Experiment and Field Demonstration of a 802.11-based Ground-UAV Mobile Ad-Hoc Network

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ABSTRACT

This paper describes a field demonstration and presents the network performance of an 802.11 ground-UAV network composed of 11 ground stations, a mobile vehicle and two fixed wing UAVs, connected by two routing gateways to a legacy wired network. The network effects demonstrated include mobility, network partitions, network merges and gateway failovers. The paper presents experimental results for recorded data traffic and for the state of the routing protocols, with the mobile nodes participating as sources of data traffic.

I. INTRODUCTION

Under the Robust Airborne Networking Extension (RANGE) research project, sponsored by the Office of Naval Research (ONR), Boeing Research & Technology and the Naval Research Laboratory (NRL) developed, tested, evaluated, and demonstrated protocols and techniques for resilient mobile internetworking of unmanned airborne vehicles (UAVs) and surface nodes to extend surveillance range and battlespace connectivity. Some of the advances in this program include:

- **CONOPS:** We developed and tested with new hybrid air/surface scenarios, rather than purely surface-based or airborne scenarios, and described operational view scenarios in terms of networking configurations.
- **Unicast Routing:** We focused on how to interconnect mobile ad hoc networking (MANET) routing domains with legacy routing domains, including how to exploit multiple routing gateways that efficiently survive network partition events [Milcom 07a].
- **Multicast Routing:** We extended our unicast work to allow for integration of multicast routing domains in the MANET with upstream legacy multicast routing domains, again in a manner that supports multiple gateways and survives partitions [Milcom 07b, Milcom 08].
- **Implementations:** We developed new or extended existing open source implementations of open standard unicast and multicast MANET routing protocols, and showed how they could be integrated with legacy protocol implementations on a small form-factor ruggedized mobile router.

This paper reports on a field demonstration conducted in April 2009 at NASA Dryden Flight Research Center on Edwards AFB. The demonstration was conducted by Boeing Research & Technology with support from NRL, the University of Illinois, Urbana-Champaign, and Boeing's Global Military Aircraft division based in Palmdale, CA. We deployed a surface (ground) network of eleven nodes, and flew two small fixed-wing UAVs above this deployed site, both individually and simultaneously. Both planes were equipped with Boeing's miniaturized mobile routers and commodity video cameras. We also placed a mobile router on a ground vehicle that drove around the site and sent audio and video back to a viewing area. The demonstration was conducted successfully and was observed by a number of technical and program representatives from ONR, NRL, SPAWAR SSC-PAC, AFRL, and Boeing.

Although this event was primarily a field demonstration and not a scientific experiment, we did log a large amount of data as we performed experiments, dry runs, a rehearsal demo and the actual demo, and this paper summarizes some of the data gathered.

The paper is organized as follows: We first review the demonstration goals and objectives, and then describe the layout and equipment used. The remainder of the paper describes and discusses a subset of the data gathered, and we summarize with some topics for further study.

II. DEMONSTRATION GOALS

As noted above, the RANGE project focused on the application of mobile ad hoc networking protocols to airborne and hybrid airborne/surface scenarios, and our demonstration vignettes were constructed to show the protocol features developed or extended in the program.

As an example, we considered a use case of two UAVs supporting a surface network consisting of largely static nodes. The UAVs served as a source of data and also could be considered as advantaged nodes in the topology. The hybrid air/surface network was interconnected by two gateways to a notional backbone network running legacy protocols and devices. A key element of the RANGE project was to show how such MANETs could be interconnected to backbone networks in the non-trivial case of using multiple gateways between the backbone and the MANET. These protocol features are described in more detail in the papers referenced in the Introduction.

Accordingly, we laid out a topology of 11 MANET routers on the field (at NASA DFRC lakebed) and complemented them with one surface and two airborne mobile routers. The MANET routing domain was connected to the backbone through two border routers that had instances of both MANET and legacy protocols running on different interfaces. Figure 1 illustrates the basic topology used for the demonstration, and is described in more detail in the following sections.

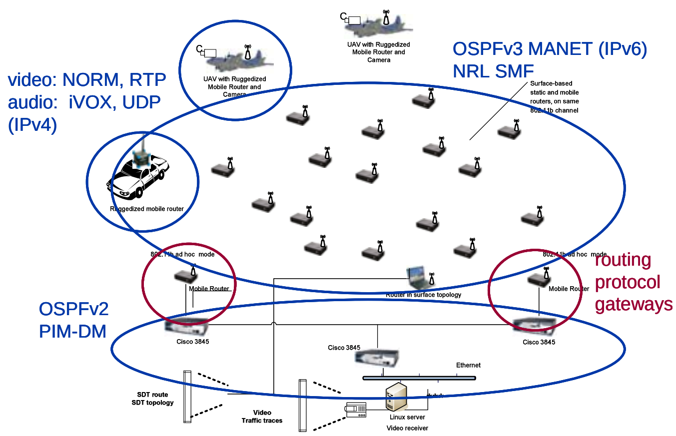


Figure 1: Demonstration topology

HARDWARE

The two fixed-wing UAVs (Figure 2) are ¼ scale Extra300s airplanes with a 2 meter wingspan. A dedicated nickel-metal hydride battery powers the electronic ignition for the Brilleli 46 GT gasoline engine. Onboard the plane are a GPS antenna, 900 MHz (0.1 Watt) communications antenna, a number of lithium polymer batteries for system power, and a Piccolo Plus autopilot. They are owned and maintained by Aerospace Laboratory for Embedded Autonomous Systems (ALEAS) of the University of Illinois at Urbana-Champaign [UIUC].

The UAV has a payload capacity of roughly 5 lb, and a flight time of 15-30 minutes. A payload bay with dimensions of 4”x 5.75”x 6.25” is available to house a Boeing mobile router.

Two modifications have been made to the UIUC UAVs to support the RANGE demonstration. First, a small hole has been cut in the bottom of the fuselage to mount a small USB-based video camera, which is connected to the Boeing mobile router. Second, a hole has been cut to allow the protrusion of a small rubber dipole antenna for the mobile router’s 802.11 radio.

Figure 2: UAV

For the airborne platform, we selected a ruggedized PC/104 based, 400MHz computer from Parvus as our mobile router platform. Packed together with a MiniPCI adapter, a 802.11 card, a power board and a GPS board, it fits into an aluminum railed card cage (also from Parvus), that fits into a cube of 4" on each dimension. We also added rubber shock absorbers (Shock Rocks from Parvus) that attach to the corners of the cube, adding about 0.5" in each direction, as seen in Figure 3. The entire hardware is about 2.5 pounds without the battery. We used the battery already on the plane, the power board allowing any input between 8 and 40Vdc; the computer consumes about 10W. Ground nodes had similar specifications, however they were not ruggedized.

We used commercial 802.11b radios and antennas. The radio model was an EnGenius EMP-8602 PLUS-S dual-band 802.11 a/b/g card with up to 600 mW of transmit power. During the demonstration, nodes were set on 802.11b mode, 5.5 Mbps base rate for both unicast and multicast, at either 600 mW or 400 mW transmit power. The antenna was a 7 dBi Rubber Duck Omni RP-SMA for the 2.4 GHz band. Link rate adaptation was turned off.

All mobile routers used a GlobalSat BU-353 USB GPS Receiver based on the SiRF Star III High Performance GPS chipset. We used the built-in patch antenna and USB connector to the router. The video cameras used were Logictech Quickcam for Notebooks Pro, and the video rate was set to 400Kbps, for an image of 320x240 pixels, 15fps.

Figure 3: Boeing Mobile Routers: miniaturized (airborne) and standard (ground) versions

We selected the Cisco 3845 Integrated Services Router for the backbone topology segment of our field demonstration configuration. More specifications are available on the web [Cisco3845].

SOFTWARE

Software in use included the following:

- OSPF MANET software with extensions developed under the RANGE project for multi-gateway operation;
- PIM/SMF gateways for multicast integration;
- NRL's Scripted Display Tool (SDT) for visualization of node position and routing links;
- NRL's MGEN traffic generation software, including and GPS integration through gpsLogger;
- NORM, RTP and VLC for video transmission and reception;
- iVoX for voice transmission and reception;

Open Shortest Path First (OSPF) is a popular routing protocol for wired networks. **OSPF MANET** is an extension of OSPF for IPv6 [OSPFv3] to support mobile ad hoc networks (MANETs). The extension, called OSPF-MDR, is designed as a new OSPF interface type for MANETs. OSPF-MDR is based on the selection of a subset of MANET routers, consisting of MANET Designated Routers (MDRs) and Backup MDRs. The MDRs form a connected dominating set (CDS), and the MDRs and Backup MDRs together form a biconnected CDS for robustness [OSPF-MANET].

Boeing has developed an implementation of OSPF MANET as an extension of the quagga routing suite. Note that while OSPF MANET is specified for IPv6, extensions exist to carry IPv4 routing information in the protocol. All of the applications in this demonstration were IPv4-based.

Protocol Independent Multicast - Dense Mode (PIM-DM) is a multicast routing protocol that uses the underlying unicast routing information base to flood multicast datagrams to all multicast routers. Prune messages are used to prevent future messages from propagating to routers without group membership information [PIM-DM]. Boeing developed a PIM-DM software implementation as an extension to the XORP routing suite.

Simplified Multicast Forwarding (SMF) is a mechanism that provides basic IP multicast forwarding suitable for wireless mesh and mobile ad hoc network (MANET) use. SMF specifies techniques for multicast duplicate packet detection (DPD) to assist the forwarding process. SMF also specifies DPD maintenance and checking operations for both IPv4 and IPv6. SMF takes advantage of reduced relay sets for efficient MANET multicast data distribution within a mesh topology [SMF].

In the demonstration, our routing software integrated a Boeing PIM-DM implementation with NRL's SMF software, which was using the OSPF MANET CDS for multicast relay set. More details on this integration are found in [Milcom08].

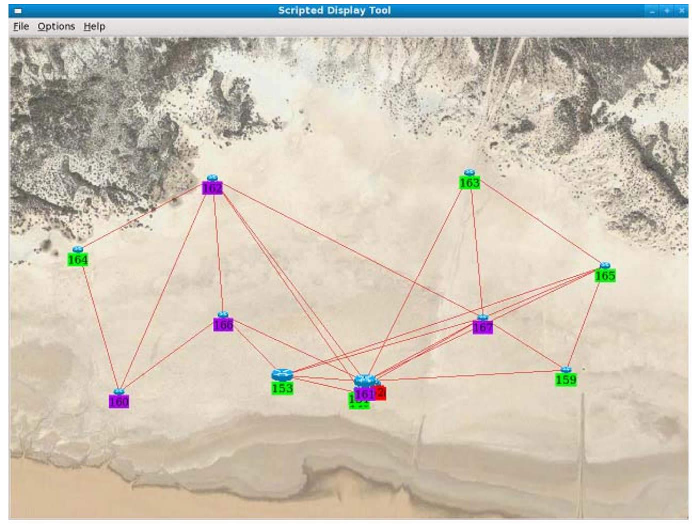


Figure 4: SDT display of the deployed surface topology.

The **Scripted Display Tool (SDT)** is open source software by NRL's PROTEAN Research Group that provides a simple visualization capability using standard image files for a background and set of overlayed nodes. A custom coordinate system can be defined for the background – in our case, the GPS coordinates of the demonstration area, as show in Figure 4 – and node positions can be dynamically updated to "move" their associated icons about the background [SDT].

The Multi-Generator (MGEN) is open source software developed by the NRL'sROTEAN Research Group. MGEN provides the ability to perform IP network performance tests and measurements both UDP and TCP. It also supports the inclusion of the node's current GPS position with each packet sent through the network, as well as the time the packet was sent (for latency measurements). [MGEN].

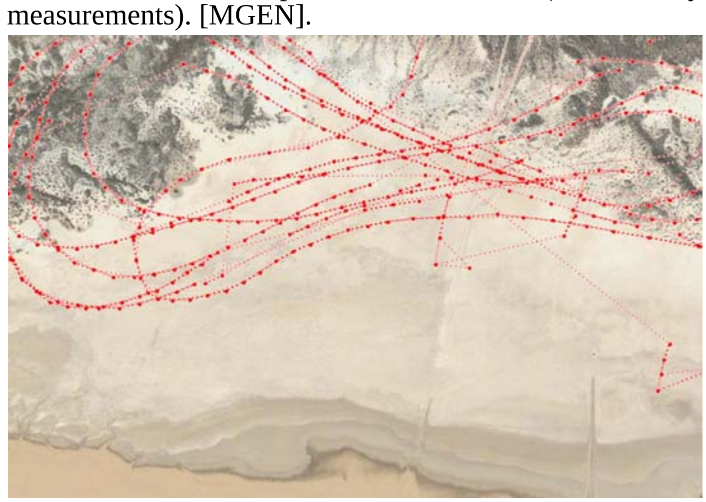


Figure 5: Trajectory of the plane that streamed video.

The **NORM** protocol and software, developed at NRL, is designed to provide end-to-end reliable transport of bulk data objects or streams over generic IP multicast or unicast forwarding services. NORM uses a selective, negative acknowledgement (NACK) mechanism for transport reliability and offers additional protocol mechanisms to conduct reliable multicast sessions with limited "a priori" coordination among senders and receivers. A congestion control scheme is specified to allow the NORM protocol fairly share available network bandwidth with other transport protocols such as Transmission Control Protocol (TCP). It is capable of operating with both reciprocal multicast routing among senders and receivers and with asymmetric connectivity (possibly a unicast return path) from the senders to receivers. The protocol offers a number of features to allow different types of applications or possibly other higher level transport protocols to utilize its service in different ways. NORM leverages the use of FEC-based repair and other IETF reliable multicast transport (RMT) building blocks in its design [NORM].

NRL's IVOX, the **Interactive VOice eXchange** application, is a Voice over IP (VoIP) application that supports unicast and multicast, and also includes NORM integration for reliable communications. IVOX supports a number of voice encoding algorithms with data rates extending from as low as 600 bps.

We have instrumented our mobile routers to store a variety of logs. The experiment logging and data collection framework is based on Python and shell scripting. It includes sending MGEN beacons (including location information) to the visualization node; logging GPS information (latitude, longitude, altitude, and time); logging signal strength information from up to 8 other wireless peers (the iwspy statistic limit); monitoring kernel route changes using rtmon; saving a full tcpdump from each specified network interface; using athstats to record wireless statistics; and saving the output of quagga, XORP, and SMF log files. Logging can be configured to start automatically at boot time, or at the time of acquiring a GPS fix.

Scripts have been developed to process the multicast experimental results to generate end-to-end outage statistics and traffic graphs at each gateway.

VISUALIZATION

We integrated our code with GPS logging and NRL's Scripted Display Tool (SDT) for visualization (Figure 4), used a Boeing custom traffic trace plotter to show OSPF overhead, and used the Video Lan Client (VLC) for video display.

We used SDT in two ways during the demonstration. The first use was to show the dynamic OSPF topology. In figure 4, the geographic layout of the surface nodes, as well as links between them, are rendered against a aerial photograph of the lakebed. We modified the quagga OSPFv3 code to log network links to a file in a format compatible with NRL's CMAP tool. The log file and update interval can be configured using a quagga vty command either interactively or from a configuration file. Specifically, nodes were color coded as follows. Purple nodes were active OSPF MANET MDR routers that were selected as MDR forwarders (also SMF forwarders in the multicast topology). Green nodes were active OSPF MANET routers that were not MDRs. Red nodes illustrate nodes for which FPS reporting is absent, such as the node 152 (airplane node) in the screenshot after it was returned to ground and powered off. The red lines between nodes displayed the links advertised by OSPF MDR routers in Router-LSAs. Note that in OSPF MANET MDR, this set of links does not represent the full topology but instead represents a pruned routing topology designed to give nearly shortest paths without the need to report all neighbor adjacencies. Therefore, the usable RF topology was actually greater than that depicted in Figure 4. In addition, we configured another display of SDT to show the active unicast route between the surface mobile router node and the gateways.

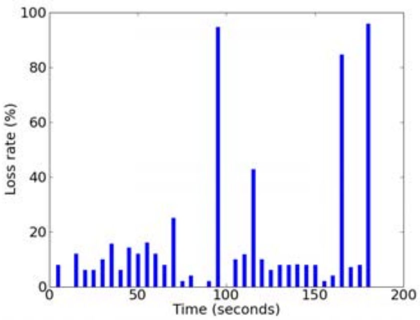
During the course of the demonstration, the SDT displays dynamically updated the network topology display as node position and connectivity changed. When the planes were airborne, they were shown as fast movers against the rest of the network on the map.

We captured and displayed real-time plots of the OSPF traffic both in the MANET and in the backbone, on similar vertical scales. The displays illustrated that the MANET routing protocol overhead was largely contained within the MANET routing domain, and the routes redistributed by the gateway nodes did not contribute much to the backbone overhead. DATA

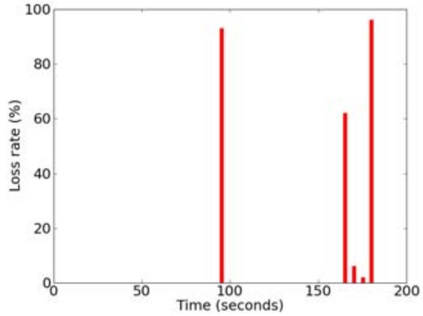
ANALYSIS

We extracted the packet delivery ratio (excluding duplicates) of multicast traffic sent from a flying plane, received at a host computer within the legacy network sitting behind the two gateways running PIM-DM/SMF. As the plane was streaming video at a rate of 400Kbps, we sent two streams of multicast traffic in parallel, each at a rate of 10 packets per second, each packet carrying a 100 byte payload. One of the streams was received natively at the host computer, while the other multicast stream was forwarded through the NRL NORM implementation. NORM was configured with a buffer of 75KB at the sender, (about 1.5 sec of video), and with a 25% FEC redundancy. Figure 5 shows the trajectory of the streaming plane during the experiment. We divided the flight test time into 5 different phases defining scenarios that were analyzed independently.

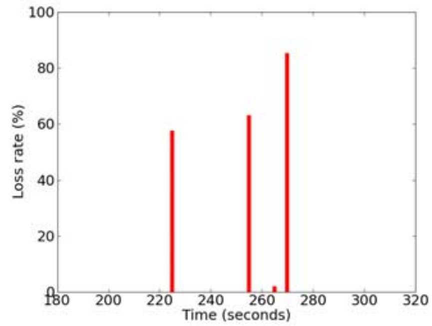
- In phase 1, both planes were in the air (nodes 150 and 152), flying, with one plane sending multicast video and data, and the second plane forwarding opportunistically depending on its MDR status. However, in this experiment we observed the second plane to be a forwarder (relay) only once, for a short amount of time (1.52 sec).
- In phase 2 we turned off the router carried by the second plane (node 150), such that the plane streaming video and data had to rely only on the ground network for forwarding.



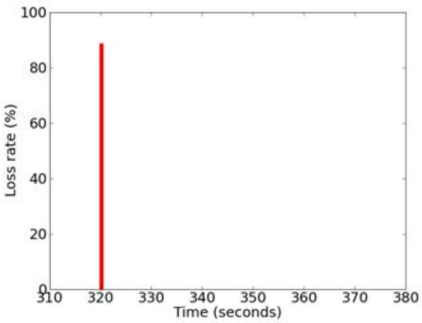
a) Native Mulitcast loss rate Phase 1 .



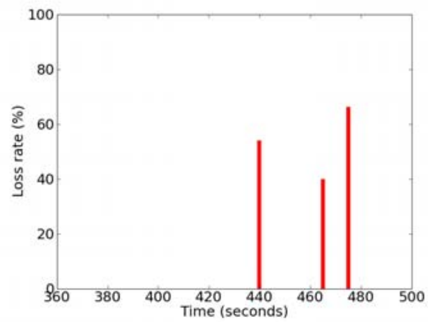
b) NORM Multicast loss rate Phase 1



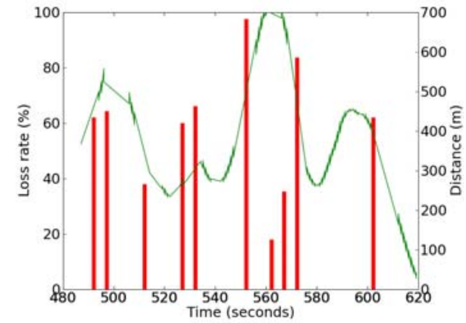
c) NORM Multicast loss rate Phase 2



d) NORM Mulitcast loss rate Phase 3 .



e) NORM Multicast loss rate Phase 4



f) NORM Multicast loss rate Phase 5

Figure 6: Multicast loss rate during the flight test.

- In phase 3, we turned off the gateway used for data forwarding between SMF and PIM, such that the multicast routing protocol had to adjust its routing paths and fail over to the second gateway.
- In phase 4 we started turning off all ground node routers, one by one, until all of them were off except the second gateway.
- Finally, in phase 5 we continued to monitor the data as the plane could only connect directly to the second gateway, as all other ground nodes were off.

Figures 6a and 6b show the loss rate of multicast traffic without and with NORM, respectively, in phase 1, when both planes were in the air. Each bar shows the loss rate averaged on a 5 second interval. We can see that for most of the time, the multicast traffic was affected by moderate loss, which could be successfully recovered by using NORM. Several instances of long term disconnections (lasting a few seconds each) could not be masked by NORM and they appear also in Figure 6b. Overall, the average loss rate for the entire phase was 24.64% without using NORM, and 14.48% using norm.

Figure 6c shows the multicast loss rate using NORM during phase 2, when only one plane was in the air. The behavior is very similar to having two planes in the air, with the total loss rate being 28.16% for direct multicast, and 14.20% for NORM multicast. This is because, in this experiment, during the entire flight of the second plane, its corresponding router has been selected to be an MDR only for 1.52 seconds, at time 65.89 seconds into flight. We did not bias the demonstration to preferentially select the other airborne node; it did so automatically according to the protocol heuristics.

Figure 6d shows the NORM multicast during phase 3, when the default gateway has been turned off. We can see one short disconnection period as the protocol had to fail over to the second gateway.

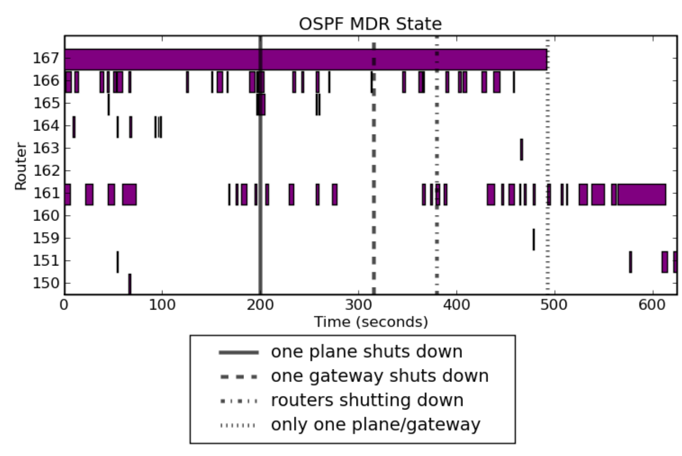


Figure 7: MDR status of the network nodes.

As we were shutting down more nodes in the ground network, we can see in figure 6e that the number of disconnection events also started to increase, to a significant number by the time that only one gateway node was still running in phase 5, as shown in Figure 6f. We also plot the distance between the plane and gateway in Figure 6f, quantified on the vertical axis, because the plane had to be directly connected to the gateway in order to be able to communicate during Phase 5.

Figure 8: Trajectory of the ground mobile node.

It is interesting to note the MDR status of different nodes during the flight test, shown in Figure 7. For most of the time, node 167 was selected as a MDR, due to its good connectivity given by its placement in the network, and also due to its high id number. The next node with a high ID number, and also well connected, node 166, was also selected as an MDR from time to time; other nodes were selected as MDRs when needed, in order to provide connectivity to the plane – note that nodes 164 and 165 were placed at the East and West limits of the network. Node 161, the second gateway and the only node left up in Phase 5 of the experiment became an MDR during that phase, as expected. However, node 161 was also selected to be an MDR occasionally during the previous phases of the experiment, which makes us believe that its radio connectivity to the other MDR nodes, 167 and 166, was not very stable, even though the nodes was relatively close to them.

In a different experiment, instead of flying planes according to a preset figure eight GPS pattern, we were driving a mobile node (node 151) on a jeep randomly throughout the network, as shown in Figure 8, which plots the recorded GPS position of the mobile node.

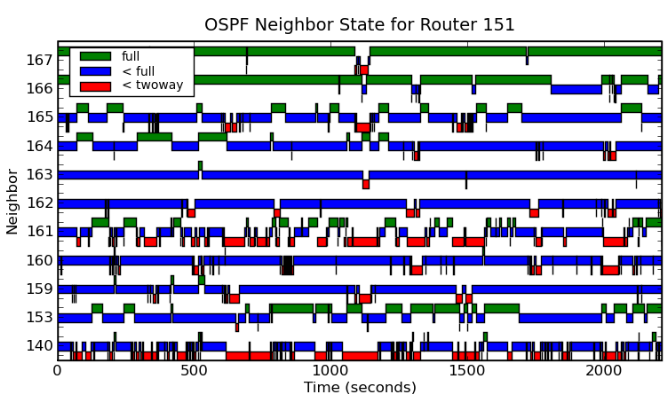


Figure 9: Link status for the ground mobile node

For this experiment, Figure 9 shows the status of neighbor links for the ground mobile node. We can see that, for most of the time, the mobile node maintained good connectivity with the other nodes, its links being in either two way (blue) or full (green), and maintained its full status to nodes 166 and 167, which were best positioned in the network and therefore were selected as MDR or BMDR. The direct link with node 161, which was one of the gateways, experienced the highest rate of state changes, indicating a poor connectivity for node 161.

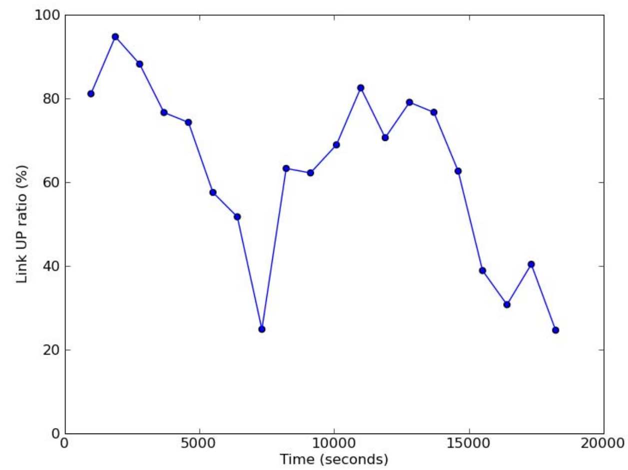


Figure 10: Percentage of time OSPF link between nodes 166 and 167 was in two way or fully connected.

During the entire demonstration we noticed a high variability of the wireless link quality throughput during the day, corresponding with changing environmental conditions (e.g. wind speed, temperature). In the morning, the wireless connectivity was in general good and the topology was fairly stable. As the day progressed, we noticed a general degradation of the wireless channel quality, at times rendering the network topology completely unstable. For a day of experiments with the entire topology deployed at 07:52:34 AM, and lasting until 01:03:35 PM, during which the ground nodes did not move, we monitored the link between the stationary nodes 166 and 167. These were, initially, reasonably well connected, and due to their position in the network, were selected to be MDRs most of the time. Figure 10 plots percentage of time the OSPF link between nodes 166 and 167 was in two way or fully connected, averaged over 15 minute intervals. These were located about 500 feet apart, with no obstacles between them, raised at about 3 feet from the ground. We can see that, even for two static nodes, the link quality varies dramatically between 24 to 95% up during the day. We were not equipped to measure wind speed, but we anecdotally observed a correlation between increased wind speed during the day, and reduced stability of the network topology. We suspect this may be due to wind kicking up dust particles. Even a small amount of dust that remains near the ground could cause problems for the wireless signal, particularly given the low antenna heights of the fixed ground nodes.

SUMMARY

This demonstration is believed to be the first airborne field demonstration that combined OSPF MANET and NRL SMF protocols with OSPFv2 and PIM-DM legacy protocols, in a multiple gateway scenario using UAVs in the MANET. While the ability to connect MANET unicast and multicast to larger legacy networks was proven, several unsolved issues remain to be adressed:

- Even when the links in the network are predicted to be static, there is a fair amount of variable link performance. We introduced some heuristics in our OSPF MANET implementation that enabled the link cost between nodes to improve (lower) over time, thereby favoring more stable links for path selection. We believe that similar approaches would be beneficial to improve the MDR selection process and stabilize the set of MDR forwarders, at the cost of more redundancy in the MDR set. Improved adaptivity of MANET protocols is a focus of a recently started research program for ONR.
- The protocols used in our demonstration were based solely on in band network discovery. To the extent that information on link quality, neighbors, and radio events can be learned out-of-band, we believe that performance will also improve.

ACKNOWLEDGEMENTS

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