Using Real World Data to Create OPNET Models DRAFT

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Abstract

The future airborne network needs to provide routing, transport protocols and quality of service over radio links which will experience periodic outages due to line of sight occlusion caused by aircraft's wings and tail. To create and test the performance of protocols under these conditions it is necessary to correctly model the outages resulting from aircraft occlusion. We extended OPNET to model this phenomenon and compared our results to connectivity status data from a Joint Expeditionary Force Exercise in 2002, (JEFX 02.)

We extended the OPNET models so the pointing direction of an antenna affixed to a moving aircraft could be determined in 3D space. This pointing direction can be used with an appropriate antenna pattern to determine the antenna gain in the direction of the destination. To verify the accuracy of our modifications, we modeled the Paul Revere aircraft experiment during JEFX02. Measurements of air-to-ground connectivity in our OPNET simulations of this JEFX experiment show a strong correlation to the recorded air-to-ground connectivity in the actual JEFX experiment.

1. Introduction

Over the years, software development has responded to the increasing growth of wireless connectivity in developing network enabled software. In the past, software development was performed in a lab environment over a wired 10/100 Mbps Ethernet connection. Developers now realize that software can not always assume there is a guaranteed link with minimal delay. Losing a link temporarily could have significant performance effects on transport and routing protocols. In an Airborne Network environment where aircraft communicate via radio links with one another and also to the ground, it is possible to lose link connectivity due to antenna occlusion. As the Department of Defense (DoD begins to move IP traffic from a strictly wired environment into a wireless environment and begins to introduce aircraft to an IP based network, consideration needs to be taken as to the effects of lost link connectivity.

The question of how applications, transport and routing protocols will react to a temporarily lost link or dropped transport connections needs to be addressed. Simulation software, such as OPNET, can be used to research these issues in a controlled environment. However, simulation packages do not provide all necessary details of wireless links, particularly those of airborne military radios. The focus of this paper is to describe enhancements we added to OPNET to correctly model wireless connections of aircraft platforms and our use of JEFX '02 live fly data to verify the performance of our enhancements.

In Section 2, we present background information on OPNET followed by descriptions of our OPNET enhancements to model wireless radio links on aircraft in Section 3. Section 4 describes the JEFX02 data used to verify our model with verification results in Section 5. Section 6 summarizes our work and areas of future research.

2. OPNET Background

OPNET Modeler is one of the leading network and modeling simulation programs allowing users to model both wired and wireless communication systems. Two wireless models have been added in recent years, one that is based on 802.11 wireless nodes with omni directional antennas and a more generic wireless model that does not incorporate the 802.11 based MAC layer. Users can customize the wireless model for their specific purpose by setting numerous attributes such as the modulation scheme, data rate, bandwidth, center frequency as well as antenna patterns.

To model airborne network connections, we examined OPNET's 802.11 and default radio (dra_*) wireless node models. We chose to base our model on the 802.11 model, but modified the MAC layer and many of the pipeline stages to better meet our needs.

The transceiver pipeline stages, shown in Figure 1, are a series of software blocks that perform all the wireless physical layer operations. Stages 1–5 are the transmitter pipeline stages and stages 6-13 are the receiver pipeline stages. Each stage is simply a piece of software that can be substituted or modified as desired.

OPNET's mobility modeling does not support node mobility with six degrees of freedom. Versions 10.5 and earlier provide

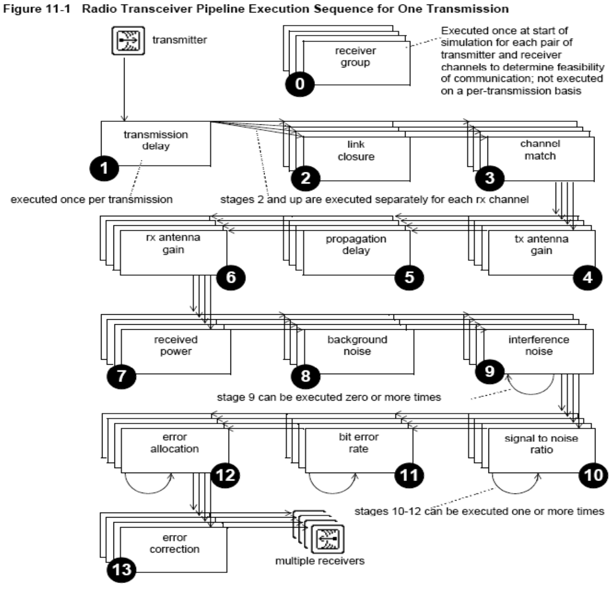

Figure 1. OPNET Transceiver Pipeline Stages [1]

mobile node position in three degrees of freedom: latitude, longitude, and altitude. In Version 11.0, OPNET includes three additional degrees of freedom, i.e. roll, pitch, and yaw. However the standard OPNET pipeline stages do not take advantage of these new variables.

3. OPNET Enhancements

The "Enhanced Antenna Positioning" model, a user supplied model available from OPNET's website [2], served as a starting point for our changes. This model includes all six variables needed to describe aircraft position: latitude, longitude, altitude, yaw (bearing), pitch (angle of ascent), and roll (rotation angle) in the Node Positioning Value attribute. In addition, the model incorporates Antenna Positioning Values, specifically pointing directional bearing (theta), horizontal angle (phi), and rotation angle describing the attitude of the antenna mounted on the node. The model also includes modified receive and transmit antenna gain pipeline stages that utilize these new variables to describe the motion of an antenna mounted to an aircraft in flight.

As we examined this model, we identified additional features that we needed to incorporate. Our plan to validate our model against actual flight data required a method of reading positional data from a file rather than entering Antenna Positioning Values manually. We modified the model by creating a process model that preprocesses aircraft attitude information to create a generic data file (gdf) containing the Antenna Positioning Values. During testing, we discovered that the calculation of rotation in the Enhanced Antenna Positioning model was valid only in cases where the antenna and the aircraft pointed in the same direction. Since this would not necessarily be the case in our flight scenario, we modified the calculations to support antenna and aircraft in different positions.

Areas that were addressed in our modifications to support modeling airborne nodes and their communications systems include:

1. Development of software to pre-process the flight path files to generate an OPNET trajectory file (*.trj) and the corresponding gdf file, to control the aircraft's attitude.
2. Development of a process model that generates a rounded rectangle flight path.
    a. controls the bearing, pitch, and roll of an aircraft when a trajectory is defined.
    b. generates rounded rectangle air paths if no trajectory is defined.
3. Modification of the facing calculation to address data variability in flight path files.
4. Modification of antenna pointing calculations.

Details of these modifications are presented in the sections that follow.

Movement Module

The movement process model is responsible for setting the node's roll, pitch and facing throughout the simulation run, and depending upon the movement required, may also determine the node's location. Currently, the module may operate in one of two modes, rounded rectangle or trajectory.

When in rounded rectangle mode the node follows a user defined rounded rectangle track pattern centered around the node's latitude, longitude and altitude. Users may set the tracks length, width, corner radius, starting location on the track, movement direction, velocity, and track rotation about the center point. The model stores this information and uses it to determine the node's position, facing and roll angle when needed. When the node is located in one of the corners, as defined by the corner radius, the bank is currently fixed at 30 degrees. Future improvements could incorporate aircraft performance measurements as defined by the FPM Group [X].

If the node is assigned a trajectory, it moves according to the trajectory file and requires a corresponding gdf file to define the node's attitude. The node changes its roll, pitch and facing according to the corresponding gdf file. The gdf file contains a list of time, facing, pitch, and roll entries which are imported as a time ordered list. The first entry is removed from the list and used to set the node's initial "Node Positioning Value." The "Node Positioning Value" attribute is described in the next section. The time value of the next entry is read, and a self interrupt is scheduled. The process then blocks until the self interrupt arrives. During simulation execution when the self interrupt is received the head of the attitude list is removed and the "Antenna Positioning Value" is updated. The self interrupt is then set to the next time entry.

Incorporating Attitude Information in the Antenna Model

The "Enhanced Antenna Positioning" model extends the antenna module's base attributes by adding a compound value, "Antenna Positioning Values." This attribute consists of rows, each specifying a time, pointing directional bearing, pointing vertical angle and rotation angle. These values represent the attitude of the node and each row is valid from the specified time until the next row's specified time. The pointing vertical angle(pitch) and rotation angle(roll) were read from the flight path attitude file and the pointing directional bearing was calculated as described in the next section.

The "Enhanced Antenna Positioning" solution allows for changes in attitude by manually creating entries in the Antenna Positioning Values for each attitude change. Since our simulation verification was based on flight path files that involved a large number of attitude changes, we modified this solution by creating a process model that would preprocess an external attitude file to create an "Antenna Positioning Values" gdf file that would then be read as the simulation progressed. This solution is backwards compatible with the "Enhanced Antenna Positioning" module and is included in our model as the "Movement Module."

Aircraft attitude information is often reported in terms of roll, pitch, and yaw. Facing is a combination of the node's yaw and geospatial facing. Facing was calculated using the latitude and longitude from the ephemeris file and the yaw value from the attitude file. The formula used to determine the node's facing is:

$$F = \arctan(x_{n+1}-x_n, y_{n+1}-y_n) + \text{yaw}_n$$

Where:

x_{n+1} is the next longitude position

x_n is the current longitude
y_{n+1} is the next latitude position
y_n is the current latitude
yaw_n is the aircraft rotation around its z axis.

We found a problem in using this formula when using external flight path files. This issue is discussed in Section 4.

Pointing Direction Calculations

During the receiver and transmitter antenna gain radio pipeline stages, the pointing direction of the antenna is needed. The antenna's pointing direction is a function of the antenna pattern's bore sight, where the antenna is mounted on the node, and the latitude, longitude, altitude, roll, pitch and facing of the node. This is true for both the receiver and transmitter, therefore the changes in the receiver and transmitter pipeline stages are identical.

Our method of calculating pointing direction fixes the antenna to the aircraft. As the aircraft changes attitude and position, so does the pointing direction of the antenna. The vector that identifies this pointing position defines the azimuth and elevation angles that map to an antenna gain in the antenna pattern. Identification of this vector is explained in the following paragraphs.

The antenna gain pipeline stages were modified to make use of the node's attitude information. First, the antenna mount and pointing direction attributes are read from the antenna module. Each value, antenna mount and pointing direction, is stored as three angles; phi, theta and rotation (ϕ, θ, ψ) [i]. The antenna mount values are used to create two vectors, one for the direction of the antenna mounted on the platform, and the other for the "up" value of the antenna's bore sight.

The two vectors are then modified by the node's facing, pitch and roll. The facing, pitch and roll are described as three angles, each representing the degree of rotation around the Z axis, Y axis and node's axis. Quaternion rotations are used to rotate the antenna vectors around the node's axis. The order of the rotations is Z, Y and node's axis, as specified in the attitude file's header. Quaternions are specified as a vector (x, y, z) with a rotation value, w, which is the rotation around the vector. For more information about quaternion mathematics see [3].

Once the antenna vectors have been modified, the antenna's actual pointing direction in the simulation's 3D space is known. The antenna's pointing direction is used to determine the antenna gain from the antenna pattern.

4. JEFX '02 Live Fly Data

To validate our model enhancements, we compared OPNET calculations of connectivity to a JEFX'02 flight. To incorporate a scenario of the JEFX'02 Paul Revere flight, it was necessary to develop OPNET node models that represent the Paul Revere and the ground station. Representative TCDL radio models were also created as well as representative ping traffic demand.

Data that was captured during JEFX'02 by the Paul Revere aircraft was used to create OPNET's Paul Revere trajectory. Navigation history was collected during the Paul Revere's JEFX '02 flight and used to create flight path files, specifically attitude and ephemeris files, that describe the node's latitude, longitude, altitude, yaw, pitch and roll for each second of the flight. The attitude and ephemeris files were provided to us by MIT Lincoln Laboratories.

These two files were used to create an OPNET trajectory file (version 2) and an attitude generic data format file. As described previously, the gdf file format is a list of time, facing, vertical incline and roll of the node. The vertical incline (pitch) and banking angle (roll) are read from the attitude file. The facing was calculated as described in the previous section. However in calculating facing from airpath flight information, we noted some wild results with the aircraft sometimes making ninety degree turns in under a second. We traced the problem to artifacts in the data, probably due to GPS errors, or side slipping of the aircraft. Due to these artifacts in the latitude-longitude data, the next position of longitude, x_{n+1}, and the next position of latitude, y_{n+1}, used to determine the facing of the aircraft were replaced with the average of the next five seconds position data so that data variations were smoothed out.

During the Paul Revere's flight, measurements were taken of the connectivity from the aircraft to the ground station via a Tactical Common Data Link (TCDL). Connectivity was measured by sending a 16 byte ping packet from the Paul Revere to the ground station every second over the TCDL link and the ping replies were recorded as a measure of link availability. Later we compare the Paul Revere's ping replies to results produced by OPNET.

Received power in the OPNET simulation was calculated using the antenna pattern values and free space path loss ($PL = \lambda^2/(16\pi^2 \times \text{dist}^2)$). The antenna pointing direction identified the (azimuth, elevation) position of the antenna. This position mapped to an antenna gain value in the antenna pattern and was used in the formula for received power below.

A screen shot of the OPNET scenario that models the Paul Revere's flight during JEFX '02 is shown in Figure 2. The scenario consists of two nodes; a ground station and the Paul Revere aircraft (shown overlapping in Figure 2), along with the aircraft trajectory (shown in dark green in Figure 2). A radio model was developed to simulate the performance of the TCDL radios used during the tests. The IP attributes of the data to be sent over the radio model were configured to match the ping packets sent during the JEFX '02 flight.

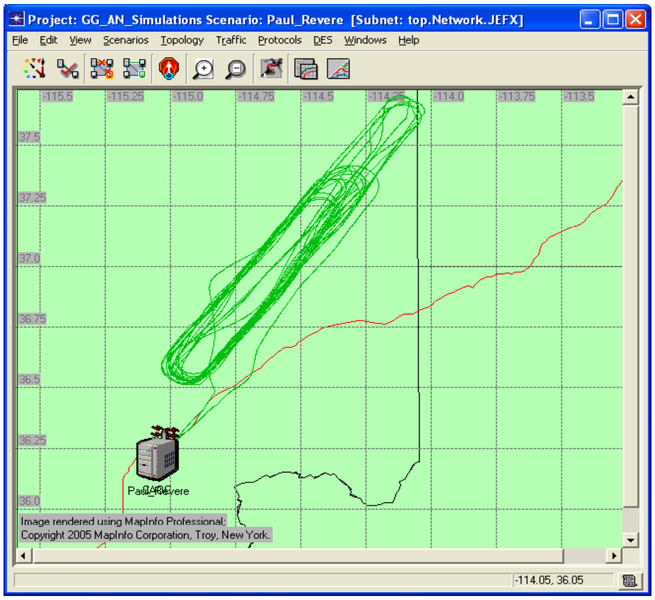

Image rendered using MapInfo Professional; Copyright 2005 MapInfo Corporation, Troy, New York.

Figure 2. OPNET scenario of JEFX'02 Paul Revere flight

A Common Data Link (CDL) antenna pattern mounted on the top of a 767 was available to use in our OPNET scenario. This antenna pattern is similar to that of the TCDL but is not precise. This is a source of error in our simulation results, however, work is in progress to create more accurate antenna patterns.

5. Validation Results

Model validation was performed at each stage of the development. First the advanced antenna positioning module was corrected and tested. Then the movement module was created and tested. Testing of these modules involved the use of custom antenna patterns, such as a half moon or narrow cone. The source and destination were positioned so that it was clearly apparent whether connectivity could be established between them.

The changes to the radio pipeline stages were tested by creating an antenna pattern with a narrow beam width. The node was then subjected to a battery of tests that changed its roll, pitch, yaw, mounting direction of antenna, facing, latitude, longitude and altitude. For each test the final vector of the antenna’s bore sight was known and confirmed to be correct.

Received power at the destination was calculated during the run of the OPNET scenario. Hand calculations of the received power confirmed the OPNET values. These values were compared to the connectivity measured by ping packets from the Paul Revere to the ground station during the exercise. Both sets of data are graphed in Figure 3.

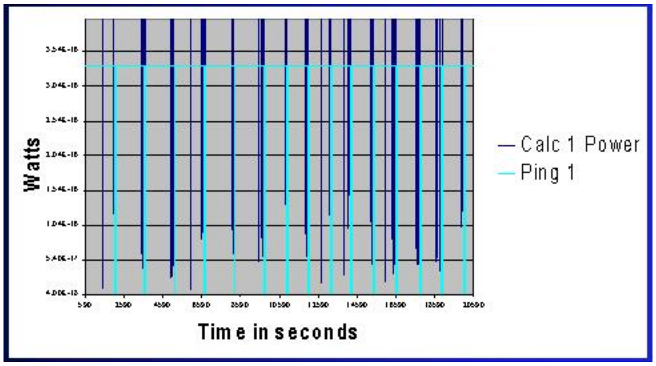

Figure 3. OPNET Received Power and JEFX'02 Flight Connectivity Data

The graph demonstrates the strong correlation between decreased received power values and lack of connectivity measured by pings. There are some instances in the simulation of decreased received power that do not match a lack of connectivity in the flight. These anomalies may be the result of an imprecise antenna pattern and are motivating efforts to acquire the correct antenna pattern for the TCDL on the Paul Revere. The antenna pattern that was available to us was an approximation of the TCDL antenna pattern and in addition, was not derived for a 707 platform.

6. Summary and Continuing Work

We have enhanced OPNET models to provide a means of evaluating communications connectivity in flight. We have created a movement module that incorporates actual flight position data into an OPNET scenario. We have verified the antenna pointing direction modifications. These modifications provide a means of measuring antenna occlusion during banking and the resultant interruption in radio connectivity. Preliminary validation of OPNET connectivity measurements to the connectivity measurements of an actual flight show a good correlation. Future validation with the incorporation of an accurate TCDL antenna pattern in correct positions on a Paul Revere 707 platform should address the inconsistencies seen in the connectivity comparisons.

In addition to efforts to validate against more precise antenna patterns, our efforts to improve OPNET flight-related models continues. Future work will include a more accurate modulation scheme with Viterbi encoding, the incorporation of FEC, and an automated model testing procedure.

Acknowledgements

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References

[1] OPNET Version 10.5 Modeler Documentation.

[2] OPNET website with user-provided models, model id 500, “Enhanced Antenna Positioning.”
https://enterprise16.opnet.com/4dcgi/Models_SearchSubmit
ftp://cmpdownload:lastkind@enterprise8.opnet.com/cmp_root/models/500/.

[3] http://mathworld.wolfram.com/Quaternion.html.

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[i] Attitude values are a series of Euler angle rotations. The rotations are defined as the yaw angle around the z-axis, pitch angle around the y-axis and the roll angle around the x-axis.