Simulation of Airborne Networks using ns-3

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Abstract— ***Airborne networks, consisting of aircraft-to-aircraft and aircraft-to-ground communications, are critical for future aviation information systems and remote Internet access. A major knowledge gap, however, is the reliability and security challenges of airborne networks in such civilian application domains. Field tests and emulations of airborne networks are expensive undertakings and would be better informed by simulation findings. This paper, hence, reports about a study that aims to simulate airborne networks to understand and characterize their performance and risks. We choose ns-3, an open source network simulation tool, to construct and evaluate airborne networks. We implement 3-D mobility models in ns-3 to capture the realistic movement of aircraft and assess the performance of elemental airborne network configurations in terms of metrics such as throughput and packet drop ratio. We conclude with lessons learnt and some future research directions.***

Keywords— Airborne Network, Cyber Security, ADS-B, ns-3, Simulation

I. INTRODUCTION

Future civil aircraft and unmanned aerial vehicles will form airborne networks to exchange information between each other and ground infrastructure [1]. A range of performance goals, from an aircraft's flight safety to an organization's operational efficiency, will be impacted. Wireless technology and Internet protocols promise to enable beneficial airborne network applications. Companies such as Amazon, Google, and Facebook along with aerospace organizations are already invested in this billion-dollar market [2].

It is crucial, therefore, that we understand airborne networks in the civilian aviation sector. Several research questions emerge, such as: how much data can an aircraft, moving at a certain speed and altitude, communicate to a wireless access point located at a certain distance? How reliably does an airborne network perform for a given air traffic density? Furthermore, how can a radio jammer disrupt the airborne network?

Current airborne networking literature focuses mostly on military studies, but is not directly applicable or scalable to civilian aviation needs and constraints. Moreover, security considerations in airborne networks are largely missing [1]. Furthermore, most of these studies rely on proprietary simulation systems or specialized infrastructure. In addition, emulation and field testing of airborne networks can be an expensive undertaking due to resource requirements. Hence, we propose to investigate the open problem of evaluating the performance of emerging civilian airborne networks.

We chose a popular, well-established, open-source network simulation tool, called ns-3 [3] based on C++ and Python programming languages. We use ns-3 to capture the unique characteristics of airborne networks such as 3-D aircraft mobility, wireless channel model, and intermittent connectivity due to mobility. This allows us to analyse network packet flows, quantify network performance, and assess security implications. In this paper, we contribute our preliminary results on airborne network performance evaluation. We will report on cyber security considerations and simulation results in our future research.

II. BACKGROUND

A. ns-3 Simulation Software

Although significant research exists today on airborne networks [2], [6]-[10], these either focus on military aviation networks or mobile routing protocol issues. Also, these studies use specialized simulation infrastructure (e.g., OPNET) or proprietary simulation systems. For our airborne network research, we used ns-3, with a focus on network security and the implementation of a security module that can be used in ns-3 to assess the robustness and resilience of airborne networks to cyber attacks. ns-3 is open source software for simulating networks, either for research or for education. It provides a visual output using PyViz as well as data output in the shell to assess the network, as shown in Figure 1. "ns-3 provides models of how packet data networks work and perform,

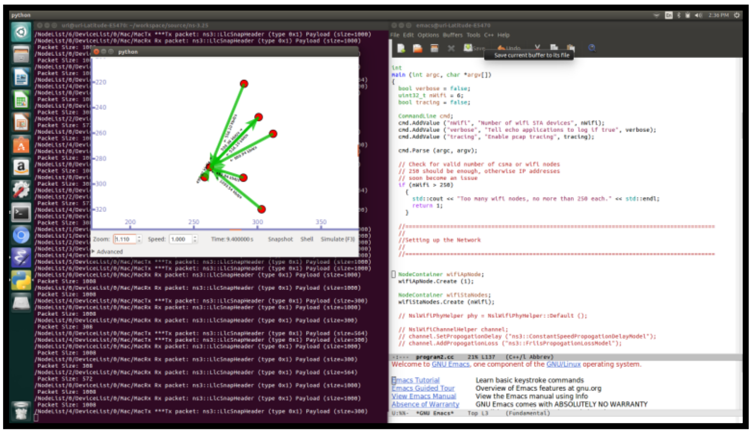


Figure 1: ns-3 Simulation Software Running

and provides a simulation engine for users to conduct simulation experiments" [3]. It allows for a highly-controlled, reproducible environment that can be used to simulate situations and understand the network. It is even used for testing scenarios too complex to do with actual systems. To contrast with other simulation tools, ns-3 uses library sets that can be combined with other, external software libraries. ns-3 is not limited to its own graphical user interface, but can also be used with other visualization, animation, and data analysis tools. It is run from a Linux system, and it uses Python and C++ development tools [3].

B. Airborne Network Information Exchanges

Global positioning system (GPS), automatic dependent surveillance broadcast (ADS-B), and Internet-protocol-based aeronautical telecommunication network (IP ATN) are expected to tightly integrate future aircraft with ground, air, and satellite systems in air traffic systems [1], [12] as shown in Figure 2. An onboard GPS sensor interacts with the global navigation satellite system for computing precise 4-D positions during flight. ADS-B broadcasts this position and the aircraft's identity allowing neighbor off-board systems to automatically, independently, safely, and securely monitor the aircraft's flight route. IP ATN communicates voice and text between pilots, air traffic controllers, and airlines for flight-critical status updates and flight optimizing services.

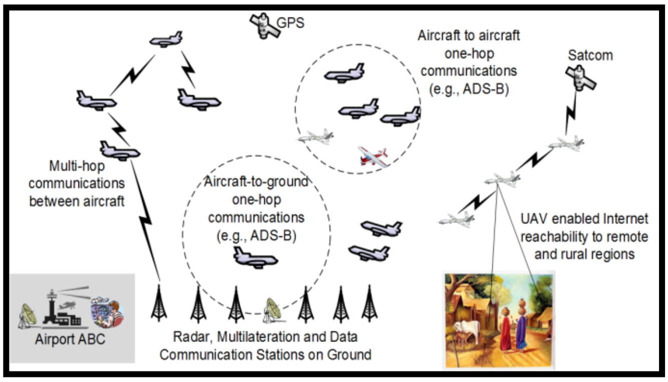


Figure 2: ADS-B networks
Courtesy of: K. Sampigethaya [12]

The FAA has regulated that, starting in 2020, all aircraft that fly in any kind of controlled airspace are to have ADS-B. As a key component of the FAA's NextGen, ADS-B will hopefully allow for better "safety, capacity, efficiency and environmental benefits" [5]. Also, for IP ATN, a potential wireless data link is the L-band Digital Aeronautical Communication System with a typical range of 135 miles or more [12].

C. Airborne Network Performance and Security

Airborne network performance can suffer from the intermittent connectivity due to node mobility, radio interference and multipath due to physical objects in the operational environment, air traffic density, weather, and several other factors. In addition, airborne networks have security flaws due to afforded open access to attackers, use of Internet protocols, and advancement of attack tools such as software-defined radio kits. For example, ADS-B communications are sent from aircraft in clear text, and there is no authentication between nodes or a way to check the integrity of the message, hence ADS-B data must be protected against spoofing and jamming attacks [1],[4],[12]. IP ATN inherits over the IP network vulnerabilities commonly exploited in the Internet today, hence packets must be protected from unauthorized disclosure, modification, or deletion. Achieving these objectives is a major challenge due to the mixed criticality of data transmitted over airborne networks.

III. SIMULATION STUDY: CONSTRUCTION OF AIRBORNE NETWORK

The base network was designed with a single access point node to represent the ground station of an airborne network and a variable number of wireless, airborne nodes. A minimum of four wireless nodes was implemented, and then the number of nodes increased up to thirteen to show the performance of the network once more nodes were introduced.

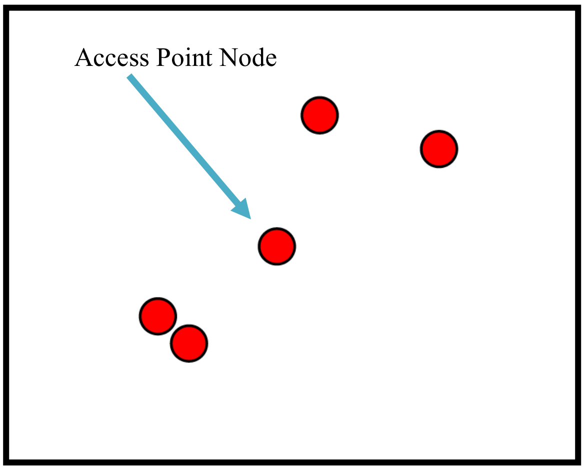


Figure 3: Simulation Start

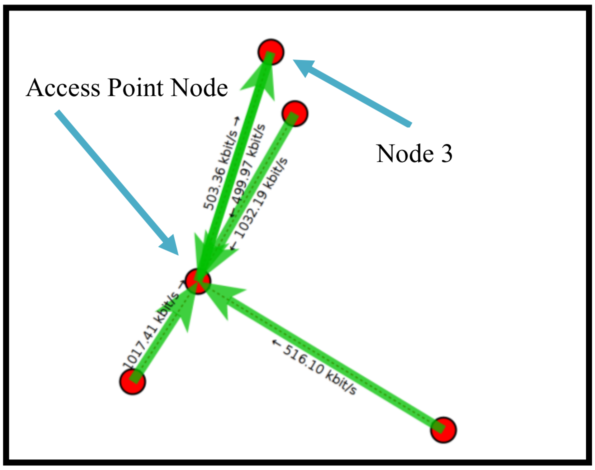


Figure 4: Progression of Simulation

Figure 3 shows the beginning of the simulation in ns-3. The node in the center of the diagram is the access point node representing the ground station. The rest of the nodes move in 3-D random motion as the simulation progresses, representing aircraft mobility around the ground station. For the physical layer of the network, we chose the default wireless channel model for our simulation.

Figure 4 shows the simulation as time progresses. Here you can see the green arrows between nodes, indicating the transfer of data in the order of kbits/sec. Traffic upon the network was simulated using the On-Off application, which generates a constant bit rate traffic. The packet size was set to values of 500 bits, 1000 bits, and 2000 bits and the airborne network performance was assessed. It was observed that packets greater than 1000 bits were fragmented into smaller packets before transmission. Hence, only one node labelled Node 3 in Figure 4, was assigned a final data transfer packet size of 512 bits and all other nodes were assigned a packet size of 1000 bits. For the extent of this project, Node 3 was often selected for experimentation. Figure 4 also shows that the transmission arrow between the access point and Node 3 is pointing both directions. This is indicating the transfer of data in both directions. Node 3 is sending information to the access point, and the access point is sending information to Node 3. In alternative scenarios in future, we will extend this communication pattern to all the nodes and assess network performance under heavier traffic loads.

Once a simple network was established and properly simulated, we aimed at increasing the network density by raising the number of mobile nodes from four to thirteen. Figure 5 demonstrates this visually. Here you cannot see the wireless access point node because all the transmission arrows cover it. As can be expected, the data transmission rates decrease with increase in the network density. Whereas the node data transmission rates in Figure 4 were 500 to 1000 kbits/sec, the node data transmission numbers in Figure 5 are much lower at around 500 to 700 kbits/sec. Hence, if there are many nodes transmitting data in an airborne network, the network flows becomes more congested and the access point cannot accept all the incoming data traffic, ultimately decreasing the node data transmission rates or completely halting node transmissions.

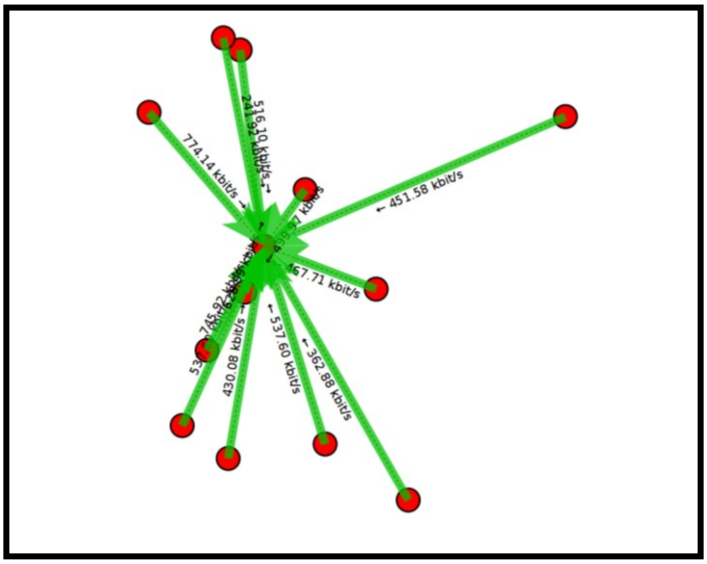


Figure 5: ns-3 Simulation of 14 nodes

IV. SIMULATION STUDY: AIRCRAFT MOBILITY IMPLEMENTATION

At first, a simple 2-dimensional node mobility was implemented in ns-3, which randomly generated the direction and speed of the nodes within a specified, bounded region. As the project progressed, we implemented the Gauss-Markov 3-dimensional model that was provided by the ns-3 core mobility module. This model was brought to our attention in [11] along with many other 3-D models as promising candidates that can be used to closely resemble an aircraft's mobility in ns-3. While the methods and techniques created by the research in [11] will prove useful for future expansion of our research, they were not all implemented in the current simulation of airborne networks.

As ns-3 uses a Cartesian coordinate system, it was noticed while attempting to input real GPS coordinates that a function would have to be built that first converted the latitude and longitude coordinates into Cartesian coordinates. This was implemented in [2], and we expect to be able to create a similar mobility system that will allow for realistic flight patterns instead of random mobility.

It was also discovered when the simulation was producing very unpredictable results that the Gauss-Markov model was the most-likely factor. Upon further investigation, it was found that some of the nodes went out of the bounded region of the model and then ceased transmitting data, which caused the performance measures to output unexpected numbers. In the future work we will explore the potential reinsertion of these departing nodes into the simulation. Further research will also be required to create a realistic representation of 3-dimensional airborne flight paths, and the understanding gained in these simple experiments will be invaluable for these research directions.

V. PERFORMANCE EVALUATION

As we proceeded with our research, the question arose of how we know whether or not our network is performing as we expect it to. How would we know if some, most, or all of the data packets were reaching their destination? We used two different performance measures as a way to monitor our network: throughput and the packet delivery ratio. As computer programmers are aware, computers only generate pseudo-random numbers, which means that each simulation run would produce the same output unless the random number generator (RNG) was given a different seed. For the following performance measure graphs, the simulation was run with different RNG seeds approximately 20 times and then the outputs per node were averaged to get an accurate assessment. With a greater amount of data points the graphs are expected to smooth out even more.

Throughput: Throughput was the first performance measure installed in our network as a measurement of the amount amount of data moved successfully from one place to another in the airborne network in a given time period. In our simple experiment, because all of the data streams were going into the access point node (with the exception of Node 3), a ns-3 trace sink was installed on the access point and the resulting numbers were examined. Figure 6 shows a graphical representation of the throughput. As expected, the throughput climbs drastically up as the nodes increase from 4 to 9, after which it levels off at about 4300 kbits/sec. This means that the access point can easily digest about 4300 kbit of data every second, but no more. This is an important discovery, as we can now ask the question: what happens to the data that doesn't reach the access point? Insight into the packet delivery ratio (PDR) can help explore this issue.

Packet Delivery Ratio: The PDR was installed as the more accurate performance measurement. Data packets are dropped when the network gets congested, such as when the access point is only capable of taking in a certain amount of data as shown in Figure 6. To calculate the PDR, it was necessary to keep track of the total number of packets received by the access point, and then divide that number by the total number of packets sent by all of the nodes. As expected from the previous graph of throughput that showed the access point receiving a maximum of about 4300 kbits/sec, the PDR drops once there are more than seven nodes, as shown in Figure 7.

Figure 6: Throughput Plot

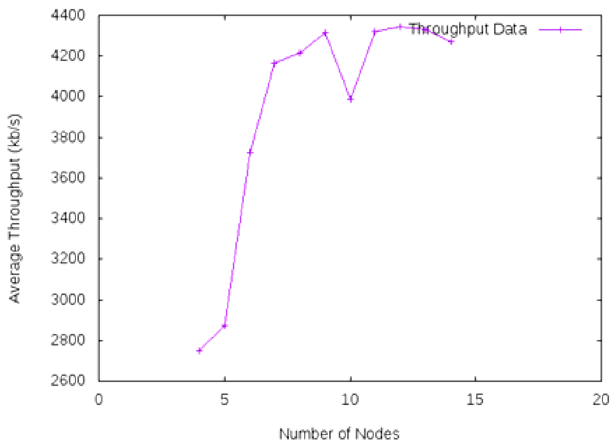
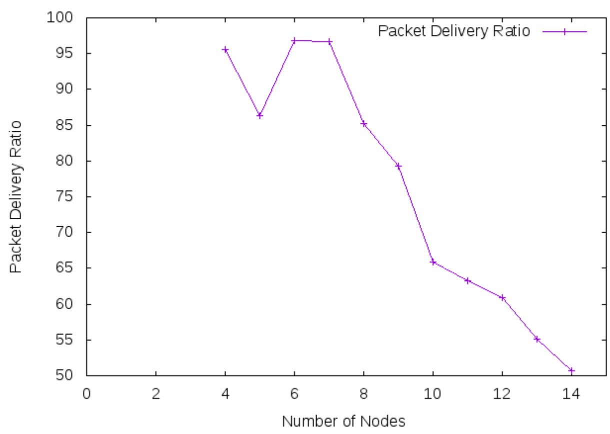


Figure 7: Packet Delivery Ratio



VI. CHALLENGES WITH NS-3

The simulation implementations involved the handling of many variables; every time an anomaly was discovered within the program, there were at least three variables that could have been the cause. It was also complicated to install ns-3 in Linux and learn the implementation details, which makes it difficult because there can be attributes to a particular module that can manipulate the network performance and we simply do not know about them during the use of that module. Also, for a simulation program, ns-3 made it surprisingly non-trivial to input data from files. Running the simulation multiple times and averaging the results to get semi-accurate graphs involved a shell script and manipulating gnu-plot, which proved challenging.

VII. CONCLUSIONS

In this paper, we showed a basic representation of an airborne network as a foundation to tackle greater problems in the future. For example, the number of nodes, node properties, access point properties, wireless channel model, source traffic type, and node mobility can all be changed to create many new scenarios. Also, basic network performance measurements can be expanded upon beyond throughput and packet drop ratio, e.g., end-to-end delay. In our future work we will implement cyber security attack modules, such as a radio jammer, to be implemented in ns-3 to investigate how different cyber attacks can impact different network structures.

This project will continue to build upon the framework described in this paper. We expect to input aircraft communicated data, such as ADS-B, in the future and use the ADS-B position information to dictate the mobility of the airborne network nodes. We also expect to implement a jammer and spoofer as attackers aiming to block or corrupt ADS-B packets and see the impact upon the network and individual nodes.

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