

Ad Hoc UAV Ground Network (AUGNet)

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This paper describes an implementation of a wireless mobile ad hoc network with radio nodes mounted at fixed sites, on ground vehicles, and in small (10kg) UAVs. The ad hoc networking allows any two nodes to communicate either directly or through an arbitrary number of other nodes which act as relays. We envision two scenarios for this type of network. In the first, the UAV acts as a prominent radio node that connects disconnected ground radios. In the second, the networking enables groups of UAVs to communicate with each other to extend small UAVs' operational scope and range. The network consists of mesh network radios assembled from low-cost commercial off the shelf components. The radio is an IEEE 802.11b (WiFi) wireless interface and is controlled by an embedded computer. The network protocol is an implementation of the Dynamic Source Routing ad hoc networking protocol. The radio is mounted either in an environmental enclosure for outdoor fixed and vehicle mounting or directly in our custom built UAVs. A monitoring architecture has been embedded into the radios for detailed performance characterization and analysis. This paper describes these components and performance results measured at an outdoor test range.

I. Introduction

Communication networks between and through aerial vehicles are a mainstay of current battlefield communications. Present systems use specialized high-cost radios in designated military radio bands. Current aerial vehicles are also high-cost manned or unmanned vehicles. Small low-cost Commercial Off-The-Shelf (COTS) radio equipment combined with powerful computer processing can be mounted on small (10kg) Unmanned Aerial Vehicles (UAV) and has the potential to revolutionize battlefield communication and open up many scientific and commercial applications.

One example COTS technology is IEEE 802.11b wireless LANs (so called WiFi) which can connect mobile nodes to a fixed infrastructure. This is being widely deployed, including in UAV applications.⁷ More interesting applications are possible when the different mobile nodes connect to each other in peer-to-peer ad hoc (aka mesh) wireless networks.^{3,8}

In this paper we consider ad hoc networks consisting of ad hoc nodes on the ground and ad hoc nodes mounted in small UAVs, which we denote Ad hoc UAV-Ground Networks (AUGNets). We envision two broad AUGNet scenarios as shown in Figure 1. In the first scenario, an ad hoc network of ground nodes is disconnected because of distance and/or terrain. The UAV, with a better view of the nodes, maintains connectivity as an ad hoc relay. In the second scenario, a small UAV because of power and payload constraints has limited communication range which in turn may limit operational range. Ad hoc relaying between multiple UAVs extends communication range. In this paper we describe our efforts to construct such an ad hoc network. It builds on our earlier work in 802.11b ad hoc network protocols and small UAV construction. We present performance results that focus on the role of the UAV in the first scenario obtained on a full scale UAV communication test bed.

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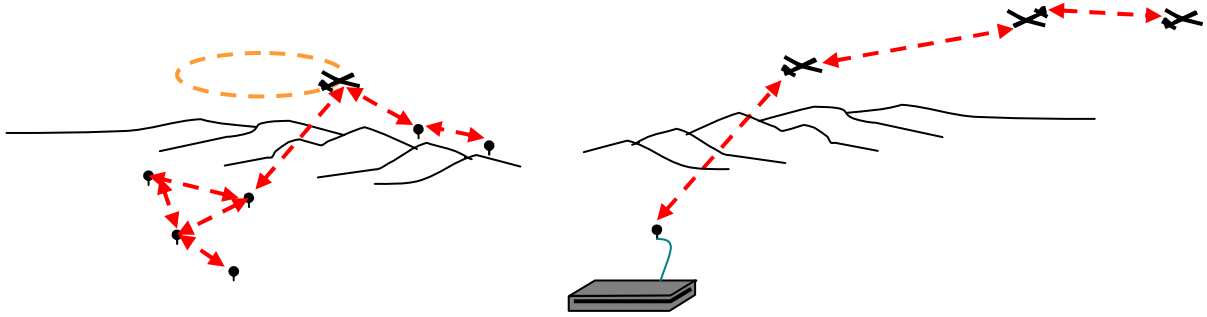


Figure 1. Scenario 1 (left): ad hoc networking with the UAV increases ground node connectivity. Scenario 2 (right): ad hoc networking between UAVs to increase operational range.

II. Approach

An AUGNet poses several challenges. Ad hoc nodes can be in a variety of configurations. Some potential configurations include a fixed site mounted on a high pole, a mobile node mounted on a vehicle, a personnel-carried node, or an aerial node mounted in a small UAV. The design should be modular enough so that it can be applied to all of these configurations. The UAV nodes present special considerations. The UAV can usually communicate with most of the ground nodes.^{‡‡} Ad hoc routing algorithms will tend to route the traffic through the UAV thus limiting communication to the UAV bottleneck bandwidth. The UAV may also have additional pilot control radios that can interfere with the ad hoc communication. Note that our use of the UAV differs with the use for ad hoc networking in Ref. 4 where the UAV is large, flies at high-altitude (60kft), and has a separate radio for UAV-ground communication.

Our approach consists of four efforts: (1) ad hoc network software, (2) communication hardware, (3) UAV platform, and (4) test bed monitoring architecture. The ad hoc network software combined with the communication hardware we denote the mesh network radio (MNR). The MNR is shown in

. The MNR hardware consists of a Soekris single board computer, Orinoco 802.11b card, a Fidelity-Comtech bidirectional amplifier with up to 1W output, and a GPS. A key to our approach is that all nodes whether mounted in a UAV, at a fixed ground site, or mounted on a vehicle node, use the same core MNR. The radios only differ in their packaging. This greatly simplifies our software and hardware development.

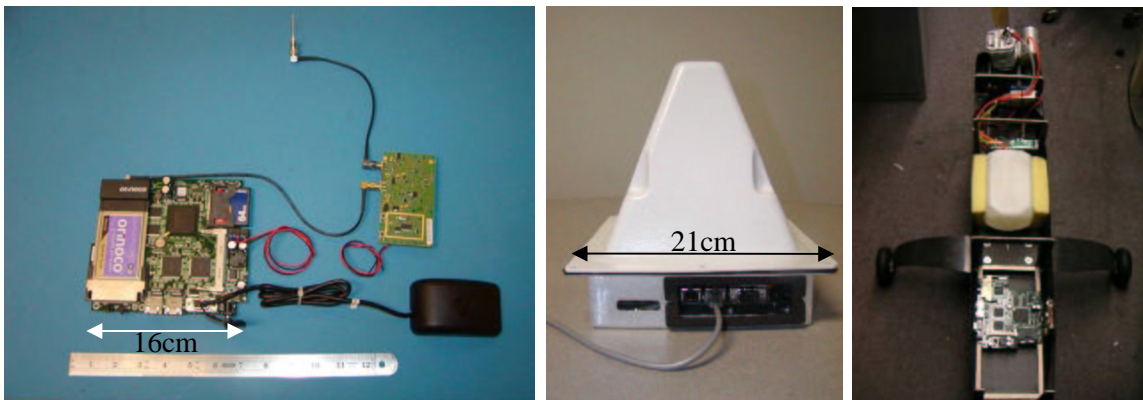


Figure 2. Mesh Network Radio (MNR) (left). MNR mounted in environmental enclosure for vehicle or fixed ground mounting (center). MNR mounted in UAV (foreground right)

^{‡‡} The small UAV is capable of high altitude flight. But, AMA RC rules limit the UAV to visual contact close to the ground for our testing. Even so, a UAV communicating with a ground node will be more likely to have line-of-site transmission and less interference with the ground than other ground nodes.

The MNR runs the dynamic source routing protocol (DSR)⁵ communicating with other nodes via 802.11b. We chose DSR because its routing is on-demand. In on-demand routing, a traffic source only seeks a route to a destination when it has data to send. Thus, nodes do not waste bandwidth trying to establish routes they will never use. When a node needs to send a packet, it initiates a *route request* process among nodes in the network to establish a route. DSR also uses source routing whereby a packet source precisely specifies which route the packet will follow. We implemented DSR ourselves using the Click modular router.^{2,6} With our own implementation we are free to modify the protocol as needed. The software runs under the Linux operating system (the WISP-Dist distribution⁸⁸, a stripped down version of Linux whose size is 8MB) and has been ported to a number of other devices including laptop and handheld computers.

The UAV is a Telemaster-based design. The main criterion is that it be flexible for different flight configurations, have long (multi-hour) endurance for uninterrupted flight testing, and, have a large payload to carry the MNR and possibly other packages. Specifications for the plane are shown below. The plane design has been constructed here at the University of Colorado using carbon fiber composite construction techniques. The UAV body is shown in Figure 2.

We tested the UAV 900MHz RC radio in the presence of the 2.4GHz 802.11b radio. Measurements with a spectrum analyzer and a Berkeley Variatronics Yellowjacket WLAN analyzer showed no discernable interference power between the bands. Even with antennas placed within a few centimeters no excessive packet loss was observed for either system. The 900MHz and 2.4GHz antennas will be mounted on opposite sides of the UAV and we do not expect any communication interference.

Ares Aircraft Properties			
Gemoetric Data			
	Wing	Horizontal	Vertical
Span (in)	95.0	35.0	10.0
Area (sq in)	1425.0	332.5	75.0
Aspect Ratio	6.33	3.68	2.67
Taper Ratio	1.00	1.00	0.50
MAC (in)	15.00	9.50	7.78
Dihedral (deg)	2.5	0.00	
Sweep (deg)	0.00	0.00	15.38
Moment Arm (in)		37.88	39.22
Tail Volume		0.589	0.138
Fuselage Length (in)	63.00		
Performance @ 6000ft			
Rate of Climb	2472		ft/min
Takeoff Speed	58.7		ft/s
Takeoff Distance	130		ft
Cruise Speed	100		ft/s
Max Speed	150		ft/s
Propulsion @ 6000ft			
Propellor	APC 20x12		
Engine Power @ S.L.	5.0		hp
Fuel Volume	1 (0.39)*		gal
Avg. Fuel Consumption	1.8		lb/h
Max Runtime	180 (60)*		min
Payload			
Payload Bay	7x15x10	in	
Max Payload Weight	10.0	lb	
Weights			
Aircraft Empty Weight	19.4		lb
Fuel Weight	5.6		lb
Max Takeoff Weight	35.0		lb
* Currently used fuel tank is only a 50 oz tank			

The testbed monitoring architecture consists of a monitoring agent on every MNR node and a data collection protocol. The monitoring agent reports information on every packet that is sent or received by each node. The information allows every packet to be tracked as it passes through the network. Information on the nodes position over time is also collected. Each node creates a periodic report with the packet and node information that it sends to an ad hoc network gateway and on to a data repository. This data can be analyzed post facto and a web-based monitor interface allows users to visualize and explore the network activity. The test bed and monitoring is described in detail elsewhere.¹

⁸⁸ leaf.sourceforge.net

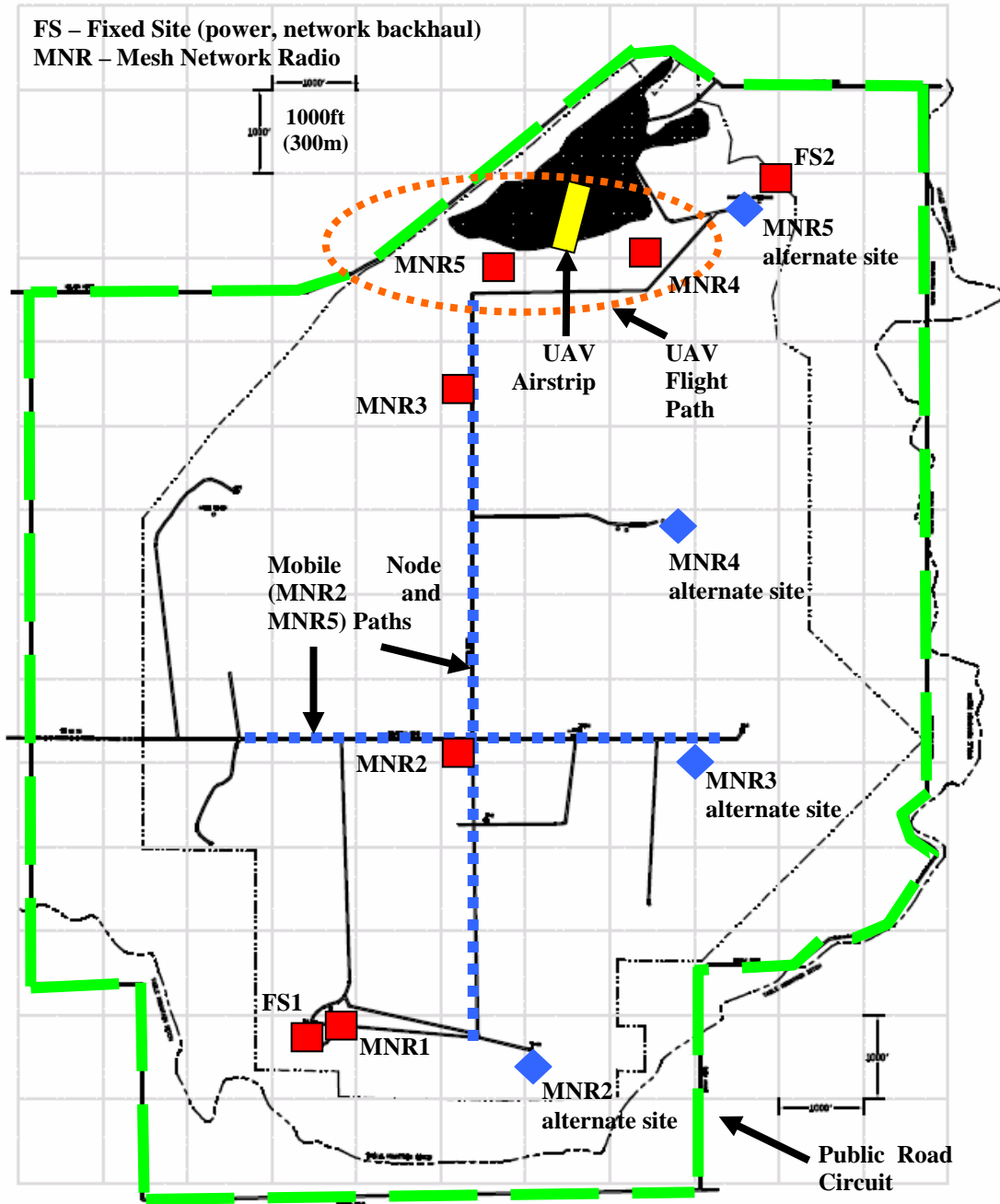


Figure 3. Table Mountain Test Site

III. Test Bed Experimentation

The AUGNet communication was tested on our test bed located at the Table Mountain National Radio Quiet Zone near Boulder, Colorado. The test bed is a 7 km² large flat area with no radio transmitters located in the vicinity. The experiments consisted of up to 5 ground nodes, 2 UAV nodes, and 2 laptop-based nodes.

Ad hoc network performance depends on several factors including the path length (in number of hops), the quality of the links, whether nodes are fixed or mobile, and whether they involve a UAV. An ad hoc network communicates between the source and destination either directly (denoted a one-hop path) or via one or more intermediate relay nodes (denoted a multi-hop path). A series of experiments were constructed to understand the

significance of these factors. The experiments tested the performance with and without mobility, with and without the UAV for one to five hops of different lengths. These experiments are organized as shown below:

Baseline Networks			Scenario 1: Improving Connectivity		
	No UAV	With UAV		No UAV	With UAV
Fixed	throughput connectivity congestion subjective	throughput connectivity congestion subjective	Disconnected Groups	node failure	node failure
Mobile	throughput connectivity congestion subjective	throughput connectivity congestion subjective	Mobile Node at Edge	range	range

Scenario 2: Increased UAV Range	
Ground-Ground	range
UAV-Ground	range
UAV-UAV	range

Figure 4. AUGNet Experiments

The experiments are comprised of a node deployment combined with a specific set of tests. The node deployment is how the nodes are physically mounted and their patterns of mobility. These will be described in the rest of this section. There are six tests that we can run during an experiment described below. Not all will be run with each experiment.

- **Throughput:** Purpose – to test the throughput that can be achieved when no other traffic is present. This test uses the netperf^{***} utility to measure throughput between node pairs over 5 seconds. A script is given a set of source destination pairs and the throughput is measured between each pair one at a time. The default is to measure between every source and destination pair in both directions.
- **Connectivity:** Purpose – to measure the ability for node pairs to send packets to each other when the network is lightly loaded. Each node sends pings once per second to a random destination node. Every 20 seconds a new destination node is randomly chosen. Ping success and round trip delay statistics are collected for each pair.
- **Congestion:** Purpose – to measure delays and throughputs when there are competing data streams in the network. Each node picks a random destination and either performs the netperf throughput for 10 seconds or pings once per second. The schedule of pings vs. throughput is chosen so that 2 competing throughputs are always in the network at the same time. Delay and throughput statistics are collected for each pair.
- **Subjective:** Purpose – to assess the performance of typical network applications as perceived by a user. A user on the test bed attempts typical web tasks as described in a later section. The user records the usability of these applications relative to T1 and dialup connections.
- **Node Failure:** Purpose – to measure the ability of the network to route around node failures. The connectivity is run with all but one node. This excluded node alternates between shutting down its interface for 60 seconds and bringing it up for 60 seconds. Performance is measured during connectivity periods when the nodes is down, when the node is up, and during the transitions from down to up and up to down.
- **Range:** Purpose – to measure the throughput as a function of separation between two nodes. This test uses the netperf utility to measure the throughput from a source to a destination every 5 seconds. In each interval the GPS coordinates of the two nodes is recorded so that throughput can be correlated with range.

The tests themselves provide performance information. Further results for each test will be derived from post analysis of the monitoring data.

A. Baseline Network Measurements

The goal of these experiments is to understand the capabilities of the underlying ad hoc network with fixed and with mobile nodes and the role that the UAV plays in this performance. The result is four experiments as shown in Figure 4. All of these experiments run the throughput, connectivity, congestion, and subjective tests.

1. Fixed Ground

Six nodes numbered 1, 2, ..., 6 are mounted 2m above the surface of the ground and arranged so that they form a five hop network (1 to 2 to ... to 6). Node spacing and local terrain will be used to enforce a five hop network without short cuts, for example, node 3 can only communicate reliably with nodes 2 and 4. The specific placement is

*** <http://www.netperf.org>

shown in Figure 3 where nodes 1 to 6 are labeled FS1, MNR1, ..., MNR5. Nodes are powered up with no scenario or location specific configuration in their communication software and then the four tests are run.

Expected Results:

The throughput experiment will establish maximum throughputs as a function of the number of hops in the network. Throughput is bounded by the 2Mbps ad hoc network channel rate. Actual throughput even between direct neighbors will be less because of 802.11, DSR, IP, and TCP overhead. The throughput will decrease with more hops. The connectivity experiment will establish the typical round trip delay and communication availability between nodes. By design the nodes will be placed so as to form a connected network so availability should be at or very near 100%. The delay will increase roughly linearly with the number of hops in the route. The congestion experiment will establish how competition for network resources impacts throughput. With two competing flows, we would expect throughput to be less than half because the resources are split between the two and there is contention overhead. The last experiment should demonstrate a user experience similar to the experience with a 100kbps DSL line.

2. *Mobile Ground*

In this test configuration, two of the nodes MNR2 and MNR5 are placed on top of vehicles and driven during the tests at speeds around 25km/h. MNR5 cycles North and South and MNR2 cycles East and West as indicated in Figure 3. Otherwise the experiment is identical to the Fixed Ground experiment.

Expected Results:

More dynamics will be observed in the network as nodes move into and out of range. Jitter will be greater as the network pauses to find new routes when old routes are no longer valid. The hop count will change for a node over time. Throughput and availability will decrease while delay increases as more communication time is devoted to control packets and route error recovery. Some end-user applications may have perceptible degradations. This will show how well the network performs when the topology is dynamic.

3. *Fixed Ground with UAV*

In this test configuration, a UAV will fly over the test bed during the experiment. Otherwise the experiment is identical to the Fixed Ground experiment.

Expected Results:

The UAV will be used occasionally when routes have too many hops or other routes are not available. The UAV scenarios will have improved availability and reduced latency for longer routes. Throughput may decrease as the UAV blankets the test bed with its signal and interferes with other nodes' communication.

4. *Mobile Ground with UAV*

In this test configuration, a UAV will fly over the test bed during the experiment. Otherwise the experiment is identical to the Mobile Ground experiment.

Expected Results:

The longer range and more stable UAV to ground links will be used more often to maintaining connectivity. The availability of the UAV node will improve throughput, delay, and connectivity measures compared to the Mobile Ground experiment.

B. Scenario 1: Improving Connectivity

These experiments are designed to show the role of the UAV in improving connectivity among ground nodes.

1. *Mobile Node at Edge*

Nodes will be setup around the top of Table Mountain at the alternate sites shown in Figure 3. A mobile vehicle-mounted node will drive around the network on the roads surrounding Table Mountain. The connectivity test will be activated while the node circuits the mountain. The placement of the nodes will help provide more coverage as the mobile node circuits the mountain. The mountain has rough and irregular sides. Five nodes, no matter how well placed, will not provide coverage all the way around its base.

Expected Results:

The mobile node will route traffic dynamically through nodes on Table Mountain as they come into and out of range. Because of the flat top and irregular steep sides of Table Mountain some portions of the road will not have connectivity to any node and availability for the mobile node will be lower than typical nodes on the mountain. This will show the limits of ad hoc networks to connect to nodes moving at the fringe of the network's collective coverage.

2. *Mobile Node at Edge with UAV*

The deployment will be the same as the Mobile Node at Edge except that a UAV mounted node will fly above Table Mountain.

Expected Results:

The connectivity will improve as the UAV provides a better vantage for connecting to the mobile node. It will not be able to reach the node at all points around the mesa and routes using the ground nodes may be used.

3. *Disconnected Groups*

Nodes will be set up at Table Mountain at the 6 primary sites in Figure 3. The node failure test is performed with MNR3 the node that shuts down its interface. When MNR3 is down, nodes MNR1 and MNR2 will have poor connectivity to nodes MNR4 and MNR5.

Expected Results:

When MNR3 is down, the connectivity between the two separated groups will be zero or near zero. Because the routing software tries for up to 30 seconds to deliver a packet, connectivity may not be zero, but, delays will be high. When MNR3 is up, connectivity and delays will be similar to the results for the Baseline Fixed Ground experiment.

4. *Disconnected Groups with UAV*

The deployment will be the same as the Disconnected Groups except that a UAV mounted node will fly above Table Mountain.

Expected Results:

The results will be independent of whether MNR3 is up or down and similar to the Baseline Fixed Ground with UAV.

C. Scenario 2: Increased UAV Range

These experiments are designed to specifically test the ability of the ad hoc routing to improve communications to and among UAVs.

1. *Ground-Ground Range*

A single fixed MNR radio will be set up at one end of the mesa. The range test will be initiated between a mobile-vehicle-mounted node and the fixed MNR radio. The vehicle will drive slowly around the test range collecting throughput data at different sender and receiver separations.

Expected Results:

Throughput will be near its maximum when the range is small and then fall off as distance increases. The throughput will become more variable as the range increases.

2. *UAV-Ground Range*

One or two MNR will be placed outside of FS2 to provide backhaul connectivity to the UAV operations area. The range test will be initiated between a ground-vehicle mounted node and a UAV-mounted node. A UAV mounted node will fly around the UAV operations field. A ground-vehicle mounted node will drive around the top of the mesa and on the roads in the area of the mesa. During range measurements, the non-mobile nodes will have their interface shut down to force all routes directly between the UAV and mobile node.

Expected Results:

The results will be similar to the Ground-Ground Range results with two differences. The throughput will be more variable due to plane dynamics. And, the range over which throughput can be measured will be increased.

3. *UAV-UAV Range*

A second plane will be added to the UAV-Ground Range setup. The range test will be initiated between the two UAVs. The two UAVs will fly at different separations. For longer ranges, planes may fly from airfields off of the test range.

Expected Results:

The results will be similar to the UAV-Ground Range setup with greater range over which through put can be measured.

IV. Results

A. Range

Since packets can be received occasionally even at long ranges, the range can be defined in a number of ways. The clearest indication is to look at the ability to communicate as a function of distance. Figure 5 shows throughput samples at different ranges for Ground to Ground node and UAV to Ground node communication. The Ground to Ground throughput falls off between 1 and 2km. The UAV to Ground throughput falls off between 2 and 4km. This suggests that the UAV doubles the communication range. Note that placing a node on the edge of the mesa and driving to a nearby hill that is in line-of-site provided reliable 1 Mbps throughputs at a distance of 10km.

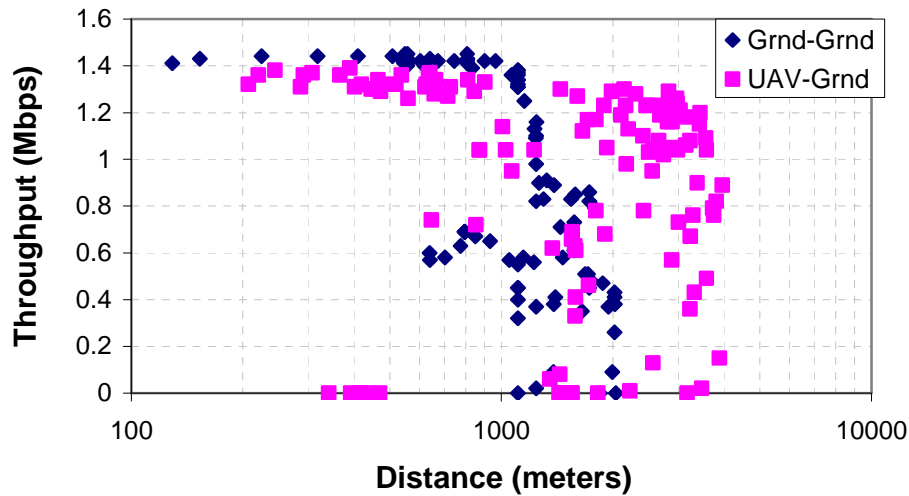


Figure 5. Throughput samples at different ranges.

B. Throughput

The nodes are placed in a linear topology so that MNR2 to MNR3 is one hop; MNR1 to MNR 4 is three hops; and so on. These hop counts are nominal since the routing may discover shortcuts that skip nodes. But, generally these connections are weak with enough packet errors to force the network into the nominal number of hops. The throughput test measured the throughput between every pair of nodes and the throughput vs. the nominal number of hops computed. The test was repeated with a UAV mounted node. In this case sustainable shortcuts through the UAV can be formed since the UAV to ground range is longer. The point is to see if the network can discover these shortcuts and if they help throughput.

The throughput with and without the UAV is shown in Figure 6. The graph without the UAV shows the throughput falls off by a factor of two to three with each additional hop. This is a known phenomenon in ad hoc networks for a small (five or less) number of hop network. As expected the UAV makes no difference on one and two hop paths since paths between ground nodes that pass through the UAV are at least two hops. For three and four hop paths the UAV is able to maintain the throughput close to the two hop throughput indicating that the network is able to find and sustain the two hop paths through the UAV.

We note that the UAV throughputs have a higher variance on average. We attribute this to the UAV maneuvering. As the UAV turns it can bank away from a target node so that the ground node is not in the main lobe of the dipole antenna. To observe this effect we measured the losses in low rate packet streams sent over 20 second intervals between every pair of ground nodes with and without the UAV. The results are shown in Figure 7. Without the UAV, given the fixed stable and connected network, no packets are ever lost. With the UAV, shorter routes are formed through the UAV. Loss samples with the UAV experience occasional losses as high as 50% whereas the majority of samples have no losses at all.

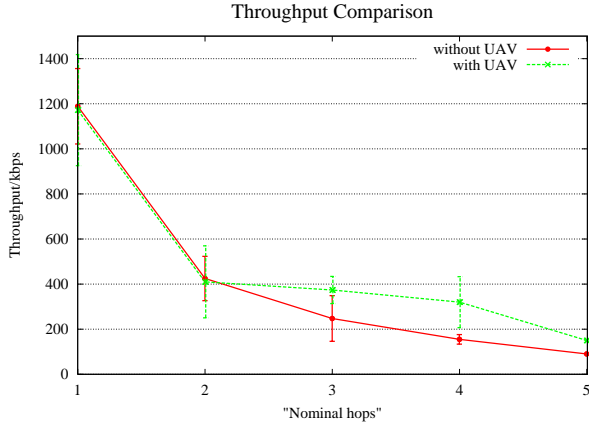


Figure 6. Throughput data with and without the UAV node vs. the nominal number of hops.

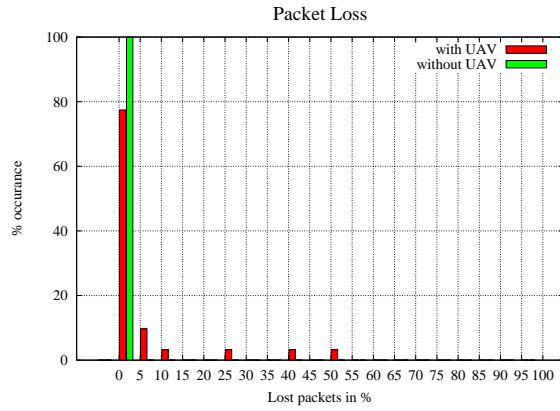


Figure 7. Loss rate over 20 second intervals with and without the UAV.

C. Connectivity

The mobile node at the edge experiment has a node drive around the mesa coming in and out of coverage of fixed nodes placed at the mesa edge. Packets are sent to the mobile vehicle and the losses recorded. This experiment tests the ability of the network to find routes to a mobile node with intermittent coverage. Table 1 shows that the UAV has a dramatic positive effect on packet completion. Interestingly, the 67% less loss with the UAV comes with only 19% of the packets actually passing through the UAV. When no route can be found after several attempts, the routing stalls with up to 30 second waits before reprobng for a new route. The UAV provides enough additional connectivity to prevent this stall state and thus keeps the connections active.

Table 1. Percentage of packets reaching destination with and without the UAV

	with UAV	without UAV
% packets lost	4	71
% packets received without UAV	77	29
% packets received with UAV	19	0
total number of packets sent	3809	12776

D. Mobility

The mobile tests divide the six node network into two groups of two adjacent fixed nodes separated by two mobile nodes. There are three classes of traffic in this scenario: within a fixed node group; traffic that has a mobile node as a source or destination; and traffic between the fixed nodes that is relayed by the mobile nodes.

Results for loss and throughput are shown in Table 2. The loss data shows that the UAV increases the loss rate in the mobile source destination cases, but decreases the loss rate in the mobile relay. The UAV flies on the north side of the mesa while the cars drive at the south side. Thus, links from mobile vehicles to the UAV are likely to be unstable and thus hurt the mobile source-destination scenario. Meanwhile, in the mobile relay case, the UAV can serve to avoid the mobile nodes altogether and thus it can provide a more reliable link for the fixed nodes. The throughput data shows that the UAV has a 10% negative effect on throughput in the first two cases, but, doubles the throughput in the mobile relay case.

Table 2. Loss percentage and throughput with and without the UAV in the mobile ground scenario

	with UAV		without UAV	
	% loss		%loss	
	mean	s.d.	mean	s.d.
within fixed node groups	6.2	12.2	0	0
mobile source-destination	45.8	36.1	10.8	25.9
mobile relay	17.5	17.5	35.8	35.3
	throughput (kbps)		throughput (kbps)	
	mean	s.d.	mean	s.d.
	within fixed node groups	1120	363	1258
mobile source-destination	454	419	482	463
mobile relay	114	60	46	64

E. Subjective Tests

While measuring throughput and delay gives good quantitative values for network performance, it does not say much about the end user experience while using the network for day-to-day activities. Browsing the web, downloading files, or using streamed media is a very subjective experience which depends on every individual's habits and preconditioning. We designed two tests to capture subjective impressions: a web-browsing test and a voice quality test.

For the web-browsing test we have the candidate browse a website consisting of several pages with a different size image on each of them, namely 10kB, 100kB, 300kB and 500kB. The web pages are served by the small-footprint, single-threaded web-server Boa (www.boa.org) installed on the gateway minimizing impact on gateway performance. Candidates report their experiences browsing the pages compared to browsing the Internet from their home connections.

The voice quality test evaluates the subjective perception of a voice conversation carried out between two test candidates using laptops associated to one of the nodes in the test bed or the gateway. The open-source, Linux-based SIP-softphone Linphone (www.linphone.org) proved to be stable and user-friendly. It supports several voice codecs and enables adjustment of SIP and RTP parameters to compensate for changes in network performance.

Preliminary experiments proved quite successful in terms of satisfying end user's expectations in a reliable, well-performing network. With a well setup network of fixed nodes browsing web pages from as far as six hops away can be compared to surfing the Internet on a fast dial-up connection. Rendering pictures gets more and more visible with increasing hop count, but is still acceptable. However, when changing positions within the network the delay incurred by finding a new route with DSR can be irritating. Also, sometimes downloads of pictures larger than 300kB stall noticeably halfway through the page, spoiling user's browsing experience. With a hybrid network of stationary and mobile nodes browsing becomes choppier as nodes move out of reach and new routes to the web-server have to be found more frequently.

Voice quality as tested from the gateway to a laptop moving around the test bed was found to be exceptionally good up to three hops and no noticeable end-to-end voice delay could be observed. New routes formed automatically and voice contact was re-established without having to re-dial or restart the phone application, although there were gaps in the speech. At a distance of four hops, voice streams became choppy and a meaningful conversation was not possible anymore. As seen with web-browsing, the time to discover a new route can also considerably impair voice conversations.

The impact of the UAV node still has to be investigated, but throughput and delay results suggest an improvement in user experience as well since most connections are three hops or less.

V. Conclusion

The AUGNet concept is an extension of traditional ad hoc networks whereby the UAV provides additional connectivity for the ground nodes. The experiments in this paper present a detailed performance evaluation of this role. Specifically, we show that the UAV has longer range and better connectivity with the ground nodes. This translates to the UAV supported network generating shorter routes that have better throughput. It also improves connectivity to nodes at the edge of network coverage. In mobile scenarios, the UAV had a small negative impact on

nodes with otherwise good connectivity, whereas in the same scenario; the UAV had a large positive impact on nodes with otherwise poor connectivity. The negative impact may be attributed to a more variable link due to the UAVs high maneuverability. Subjective tests showed that the ad hoc network would support web browsing over up to 6 hops when the network was stable. A real-time voice application worked well up to three hops.

All of these results used no optimizations for either the UAV or the different traffic types. Future work will analyze the large volume of detailed data collected in these experiments to develop better tuned AUGNet routing protocols.

Acknowledgments

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References

- ¹ Brown, T.X, Doshi, S., Sushant J., Himmelstein, J., "Test Bed for a Wireless Network on Small UAVs," AIAA 3rd Unmanned Unlimited Technical Conference, Chicago, IL, 20-23 Sep 2004
- ² Doshi, S. Bhandare, S., Brown, T. X , "An On-demand minimum energy routing protocol for a wireless ad hoc network," *Mobile Computing and Communications Review*, vol. 6, no. 2, July 2002.
- ³ Elliott, C.; Heile, B.; "Self-organizing, self-healing wireless networks," Personal Wireless Communications, 2000 IEEE International Conference on, 17-20 Dec. 2000, Page(s): 355-362
- ⁴ Gu, D.L., Pei, G., Ly, H., Gerla, M., Zhang, B., Hong, X., UAV Aided "Intelligent Routing for Ad-Hoc Wireless Network in Single-Area Theater," Wireless Communications and Networking Conference, 2000. WCNC. 2000 IEEE , Volume: 3, 23-28 Sept. 2000 Page(s): 1220 -1225 vol.3
- ⁵ Johnson, D., Maltz, D., "Dynamic Source Routing in Ad Hoc Wireless Networks," *Mobile Computing*, Chapter 5, pp. 153-181, Kluwer Academic Publishers, 1996.
- ⁶ E. Kohler, R. Morris, B. Chen, J. Jannotti, and M. F. Kaashoek, "The click modular router," *ACM Transactions on Computer Systems*, vol. 18, no. 3, pp. 263–297, August 2000. <http://www.pdos.lcs.mit.edu/click/>
- ⁷ Schulze, K., Buescher, J., "A Scalable, Economic Autonomous Flight Control and Guidance Package for UAVs," 2nd AIAA "Unmanned Unlimited" Systems, Technologies, and Operations—Aerospace, 15-18 September 2003, San Diego, California
- ⁸ Toh, C.-K., *Ad Hoc Mobile Wireless Networks: Protocols and Systems*, Prentice Hall, 336p., 2001.