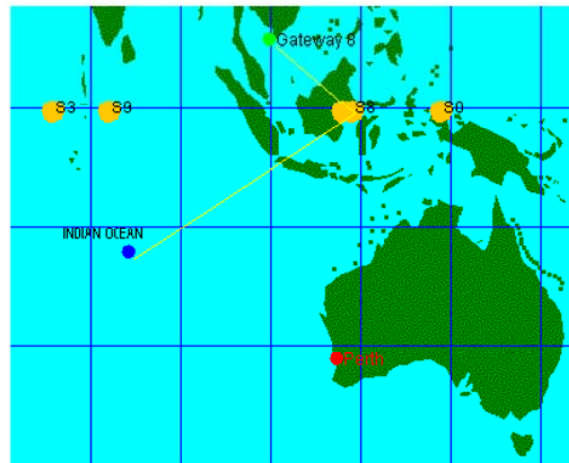


Figure 2. An Example of Routing in Aerouter™.



Figure 3. Aerouter™ Routing Information.

and routing. It shows how the aircraft routes as it moves from its source to its destination from a “birds-eye” perspective, and simulates the way the aircraft would route to satellites and gateways in reality. Part 3 is an interface showing routing information such as number of handoffs, average link cost, and other routing values in real-time. Figures 1, 2 and 3 demonstrate these features, respectively.

During the course of the simulation, the user can change routing parameters such as the threshold, speed of aircraft, and visually see its effect on the total system. In order to find the optimal routing parameters, one can use the Aerouter™ Optimizer, which is the command based counterpart simulator to Aerouter™ that runs the simulation with variable parameters, and outputs the routing results onto a file. The optimal values can be extracted from these files and tested using the Aerouter™. The Aerouter™ provides means for sanity checking the results obtained from the Aerouter™ Optimizer, visually. The Aerouter Optimizer provides a fast way of obtaining results, by simulating the scenario with different parameters and rapidly outputting them onto a file, without the need of visually checking it (this will be done in the Aerouter™).

All the routing parameters and positions (in latitude/longitude format) for all satellites and gateways are read from files (or databases). Information about the source and destination of flight is also obtained in a similar fashion. In future versions of Aerouter™, live weather information could also be inputted into the system in order to cater for atmospheric and rain attenuations, which are especially significant in the case of using broadband, as higher frequencies are used.

For the first analysis, we will consider the *link cost*, which is a measure of the quality of the link, affected by such things as distance (medium path loss [12]), attenuation and congestion in the network, and other static and variable QoS and cost-related parameters related to the link and the nodes (satellites and gateways). For the initial calculation we associate link cost with QoS for simplicity.

For initial calculations, we calculate link costs using a single mixed metric (SMM), calculated from the weighted sum of the QoS and cost related parameters for the link as shown in (1), where w_i is the weight of the i th normalized parameter p_i , and n is the total number of parameters in the link cost. The weight w_i represents how important parameter p_i is to our routing. We make an assumption that the link cost is proportional to the inverse of link quality. Hence as the link quality deteriorates, the link cost increases. This assists in performing QoS routing [13, 14, 15] with respect to link cost as a single mixed metric, which reduces the complexity by avoiding the use of multiple metrics in our routing.

$$Link\ Cost = \sum_{i=0}^n w_i \cdot p_i \quad (1)$$

In the real scenario the link quality is measured as the QoS parameters related to the link. This is specified by the on-board application, since different applications have different level of QoS needs. For example some applications are delay sensitive

whilst others are bandwidth sensitive. In Aerouter we consider several parameters which can be defined by the network administrator. Aerouter™ will use a normalized value between 0 and 1 for each of the cost parameters. Additionally we can incorporate random attenuation to cater for atmospheric attenuations (e.g. rain), and distance related parameters such as power and delay. Effectively fixed and variable QoS and cost parameters are used to determine link quality and link cost. Some of the parameters that can affect the link cost (again this is application specific) are but not limited to bandwidth, delay, delay jitter, power, security, and attenuation parameters. We will deal with these parameters in future simulations.

A. Routing Algorithm

There are many routing algorithms that are used for both static and dynamic systems; more suitably are QoS routing algorithms, which supplement mobile and ad-hoc systems [16]. However we devise a unique algorithm suitable for mobile routing, specifically for use with airplanes using the satellite system to route to ground stations.

We explain the nature of the routing algorithm as it could be used in a real system, and how the Aerouter™ System adapts this algorithm. For our example we will look at how an aircraft routes to ground stations using satellites in a real world scenario. The nodes sending the “hello” message become the *parent* of the receiving nodes. Thus the *child* node of the previous parent node yet becomes the parent of the next set of nodes. The routing algorithm works as follows:

- 1) *The Airplane (Master Parent) sends a hello message to all nodes within the line-of-sight(LOS)*
- 2) *The nodes do the same if they are satellites*
- 3) *If the node is a gateway(child) it will produce a reply*
- 4) *The (parent) node that receives the replies works out the link cost for all the replies, and evaluates the best replying (child) node*
- 5) *It will then send this detail along with the received hello from the previous node back to the previous (parent) node*
- 6) *This continues until the original node receives the replies within a predefined time*

In the Aerouter™ System, a recursive route discovery algorithm is devised which allows the aircraft to either directly communicate to gateways on ground, or through satellite to gateway. This is an effective extension to the existing aeronautical architecture which only consists of aircraft – satellite – gateway links. By allowing the airplane to directly communicate to ground stations, we can decrease delay for delay sensitive applications, and reduce satellite service costs at some instances. The routing algorithm adapted in Aerouter™ does not exchange messages (conserving time), since this is happening at a much smaller scale. The algorithm finds all existing paths and sorts them according to their link cost as defined in (1).

New routing decisions need to be made in the case when:

- 1) A direct neighbor node goes out of line of sight

- 2) The threshold value is compromised
- 3) When a node fails.

Each time one of the above cases becomes true, a new routing decision needs to be made, where a new path is chosen.

B. Threshold

Threshold is our first introduced parameter that will assist in reducing the number of handoffs, at the price of reduced average link quality. The threshold value is directly related to the link cost (and link quality). The higher the threshold value, the more relaxed the link cost (and QoS) constraint. A smaller threshold value puts a higher constraint on link cost and thus the smaller the link cost needs to be to satisfy QoS/cost requirements.

A new routing decision is made once the threshold is compromised (i.e. once the link quality goes below the threshold value). In Aerouter™ this corresponds to a link cost going above the threshold value, for our initial assumptions. Figure 4 illustrates this idea. It is important to note that if the threshold value is met, it is the *single-mixed metric* QoS requirement that is met. The fewer the number of parameters in the single mixed metric, the more likely each individual parameter constraint will be met. We will investigate this in future simulations.

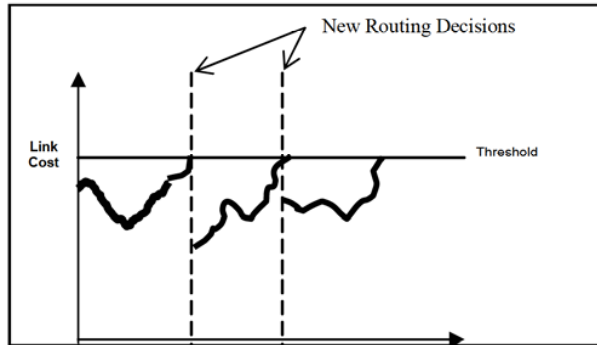


Figure 4: Routing using thresholds.

Currently, the Aerouter™ works on a single threshold basis. However in the future we will introduce the concept of *temporal hysteresis*, which allows a time t for the link quality to be below a threshold, before it makes a new routing decision. We also introduce another threshold: the *critical threshold*.

Temporal Hysteresis is a scheme proposed to avoid unnecessary handoffs caused by temporary link degradation such as brief obstacles (e.g. buildings), brief attenuations (e.g. cloud patches), shadowing and diffraction [17], and similar degradation caused by aircraft maneuvers. This scheme becomes very effective when we introduce the use of non-GEO satellite systems in the Aerouter™ System, which require more frequent handoffs.

The Critical Threshold, on the other hand, would cause a routing decision be made instantaneously once it is compromised. This threshold is below the temporal threshold.

C. A New Paradigm – Using the Doppler Factor in Routing

The Doppler Factor is introduced to further produce efficient routing by reducing the total number of handoffs during a flight journey. By introducing the Doppler factor into our system, an airplane (or a mobile system) would be able to route to nodes it is approaching rather than nodes it is receding from. Nodes having higher Doppler factors are approaching the aircraft, whilst nodes receding have larger negative Doppler factors. Approaching nodes are within Line-Of-Sight of the airplane for a longer period of time. Consequently, the time taken for the next handoff is increased, and effectively the total number of handoffs during the whole journey is decreased. As explained in [17], the Doppler Effect is particularly noticeable in aeronautical systems, due to their high speeds.

The Doppler shift is the apparent change in the frequency of a (electromagnetic) signal caused by the relative motion of the transmitter and receiver. This property has many uses in real-world applications ranging from astronomy (Red Shift) to its use by police in determining how fast a car is moving [18]; and now its use in routing is introduced.

Equation (2) and (3) are adapted from [17] for this approach. The Doppler shift frequency is calculated in hertz. V_d is the Doppler velocity, c is the speed of light (3.0×10^8 m/s) and the carrier frequency is taken as 20 GHz.

$$f_{doppler} = \frac{v_d}{c} \cdot f_{carrier} \quad (2)$$

$$v_d = \frac{v_z \cdot [r_p - r_s \cdot \cos \alpha \cdot \cos \beta] - v_{lat} \cdot [r_s \cdot \sin \beta] - v_{long} \cdot [r_s \cdot \cos \beta \cdot \sin \alpha]}{\sqrt{r_p^2 - 2 \cos \alpha \cdot \cos \beta \cdot r_p \cdot r_s + r_s^2}} \quad (3)$$

r_s : Radius of the satellite orbit (42000km)

r_p : Radius of airplane (from centre of earth)

α : Latitude of airplane

β : Longitude difference

v_z : Vertical velocity of the airplane

v_{lat} : Airplane velocity in latitude direction

v_{long} : Airplane velocity in longitude direction

We further see the effect of using the Doppler factor in routing in Figure 5. The thick black line represents the direct path of the aircraft. In Figure 5, assume all satellites meet the threshold value (QoS/cost constraint); however Satellite 2 provides a slightly better link cost than Satellite 3. For the first case of Figure 5, at the initial position of aircraft, the aircraft first routes to Satellite 1 until it reaches position A where Satellite 1 is either out of line-of-sight of the airplane or the threshold value is compromised. At this point the aircraft can either route to Satellite 2 or Satellite 3. If the Doppler factors of the satellites are not considered, the aircraft would route to Satellite 2, since it provides a smaller link cost. However at point B, Satellite 2 would go out of line-of-sight, and thus a

new handoff must take place, to Satellite 3. Ultimately there are 2 handoffs for the first case. Had the aircraft used the Doppler factors of the satellites, it could have routed to Satellite 3 at position A, reducing the number of handoffs to one, as shown in the second case of Figure 5. Of course, the link quality may (or may not) have been reduced. However if the threshold (QoS/cost) is met in both scenarios, the Doppler scenario would be superior as it provides a better routing scheme by reducing the number of handoffs. We will investigate the use of the Doppler factors in more detail in the simulations of Section IV.

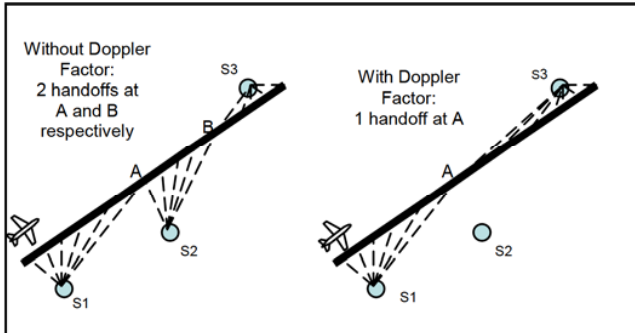


Figure 5. The effect of using Doppler parameters in routing.

In the real-world scenario, the Doppler factor can be calculated using radio signals sent and received from the aircraft and the satellites (during data transmission and reception or in a form of beacons). By comparing the expected frequency and the actual frequency of the signal, the Doppler factor can be calculated. The larger the (positive) Doppler factor, the closer the approaching node is to the direct path of aircraft (assuming a straight path); hence the longer the period of time the node remains within line-of-sight (LOS) of aircraft. The great thing about this new application is that no new hardware technology is necessary to be implemented. By utilizing the technology already on-board, a more efficient routing can be achieved.

IV. AEROUTER SIMULATION: DOPPLER & THRESHOLD PARAMETER FOR ROUTING

In our first attempt of demonstrating the effect of Doppler factor and showing how the Aerouter™ simulator works, we will run a simulation involving the threshold variable and the Doppler factors relating to the nodes within LOS of the aircraft and investigate the effect it has on the number of handoffs during the flight. The threshold value is directly related to the cost and QoS constraint. However at the same time it will define how much the Doppler factor affects which nodes are chosen. As the threshold value approaches zero, the QoS requirements approach infinity, thus the smallest cost links are selected for routing without regard to looking at the Doppler factors. As the threshold value increases, the QoS requirements are relaxed and the route selection will begin looking at all nodes and links satisfying the threshold (QoS/cost) value and selecting the one with the largest

positive Doppler factor for routing. Hence we have met our QoS/cost constraints, whilst selecting nodes which will be within LOS for a greater period of time. Effectively this should reduce the total number of handoffs for the journey. We consider a return trip journey between two destinations: namely Melbourne to New York, with randomly generated GEO satellites and gateways (Actual position of all satellites and gateways are not yet known but will be used in future calculations, however for the purpose of demonstrating Doppler routing, actual position of nodes is deemed unnecessary). For our initial simulations we will consider only bandwidth as our QoS parameter, and assume zero attenuation and zero weight for other parameters in (1), whilst setting the weight for bandwidth to one. Effectively this can be a routing scheme for bandwidth sensitive applications. We assume that each selected link provides a constant level of bandwidth.

To further demonstrate the effect of Doppler, we need to create a scenario where frequent handoffs are necessary. This could be smaller satellite spot beams, or frequent compromises of threshold (due to link QoS degradation), where new paths need to be discovered on a frequent basis. However in this simulation QoS is not degraded, as we assume each link will provide a constant bandwidth. Thus the only time handoffs could occur in this scenario is when a node goes out of LOS (we assume no node failure). In order to supplement frequent handoffs in this simulation we will make the primary means of communication, aircraft to ground station, since ground stations would only stay within line-of-sight of aircraft for a short period of time. At the edge of line-of-sight of aircraft-to-ground station, a new handoff must take place. The aircraft will look first for available ground stations which may exist within LOS. If there are no ground stations in sight, the aircraft will proceed to use the satellite system.

We note that this is a bandwidth routing scheme, such that in any case, either the best bandwidth path is chosen (in the case of using close-to-zero threshold) or the “best” (Doppler-bandwidth combination) path that satisfies the threshold (QoS/cost) is chosen in the simulation.

We note that a threshold value of zero (infinite QoS requirement) would correspond to finding the best bandwidth path regardless of the Doppler factors, and as the threshold value increases (i.e. link cost and QoS constraints are relaxed), the Doppler factors of nodes become more dominant.

The bandwidth (QoS) requirement for the link would simply be the inverse of the threshold. We will analyze the average bandwidth of the whole journey with regard to the QoS constraint bandwidth. It is important to note that at any one time, there may be no nodes satisfying the required bandwidth constraint, in which case the smallest cost bandwidth (largest bandwidth) path is selected.

V. NUMERICAL RESULTS AND DISCUSSIONS

The simulation results are shown in Figure 6 and Table I. . . As shown in the graph, the smaller threshold values (corresponding to very high bandwidth requirements) yield

greater number of handoffs. However when the threshold is increased and QoS requirements relaxed, fewer numbers of handoffs occur. This can be explained as at the lower threshold values, the path selection is restricted by the high level of QoS requirement, and hence there are fewer options of selecting nodes with higher Doppler factors that also meet the QoS requirement. Table I further supports this statement. We note that these values are strictly relative values. Actual bandwidth requirements depend on application.

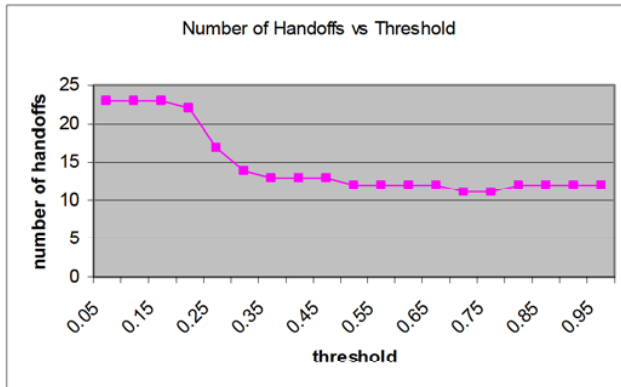


Figure 6. number of handoffs vs. threshold.

TABLE I. SAMPLE SIMULATION RESULTS

Thresh	Routing Information			
	Bandwidth (BW) Requirement	Av. BW	No. of Handoffs	Av. Link Cost
0.2	5	6.06	22	0.18
0.25	4	5.77	17	0.19
0.5	2	3.82	12	0.31
0.7	1.43	2.10	11	0.52

VI. CONCLUSIONS AND FUTURE WORKS

From the simulation results, we can see that by introducing the Doppler factor into routing decision, we reduce the number of handoffs, at the price of slightly lowering the link quality (in this case bandwidth). By increasing the threshold, we relax the QoS constraint, and allow more optional nodes for routing, hence when using the Doppler factor, nodes that both satisfy the minimum constraint and have larger Doppler factors are selected for routing, and since these nodes are within LOS for a greater period of time, the total number of handoffs during the whole journey is reduced.

The Aerouter™ System is still a very young system, and there are many improvements that need to be incorporated. In the near future we will further implement new parameters and rectify existing functions to better resemble as much as possible the real-world scenario. Attenuation parameters, both random, and weather attenuation parameters will be implemented in future versions of Aerouter™ System. Also the concept of ad-hoc networking between aircrafts, as a means of sharing cached data, and support for non-GEO satellite systems is currently being implemented in the Aerouter™ System.

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