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Wireless Experiments on a Motorola Mesh Testbed

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Wireless Experiments on a Motorola Mesh Testbed

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Abstract

Motomesh™ is a Motorola product that performs mesh networking at both the client and access point levels and allows broadband mobile data connections with or between clients moving at vehicular speeds. Sandia National Laboratories has extensive experience with this product and its predecessors in infrastructure-less mobile environments. This report documents experiments, which characterize certain aspects of how the Motomesh™ network performs when mobile units are added to a fixed network infrastructure.

Our key findings include: (1) If an Intelligent Access Point (IAP) loses connectivity to the wired network, it will eventually fail-over into a mode where it behaves as a Mesh Wireless Router (MWR). (2) Although the mesh enabled architecture (MEA) had a lower average throughput, it was much more consistent than the 802.11 technology in mobile client tests at vehicular speeds. (3) In high multipath interference environments, 802.11 suffered a much more pronounced reduction in throughput than did MEA. (4) Increasing effective radiating power is not a useful technique for mitigating throughput degradation resulting from multipath interference. (5) Although network performance can be affected by not having enough connections to the wired network if there are too many MWRs per IAP, having more IAPs in favor of fewer MWRs in the wireless network does not adversely affect network performance. This also makes the network more robust and more tolerant of wired communication line failures.

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Motomesh™ is a registered trademark of Motorola, Inc.

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1 Introduction

Motomesh, a Motorola product, is a wireless networking technology that offers the advantages of mesh networking at both the client and access point levels and mobile data connections with or between clients moving at vehicular speeds. Sandia National Laboratories has extensive experience with this product and its predecessors in infrastructure-less mobile environments. This report documents experiments, which characterize certain aspects of how the Motomesh network performs when mobile units are added to a fixed infrastructure.

The intent of this report is to capture and document the results and conclusions drawn from a set of experiments conducted in Sandia's wireless testbed, published in an unlimited release format. This report supplements and compliments the information in the limited distribution report by Riblett, et al. [10] completed in March 2009.

1.1 Overview

The U.S. Department of Energy (DOE), U.S. Department of Defense (DoD), civilian police and fire agencies, and companies in mining industries use Motomesh equipment to provide wireless data communication and geolocation services.

Since 2004, Sandia's Communications Systems department has researched and conducted tests with Motorola's mesh enabled architecture (MEA) units in a mobile environment. These tests demonstrated the advantages of a mesh network system in a secure, mobile environment. Motomesh's units essentially form a wireless network with the capability to self-form and reconfigure on a second-to-second basis. Incorporating the Motomesh equipment into a fixed, wired network infrastructure may offer significant advantages with regard to security and ease of communications. The experiments described in this report are intended to characterize Motomesh performance with both MEA and 802.11 units.

A brief description of the experiment set is as follows:

1. With MEA unit and from the client perspective, observe failover of an Intelligent Access Point (IAP) that loses wired connectivity and measure baseline throughputs.
2. With MEA unit and from the Mobile Wireless Router (MWR) perspective, observe failover of an IAP that loses wired connectivity and measure baseline throughputs.
3. With a single IAP, measure throughput degradation of MEA links at speeds above 30 mph.
4. With a single IAP, measure throughput degradation of 802.11 links at speeds above 30 mph.
5. Incorporating handoffs, measure throughput degradation of MEA links at speeds above 30 mph.

6. Incorporating handoffs, measure throughput degradation of 802.11 links at speeds above 30 mph.
7. Given the same frequency band, determine performance difference, if any, between (a) using 802.11 as the backbone that connects the infrastructure devices and (b) using MEA as the backbone.

This report provides the procedures for each experiment, the test results, and a summary.

1.2 Mobile Mesh Networking

Portability allows a user to be connected to the network while at various stationary locations, such as conference rooms, hot spots, or designated drive-up locations (e.g. fire station, vehicle maintenance garage). Mobility allows a user to be continuously connected to the network while in transit or on the move [11]. Mobility is a superset of portability, requiring not only network location management functions, but also handoff functions [12]. Maintaining continuity to the network at vehicular speeds of 50 km/h (about 30 miles per hour) and greater, presents a challenge. Numerous authors [3] [9] [5] [4] [7] have discussed the issues relating to the vehicular mobility challenges. These mobility issues are summarized in a paper by Witzke and Riblett [11].

A wireless mesh network (WMN) can be grouped into one of three types based upon its architecture [1]:

- Infrastructure/Backbone WMNs
- Client WMNs
- Hybrid WMNs

In the Infrastructure/Backbone WMN architecture, mesh routers or access points form a wireless backbone between the wireless infrastructure devices. The wireless infrastructure devices form a mesh of self-configuring, self-healing wireless links among themselves. Some, but likely not all, of the wireless infrastructure devices are connected to the wired network. Clients associate to the wired infrastructure devices, but do not communicate directly with other clients. If the device with which a particular client is associated, does not have a direct connection to the wired network, the node relays the data to (and if necessary, through) other devices until said data can be transmitted onto the wired network. This is shown in Figure 1.

Client wireless mesh networks provide peer-to-peer networking among client devices. This is also known in more conventional terms as an ad hoc network. Wireless client devices communicate with each other and usually, wireless infrastructure devices (access points or mesh routers) are not involved. This is illustrated in Figure 2.

Hybrid wireless mesh networks (or fully meshed wireless networks) combine infrastructure and client meshing, as shown in Figure 3. This extends the robust, self-healing, self configuring properties of an infrastructure mesh network to the wireless clients. In this form of network, clients can not only communicate with each other, but can communicate <u>through</u> each other to reach available infrastructure (which also meshes for robustness).

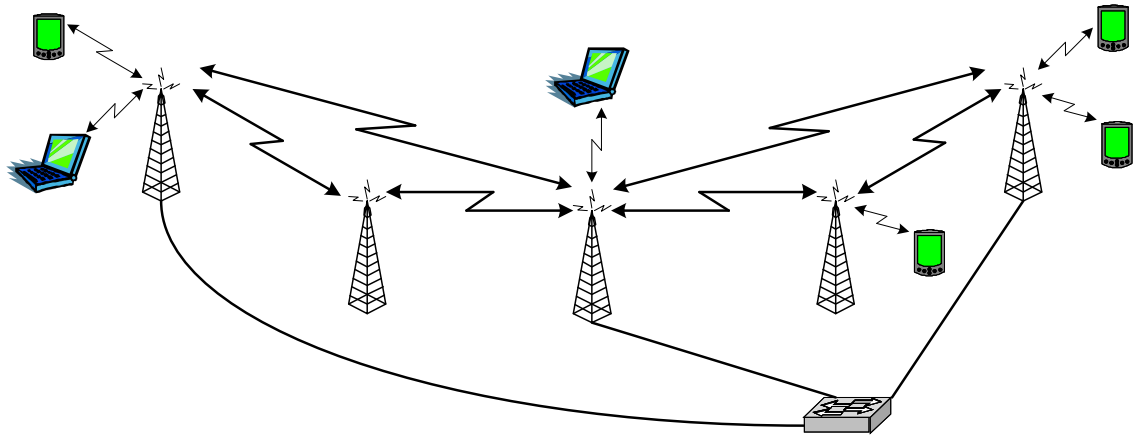


Figure 1. Infrastructure wireless mesh network.

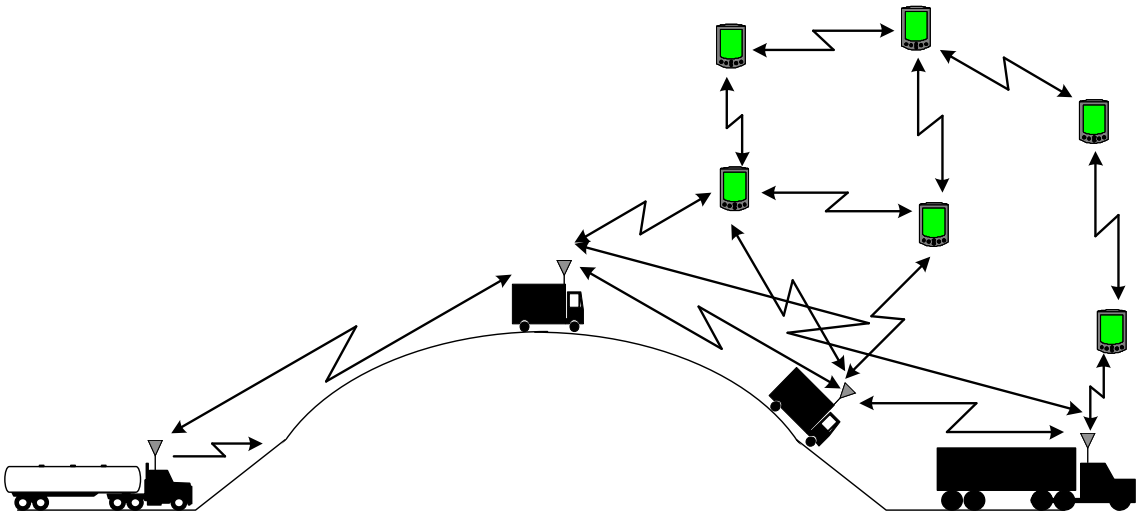


Figure 2. Client wireless mesh network.

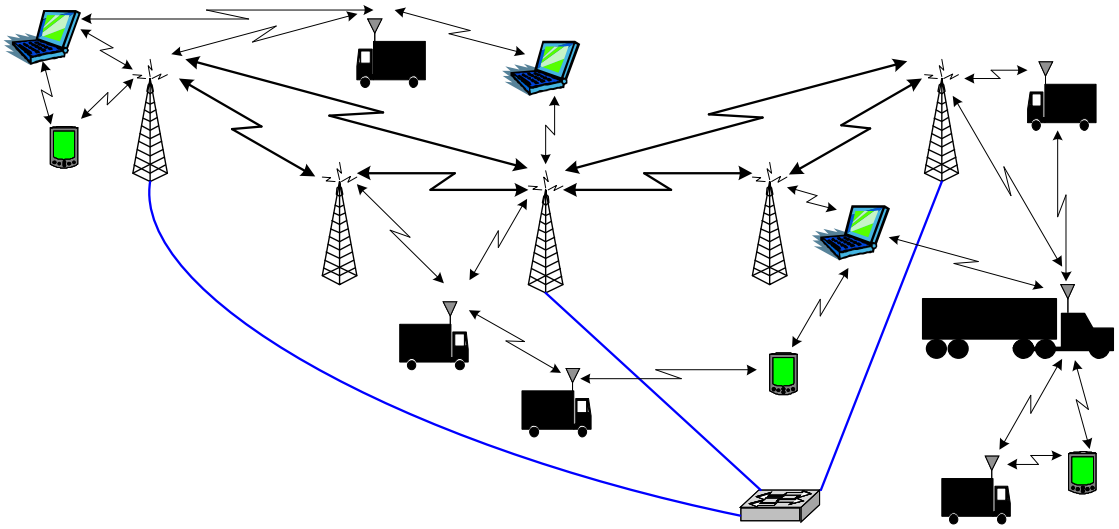


Figure 3. Fully meshed wireless network (Hybrid WMN).

Wireless mesh networks are described more completely in the book by Akyildiz and Wang [2].

1.3 Description of Testbed

The Motomesh testbed at Sandia was designed to evaluate specific technologies with regard to wireless infrastructure design. The testbed, which covered about 64 square miles at the time of these experiments, provides investigators the opportunity to conduct research on a variety of units which, in turn, allows for the design and development of an infrastructure at a specific site that may include mobile units (e.g., vehicles) and/or fixed units.

Intelligent Access Points (IAPs) and Mesh Wireless Routers (MWRs): For the series of experiments described here, the following devices are deployed in the testbed:

- IAPs:
  - Research Site IAP (Tech Area IV) (Figures 4a and 4b)
  - Area III IAP (Tech Area III) (Figures 5a and 5b)
  - RVR IAP (Robotic Vehicle Range) (Figures 6a and 6b)
- MWRs:
  - Storage Site MWR (Figures 7a and 7b)
  - Manzano MWR (Manzano Area) (future deployment)

Each IAP and MWR is equipped with omnidirectional antennas having gains of 8 dBi in the 2.4 GHz band. The Quadrature Division Multiple Access (QDMA) MEA radio in each IAP and MWR has a maximum transmit power of 250 mW, while the 802.11g radios in the IAPs and MWRs have a maximum transmit power of 125 mW.

The IAPs and MWRs are shown on the testbed map (Figure 8), including each device's name, device type, location (latitude/longitude), and elevation.

(a) (b)

Figure 4. Intelligent Access Point (IAP) (a) located at a research site at Sandia National Laboratories and (b) in closeup.

(a)

(b)

Figure 5. Intelligent Access Point (IAP) (a) located at Sandia National Laboratories Tech Area III site and (b) in closeup.

(a)

(b)

Figure 6. Intelligent Access Point (IAP) (a) located at Robotic Vehicle Range (RVR) research site and (b) in closeup.

(a)

(b)

Figure 7. Mesh Wireless Router (MWR) (a) located at a storage site at Sandia National Laboratories and (b) in closeup.

Figure 8. Map of Motorola Mesh Testbed at Sandia National Laboratories

Vehicle Mounted Modem: The vehicle used in the test included a Vehicle Mounted Modem (VMM6300) with a WMC6300 card (mesh radio). The firmware in the VMM is as follows:

- Transceiver firmware 8.0.8.8, Build date 2/14/07, 5:36:07 PM
- SBC MEM_MEM_SBC_8.1.2.18 Thu Sep 14 16:11:56 EDT 2006

The VMM operates with a maximum transmit power of 250 mW. Several different omnidirectional antennas were used, having different gains.

802.11 RF interface: For the experiments involving 802.11, in the vehicle we used a Proxim ORiNOCO 8470, 802.11b/g PC card inserted into a laptop computer. This card operated at about 60 mW and was connected to different (depending on the specific experiment) omnidirectional antennas.

2 Description of Experiments

The experiments described in this report are intended to characterize how Motomesh performs when mobile units are integrated into a fixed infrastructure. A brief description of each experiment in the set is provided in Section 1.1. Detailed descriptions are provided here. Note that the original intent of most of the experiments was to conduct the test using both UDP and TCP. However, excessive packet loss rates prevented collecting usable TCP data.

2.1 Experiment 1: Failover at IAP with Mobile Client

2.1.1 Objective

From the client perspective, (1) observe failover of an IAP that loses wired connectivity and (2) measure baseline throughputs.

2.1.2 Description

Two IAPs (Research Site IAP and RVR IAP) are within line-of-sight (LOS) and communication distance of each other; a stationary mobile client is associated with one of them (Figure 9). To establish a baseline, investigators will use Iperf to measure the throughput of the client-IAP-server path with UDP (using the "-u" switch on Iperf), and then repeat for TCP. Then with the IAP still powered on, the investigators will disconnect the communication line between the IAP with whom the stationary mobile client is associated, and the wired network. The investigators will observe behavior, including whether (a) the mobile client continues to communicate with the wired network by repeating traffic to the remaining IAP or (b) whether the impaired IAP drops its association with the mobile client, thereby forcing the client to associate to the other IAP. If continuity is maintained – by the first IAP repeating traffic to the second IAP and into the wired network – the investigators will record how much time the network takes to reform and regain connectivitity, and will check the throughput of the client through the disconnected IAP to the wired IAP to Iperf server for both protocol types, UDP and TCP.

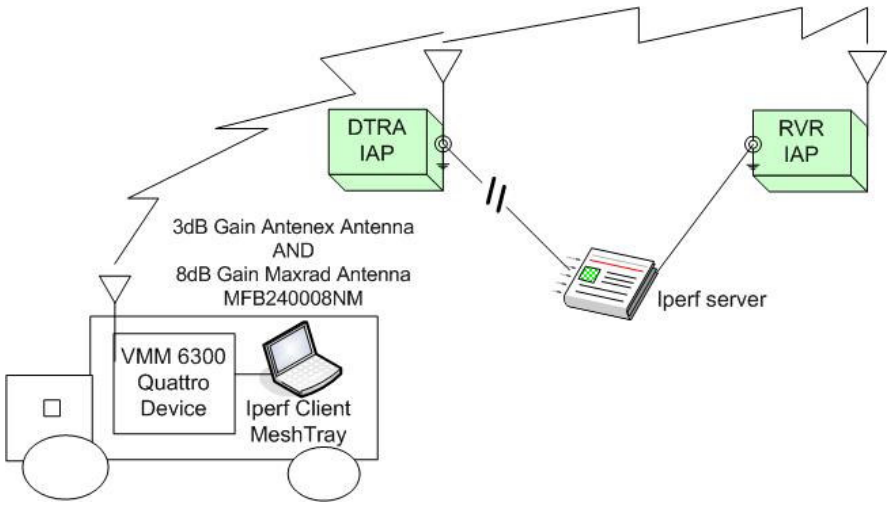


Figure 9. Experiment 1 Setup

2.1.3 Devices

- Two IAPs (RVR IAP, Research Site IAP) with two radios active (2.4 GHz mesh, 802.11)
- 3 dB gain Antenex antenna and 8 dB gain Maxrad antenna (fiberglass omnidirectional)
- Iperf server (located in Building 821, room 2137)
- Stationary vehicle with (a) laptop (Iperf client) and (b) vehicle-mounted modem (VMM)

2.1.4 Software

- Laptop: Iperf, MeshTray, MeshView
- Server: Iperf

2.1.5 Test Procedure

Prerequisites

- Investigators have determined which IAPs will be used and which will be disconnected
- Investigators have (a) driven to site, (b) determined favored association of VMM with IAP-2, and (c) set up VMM to associate with IAP-2.
- Investigators have marked the location for the stationary vehicle and obtained latitude/ longitude.
- At least three personnel are available: Investigator-1 at stationary vehicle, Investigator-2 at IAP-2, and Investigator-3 at Iperf server (in Bldg. 821)
- Logistics are in place for conference call so investigators can dial in to coordinate time.
- If needed, investigator has access to the Research Site so that cable can be disconnected.

No.	Step
1	Investigator-1 parks vehicle at location determined in prerequisites.
2	Investigator-1 powers up laptop.
3	Investigator-1 verifies through routing tables (using MeshTray) that LOS exists between VMM in stationary vehicle and both IAP-1 and IAP-2.
4	All: via conference call, start test (T) at signal from Investigator-3. *Note*: Duration of test is expected to be 2 minutes.
5	At time = T, Investigator-1 measures and records throughput from mobile client to Iperf server using UDP packets.
6	At T + 60 seconds (announced via conference call by Investigator-3), Investigator-2 unplugs cable from IAP-2.
7	Investigator-1 observes and records whether IAP-1 provides alternate path.
8	If IAP-1 provides alternate path, Investigator-1 records the amount of time taken for the path to heal and measures throughput on the new path.
9	(a) Reconnect cable at IAP-2 and then (b) repeat Steps 5 through 8 for TCP packets.
10	Turn off 802.11 at IAP-1 and IAP-2, and repeat Steps 4 through 9.

2.2 *Experiment 2: Failover at IAP with Mesh Wireless Router*

2.2.1 Objective

From an MWR perspective, (1) observe failover of an IAP that loses wired connectivity, (2) measure baseline throughputs, and (3) capture how long it takes the network to reform.

2.2.2 Description

This test is essentially a repeat of Experiment 1, but an MWR replaces the mobile client as the node associated to the primary IAP (Figure 10). The investigators will check continuity by associating a stationary mobile client (laptop and VMM) to the MWR (which is communicating to an IAP). Investigators will check throughput on (a) the path between client, MWR, IAP, and Iperf server, and (b) the same path after the is disconnected from the wired network, for both UDP and TCP.

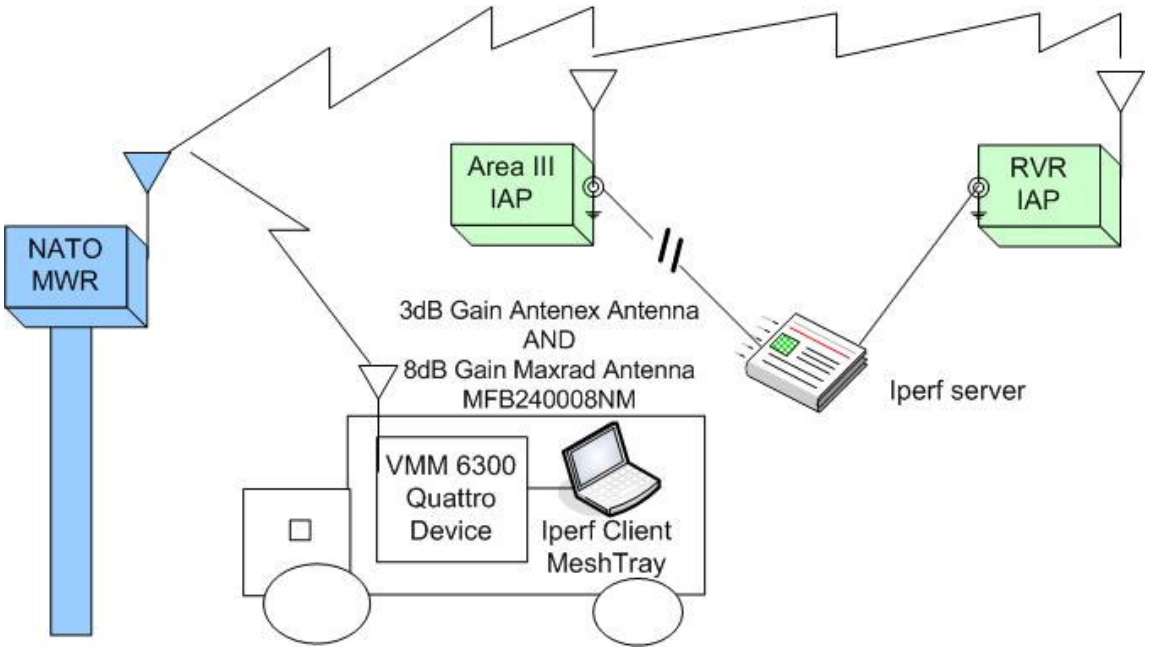


Figure 10. Experiment 2 Setup

2.2.3 Devices

- Two IAPs (RVR IAP, Area III IAP) with two radios active (2.4 GHz mesh, 802.11)
- 3 dB gain Antenex antenna and 8 dB gain Maxrad antenna (fiberglass omnidirectional)
- Iperf server (located in Building 821, room 2137)

- Stationary vehicle with (a) laptop (Iperf client) and (b) VMM
- MWR (Storage Site)

2.2.4 Software

- Laptop: Iperf, MeshTray, MeshView
- Server: Iperf

2.2.5 Test Procedure

Prerequisites
• Investigators have (a) driven to site and (b) determined path back to server from the stationary vehicle (VMM). • Investigators have determined which IAPs will be used and which will be disconnected • Investigators have marked the location for the stationary vehicle and obtained latitude/longitude. • At least three personnel are available: Investigator-1 at stationary vehicle, Investigator-2 at IAP to be disconnected, and Investigator-3 at Iperf server (in Bldg. 821) • Logistics are in place for conference call so investigators can dial in to coordinate time. • If needed, investigator has access to Area III site.

No.	Step
1	Investigator-1 parks vehicle at location determined in prerequisites.
2	Investigator-1 powers up laptop .
3	Investigator-1 verifies through routing tables (MeshTray) that LOS exists between VMM in stationary vehicle and MWR.
4	Investigator-1 confirms there is no LOS between VMM in stationary vehicle and IAP-1 and IAP-2.
5	All: via conference call, start test (T) at signal from Investigator-3. *Note*: Duration of test is expected to be 2 minutes.
6	At time = T, Investigator-1 measures and records throughput from mobile client to Iperf server using UDP packets.
7	At T + 60 seconds (announced via conference call by Investigator-3), Investigator-2 unplugs cable from wired IAP (see prerequisites).
8	Investigator-1 observes and records whether wired IAP provides alternate path.
9	If RVR IAP provides alternate path, Investigator-1 measures throughput.
10	Investigator-3 allows Iperf to run until a new connection has been formed and notes timestamp.
11	(a) Reconnect cable and then (b) repeat Steps 5 through 10 for TCP packets.
12	Turn off 802.11 at IAP-1 and IAP-2 and repeat Steps 5 through 11.

2.3 Experiment 3: Single IAP with Mesh at Speeds >30 mph

2.3.1 Objective

With a single IAP, measure throughput degradation of MEA links at speeds above 30 mph.

2.3.2 Description

Investigators will associate a mobile client (Figure 11) with an IAP. While driving, investigators will check continuity and how many seconds the client remains in the target area or zone of connectivity. After establishing a route that can be repeated, with accurately measured start/stop points, the investigators will (a) drive past an IAP at 10, 20, 30, 40, and 50 mph and (b) gauge performance in terms of throughput for UDP. Investigators will repeat route at stated speeds to gauge performance for TCP. Figure 12 shows the route taken for both Experiments 3 and 4.

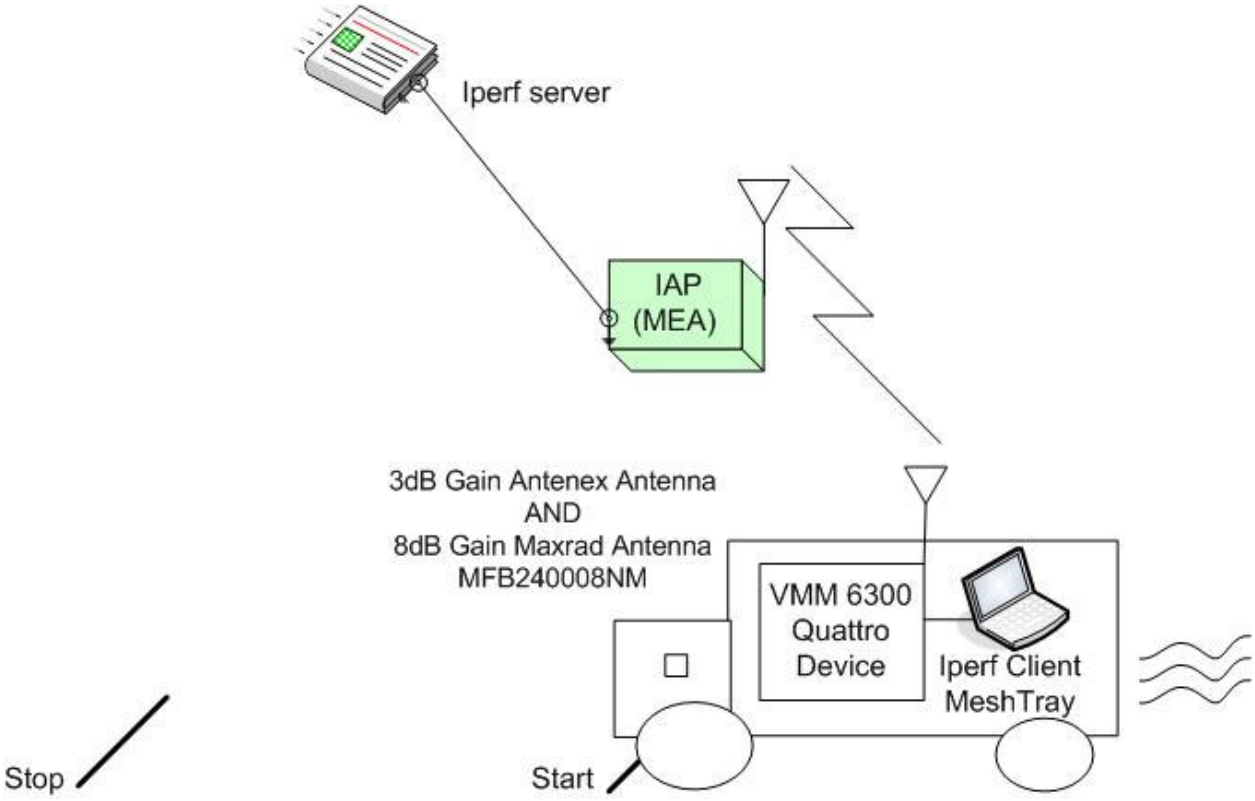


Figure 11. Experiment 3 Setup

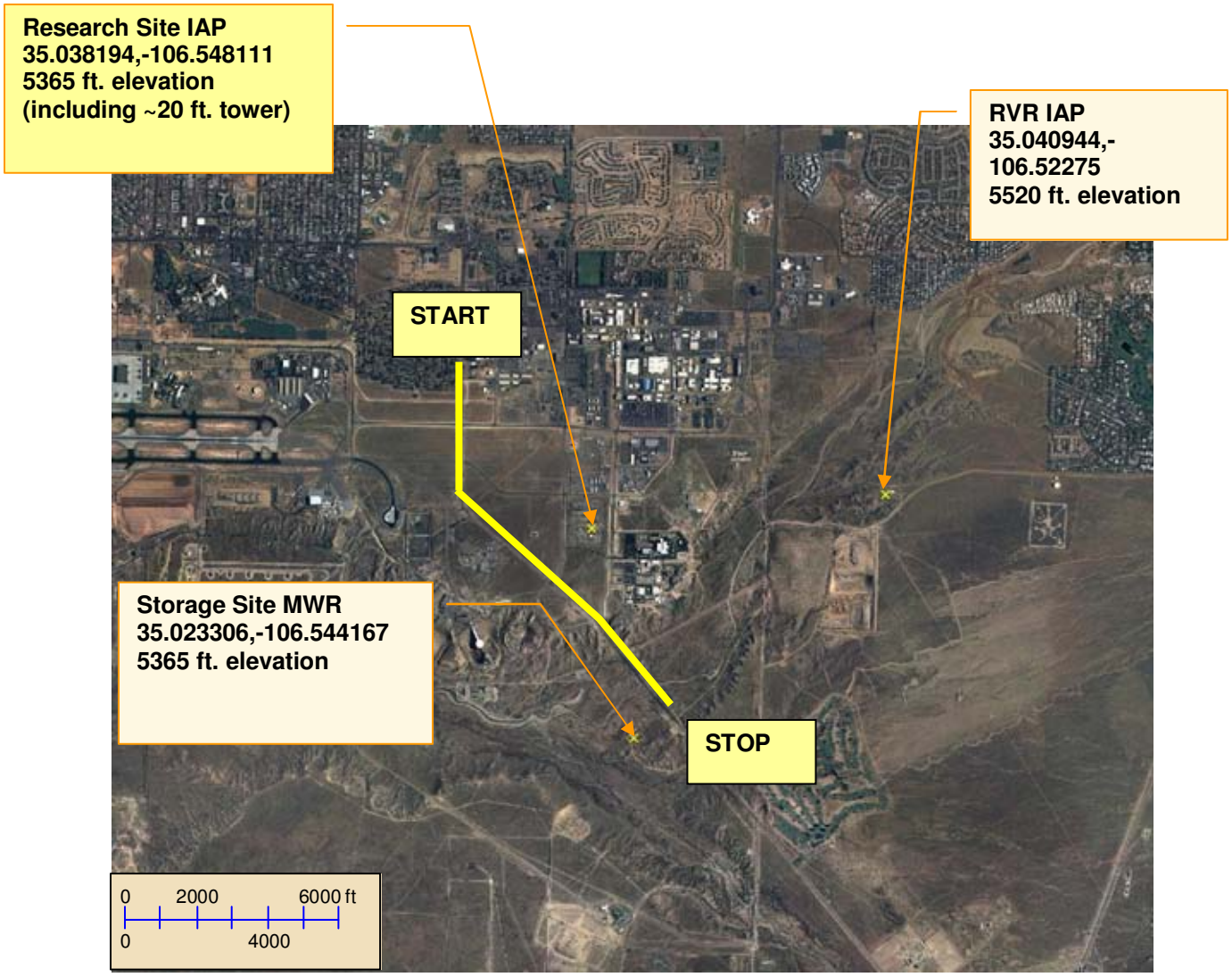


Figure 12. Route for Experiments 3 and 4.

2.3.3 Devices

- One IAP with 2.4-GHz mesh radio active
- 3 dB gain Antenex antenna and 8 dB gain Maxrad antenna (MBF 240008NM) (fiberglass omni)
- Iperf server (located in Building 821, room 2137)
- Mobile vehicle with (a) laptop (Iperf client) and (b) VMM

2.3.4 Software

- Laptop: Iperf, MeshTray, MeshView
- Server: Iperf

2.3.5 Steps

Prerequisites

- Based on the path, investigators have determined which IAP will be used.
- Investigators have (a) driven to site, (b) determined favored association of VMM with IAP-1, and (c) set up VMM to associate with IAP-1.
- At least three personnel are available: Investigator-1 as the driver of vehicle, Investigator-2 to run Iperf client in vehicle, and Investigator-3 at Iperf server (in Bldg. 821).
- Investigator has determined course that indicates range for IAP-1 (see Figure 12).
- Investigator has accurately determined start/stop points, marking with spray paint.
- Note distance between the course and the IAP including the angle of the mobile unit in relation to the IAP (e.g., parallel to the IAP, moving toward the IAP, or moving away).
- Investigator has determined whether amplification is needed and configured such appropriately.

No.	Step
1	Investigator-1 parks vehicle at Start location determined in prerequisites.
2	Investigator-2 powers up laptop.
3	Investigator-2 verifies through routing tables (MeshTray) that LOS exists between VMM and IAP-1 (for example, confirming signal levels in MeshTray).
4	At time = T, Investigator-1 drives pre-specified course at 10 mph.
5	Investigator-1 indicates when vehicle is up to speed so that Investigator-2 can record time T.
6	Investigator-2 measures and records throughput from mobile client to Iperf server using UDP packets.
7	Investigator-1 indicates when vehicle is below speed so that Investigator-2 can record time T.
8	For return trip (Stop to Start), repeat Steps 4 through 7.
9	Repeat Steps 4 through 8 with vehicle traveling course at 20 mph.
10	Repeat Steps 4 through 8 with vehicle traveling course at 30 mph.
11	Repeat Steps 4 through 8 with vehicle traveling course at 40 mph.
12	Repeat Steps 4 through 8 with vehicle traveling course at 50 mph.
13	Repeat Steps 4 through 12 for TCP packets.

2.4 Experiment 4: Single IAP with 802.11 at Speeds >30 mph

2.4.1 Objective

With a single IAP, measure throughput degradation of 802.11 links at speeds above 30 mph.

2.4.2 Description

This test repeats Experiment 3 but with an 802.11 access point (Figure 13). The IAP will be reconfigured for this purpose by disabling the MEA radio and enabling the 802.11 radio for client access rather than backbone connectivity. The route taken can be seen in Figure 12.

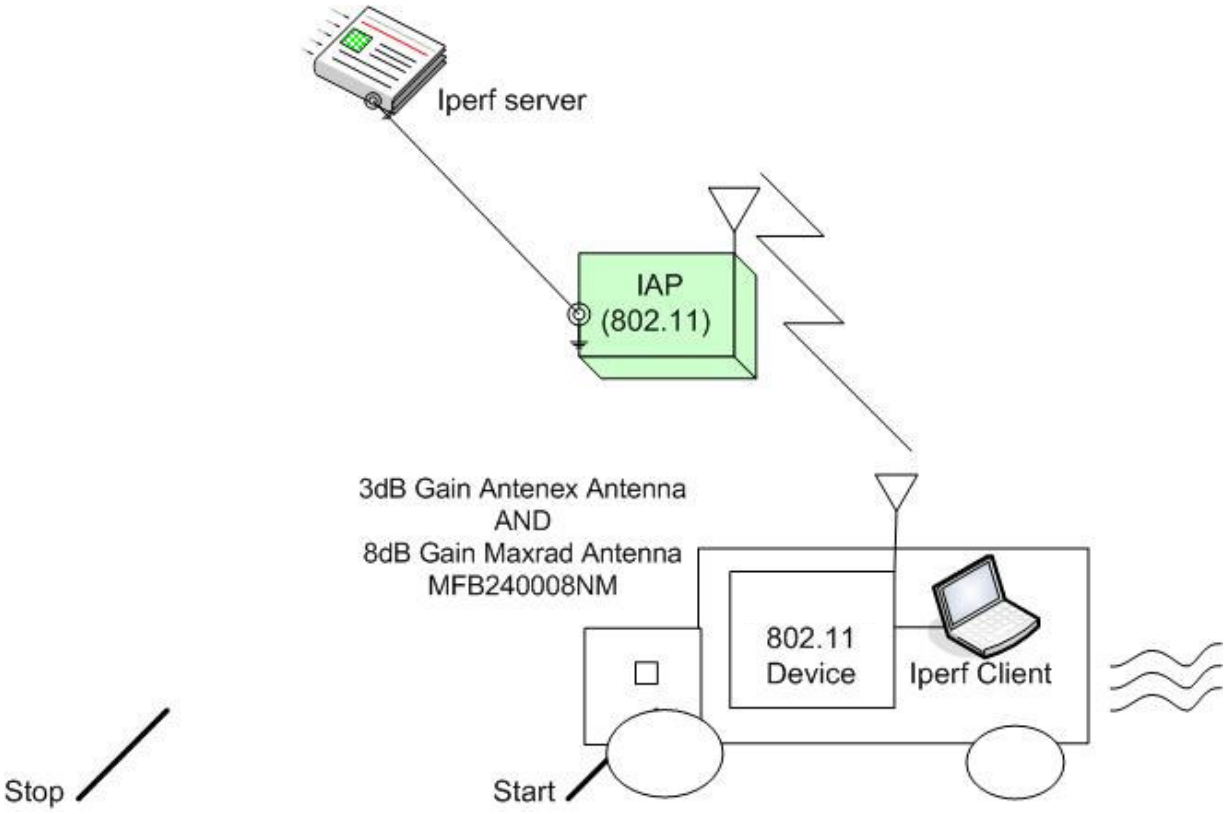


Figure 13. Experiment 4 Setup

2.4.3 Devices

- One IAP configured for 802.11 radio
- 3 dB gain Antenex antenna and 8 dB gain Maxrad antenna (MBF 240008NM) (fiberglass omni)
- Vehicle with laptop (Iperf client) and Proxim ORiNOCO 802.11 B/G PCMCIA card with external antenna

- Iperf server (located in Building 821, room 2137)

2.4.4 Software

- Laptop: Iperf, ORiNOCO driver software
- Server: Iperf

2.4.5 Steps

Prerequisites

- Based on the path, investigators have determined which IAP will be used.
- Investigators have (a) driven to site, (b) determined favored association of 802.11 device with IAP-1, and (c) set up 802.11 device to associate with IAP-1.
- At least three personnel are available: Investigator-1 as the driver of vehicle, Investigator-2 to run Iperf client in vehicle, and Investigator-3 at Iperf server (in Bldg. 821).
- Investigator has determined course that indicates range for IAP-1. (See Figure 12.)
- Investigator has accurately determined start/stop points, marking with spray paint.
- Note distance between the course and the IAP including the angle of the mobile unit in relation to the IAP (e.g., parallel to the IAP, moving toward the IAP, or moving away).

No.	Step
1	Investigator-1 parks vehicle at Start location determined in prerequisites.
2	Investigator-2 powers up laptop.
3	Investigator-2 verifies reasonable connectivity between 802.11 device in vehicle and IAP-1 using ORiNOCO and Windows connectivity message.
4	At time = T, Investigator-1 drives pre-specified course at 10 mph.
5	Investigator-1 indicates when vehicle is up to speed so that Investigator-2 can record time T.
6	Investigator-2 measures and records throughput from mobile client to Iperf server using UDP packets.
7	Investigator-1 indicates when vehicle is below speed so that Investigator-2 can record time T.
8	For return trip (Stop to Start), repeat Steps 4 through 7.
9	Repeat Steps 4 through 8 with vehicle traveling course at 20 mph.
10	Repeat Steps 4 through 8 with vehicle traveling course at 30 mph.
11	Repeat Steps 4 through 8 with vehicle traveling course at 40 mph.
12	Repeat Steps 4 through 8 with vehicle traveling course at 50 mph.
13	Repeat Steps 4 through 12 for TCP packets.

2.5 Experiment 5: Handoff with Mesh at Speeds >30 mph

2.5.1 Objective

Incorporating handoffs, measure throughput degradation of MEA links at speeds above 30 mph.

2.5.2 Description

Investigators will set up two or three IAPs in a rough line with overlapping coverage areas (Figure 14). (Note that investigators will also consider 802.11 access; see Experiment 6.) While driving, investigators will check continuity and how many seconds the client remains in the target area or zone of connectivity. After establishing a route that can be repeated, with accurately measured start/stop points, the investigators will (a) drive past the IAPs at 10, 20, 30, 40, and 50 mph, and (b) gauge performance in terms of throughput for UDP. Investigators will repeat route at stated speeds to gauge performance for TCP. The route taken is shown in Figure 15.

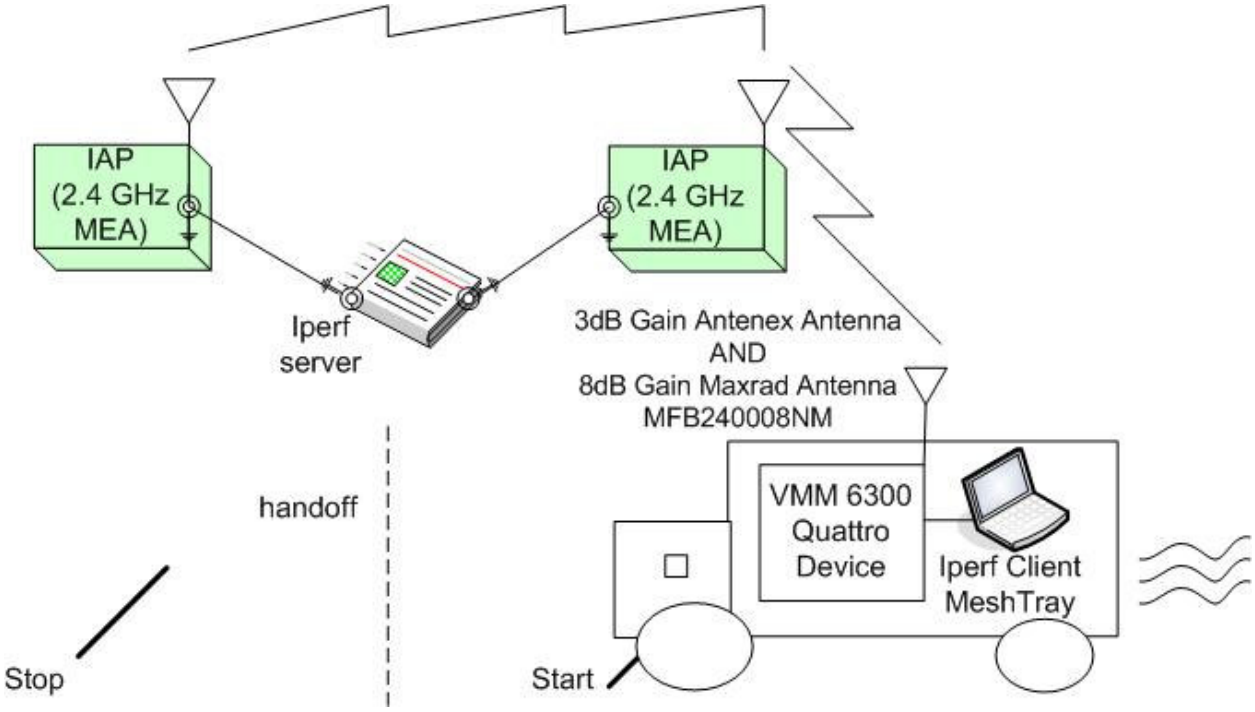


Figure 14. Experiment 5 Setup

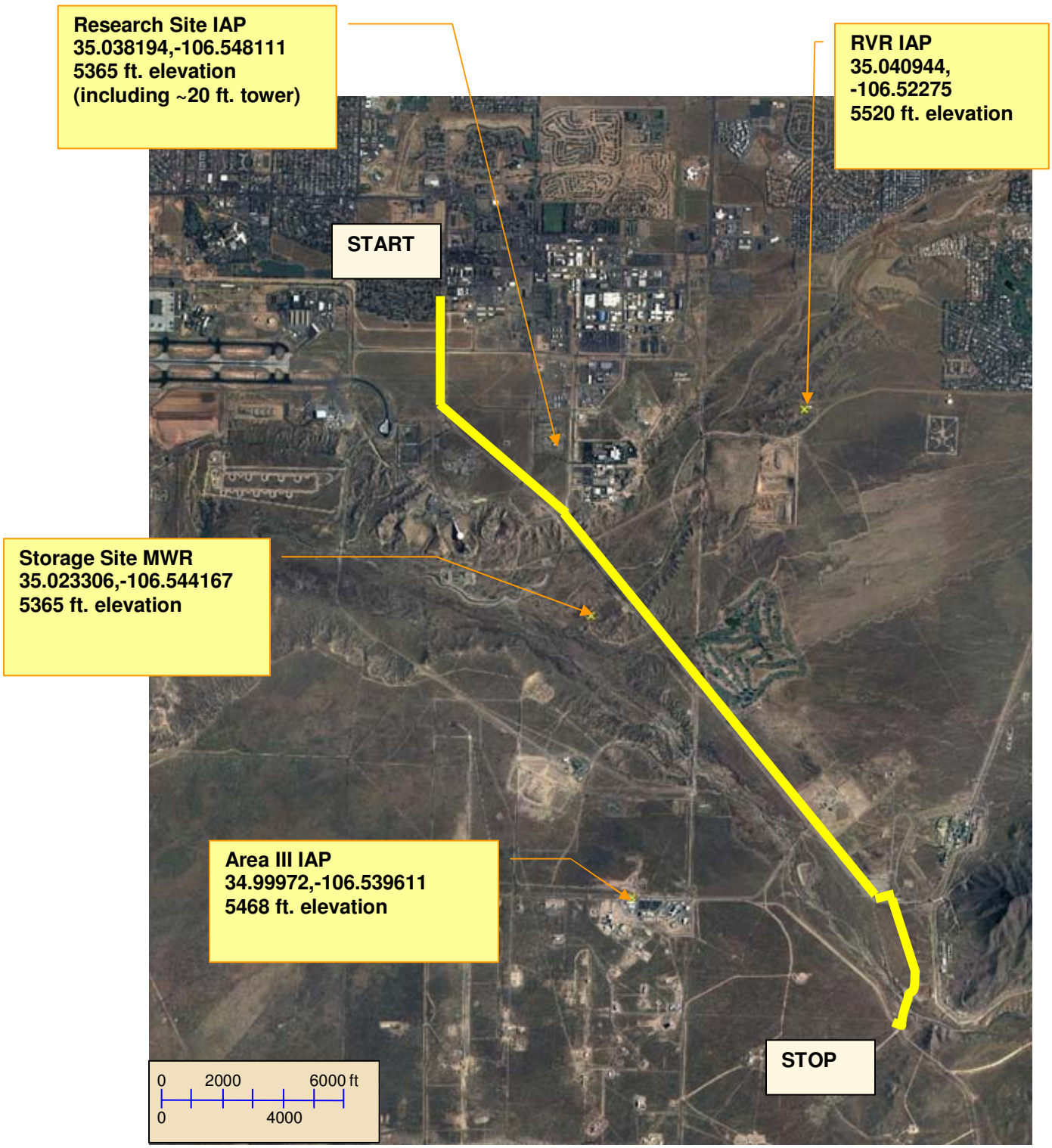


Figure 15. Route for Experiments 5 and 6.

2.5.3 Devices

- At least two IAPs with two radios active (2.4 GHz mesh, 802.11)

- 3 dB gain Antenex antenna and 8 dB gain Maxrad antenna (MBF 240008NM) (fiberglass omni)
- Mobile vehicle with (a) laptop (Iperf client) and (b) VMM
- Iperf server (located in Building 821, room 2137)

2.5.4 Software

- Laptop: Iperf, MeshTray, MeshView
- Server: Iperf

2.5.5 Steps

Prerequisites

- Based on the path, investigators have determined which IAPs will be used.
- Investigators have (a) driven to site, (b) determined favored association of VMM with IAPs, and (c) set up VMM to associate with IAP-1.
- At least three personnel are available: Investigator-1 as driver in vehicle, Investigator-2 at Iperf client in vehicle, and Investigator-3 at Iperf server (in Bldg. 821).
- Investigator has determined course that indicates range for IAP-1 and IAP-2 (see Figure 15).
- Investigator has accurately determined start/stop points, marking with spray paint.
- Note distance between the course and the IAP including the angle of the mobile unit in relation to the IAP (e.g., parallel to the IAP, moving toward the IAP, or moving away).

No.	Step	☑
1	Investigator-1 parks vehicle at location determined in prerequisites.	
2	Investigator-2 powers up laptop.	
3	Investigator-2 verifies through routing tables (MeshTray) that LOS exists (for example, confirming signal levels in MeshTray).	
4	Investigator-1 confirms LOS from IAP-1 to client vehicle.	
5	Investigator-1 confirms LOS from IAP-2 to client vehicle.	
6	At time = T, Investigator-1 drives pre-specified course at 10 mph.	
7	Investigator-1 indicates when vehicle is up to speed so that Investigator-2 can record time T.	
8	Investigator-2 measures and records throughput from mobile client to Iperf server using UDP packets.	
9	Investigator-1 indicates when vehicle is below speed so that Investigator-2 can record time T.	
10	For return trip (Stop to Start), repeat Steps 6 through 9.	
11	Repeat Steps 6 through 10 with vehicle traveling course at 20 mph.	
12	Repeat Steps 6 through 10 with vehicle traveling course at 30 mph.	
13	Repeat Steps 6 through 10 with vehicle traveling course at 40 mph.	
14	Repeat Steps 6 through 10 with vehicle traveling course at 50 mph.	
15	Repeat Steps 6 through 14 for TCP packets.	
16	Turn off 802.11 at IAP-1 and IAP-2 and repeat Steps 6 through 15.	

2.6 Experiment 6: Handoff with 802.11 at Speeds >30 mph

2.6.1 Objective

Incorporating handoffs, measure throughput degradation of 802.11 links at speeds above 30 mph.

2.6.2 Description

This test is a repeat of Experiment 5 with 802.11 access points (Figure 16).

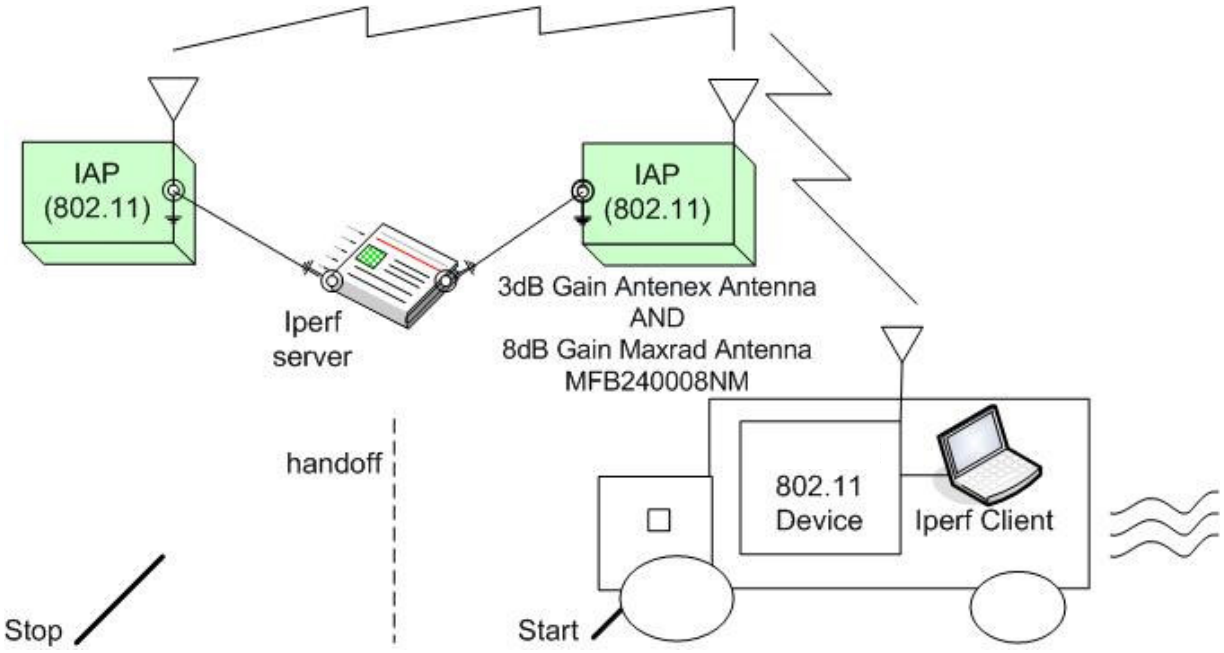


Figure 16. Experiment 6 Setup

2.6.3 Devices

- Two IAPs configured for 802.11
- 3 dB gain Antenex antenna and 8 dB gain Maxrad antenna (MBF 240008NM) (fiberglass omni)
- Vehicle with laptop (Iperf client) and Proxim ORiNOCO 802.11 B/G PCMCIA card with external antenna
- Iperf server (located in Building 821, room 2137)

2.6.4 Software

- Laptop: Iperf, ORiNOCO driver software
- Server: Iperf

2.6.5 Steps

Prerequisites

- Based on the path, investigators have determined which IAPs will be used.
- Investigators have (a) driven to site, (b) determined favored association of 802.11 device with IAP-1, and (c) set up 802.11 device to associate with IAP-1.
- At least three personnel are available: Investigator-1 as driver in vehicle, Investigator-2 at Iperf client in vehicle, and Investigator-3 at Iperf server (in Bldg. 821).
- Investigator has determined course that indicates range for IAPs (see Figure 15).
- Investigator has accurately determined start/stop points, marking with spray paint.
- Note distance between the course and the IAP including the angle of the mobile unit in relation to the IAP (e.g., parallel to the IAP, moving toward the IAP, or moving away).
- Investigator has determined whether amplification is needed and configured such appropriately.

No.	Step
1	Investigator-1 parks vehicle at Start location determined in prerequisites.
2	Investigator-1 powers up laptop.
3	Investigator-1 verifies reasonable connectivity through ORiNOCO and Windows connectivity message.
4	Investigator-1 confirms LOS from IAP-1 to client vehicle.
5	Investigator-1 confirms LOS from IAP-2 to client vehicle.
6	At time = T, Investigator-1 drives pre-specified course at 10 mph.
7	Investigator-1 indicates when vehicle is up to speed so that Investigator-2 can record time T.
8	Investigator-2 measures and records throughput from mobile client to Iperf server using UDP packets.
9	Investigator-1 indicates when vehicle is below speed so that Investigator-2 can record time T.
10	Repeat Steps 6 through 9 for return trip.
11	Repeat Steps 6 through 10 with vehicle traveling course at 20 mph.
12	Repeat Steps 6 through 10 with vehicle traveling course at 30 mph.
13	Repeat Steps 6 through 10 with vehicle traveling course at 40 mph.
14	Repeat Steps 6 through 10 with vehicle traveling course at 50 mph.
15	Repeat Steps 6 through 14 for TCP packets.

2.7 Experiment 7: Determine Performance Difference with Mesh and 802.11 as Backbone

2.7.1 Objective

Given the same frequency band, determine performance difference, if any, between (a) using 802.11 as the backbone that connects the infrastructure devices and (b) using MEA as the backbone.

2.7.2 Description

Investigators will build a network using two radios (MEA, 802.11) on the 2.4-GHz band in each wireless infrastructure device (IAPs, MWRs) (Figure 17). Investigators will associate to an IAP and measure throughput for both protocol types, UDP and TCP. Investigators will then rebuild the network with only the 2.4-GHz MEA radio in each IAP and MWR. Investigators will again associate to the selected IAP and measure throughput for UDP and TCP.

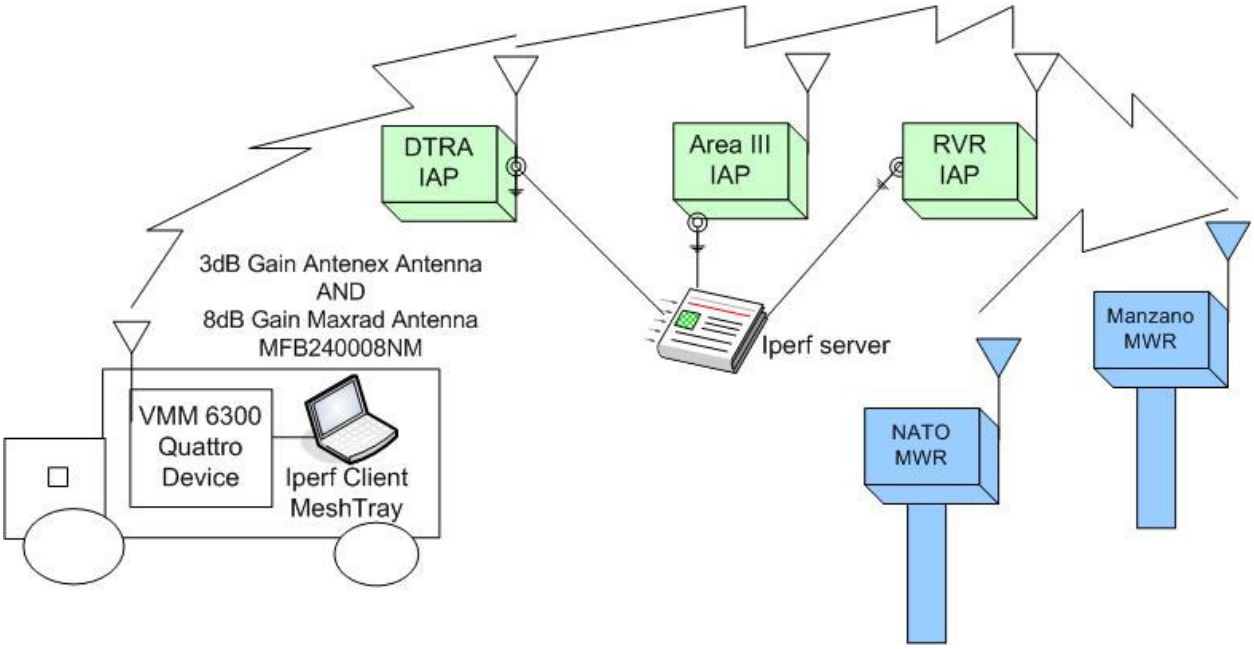


Figure 17. Experiment 7 Setup

2.7.3 Devices

- Two or more IAPs with two radios active (2.4 GHz mesh, 802.11)
- One or more MWRs
- 3 dB gain Antenex antenna and 8 dB gain Maxrad antenna (MBF 240008NM) (fiberglass omni)
- Iperf server (located in Building 821, room 2137)

- Stationary vehicle with (a) laptop (Iperf client) and (b) VMM

2.7.4 Software

- Laptop: Iperf, MeshTray, MeshView
- Server: Iperf

2.7.5 Steps

Prerequisites
• Investigators have determined which IAPs will be used.
• Investigators have determined which MWRs will be used.
• Investigators have (a) driven to site, (b) determined favored association of VMM with IAP an, and (c) set up VMM to associate with the selected IAP.
• Investigators have marked the location for the stationary vehicle and obtained latitude/longitude.
• At least three personnel are available: Investigator-1 at vehicle, Investigator-2 at Iperf client in vehicle, and Investigator-3 at Iperf server (in Bldg. 821).

No.	Step
1	Investigator-1 parks vehicle at location determined in prerequisites.
2	Investigator-2 powers up laptop.
3	Investigator-2 verifies through routing tables (MeshTray) that LOS exists (for example, confirming signal levels in MeshTray).
4	Investigator-3 configures the wireless network infrastructure devices to use (a) the 2.4-GHz MEA radio for client communication and (b) the 2.4-GHz 802.11 radio for backbone communication between wireless infrastructure devices.
5	Investigator-2 associates with an IAP over the 2.4-GHz MEA radio.
6	Investigator-2 measures throughput from client through IAP to Iperf server for UDP packets.
7	Investigator-3 disables the 802.11 radios.
8	Investigator-2 associates with the same IAP as in Step 5.
9	Investigator-2 measures throughput from client through IAP to Iperf server for UDP packets.
10	Repeat Steps 4 through 9 for TCP packets.

3 Results of Experiments

A challenge in wireless network performance testing is obtaining repeatable results. The inability to control wireless channel characteristics in outdoor environments, makes testing difficult. Most outdoor environments suffer from radio frequency (RF) interference in the unlicensed frequency spectrum. To further complicate the test environment, the Motomesh testbed is located on a U.S. Air Force Base, which has a significant amount of RF activity. Interference can vary due to the presence of structures, fences, or other vehicles. At the frequencies used in these experiments, small spatial changes can have large impacts on the multipath interference. In addition, the activity from all sources varies significantly over time, so that snapshots measured within minutes may differ. This variance makes attempts to isolate background activity through measurements before and after the tests infeasible. Therefore, the investigators did not measure the dynamic background RF activity during the experiments.

Because the mobile wireless testbed at Sandia is fairly sparse (with four access points covering about 64 square miles), throughput is limited. On the route covered by the vehicle in some of the experiments, the closest approach to an access point was about 1500 feet. Greater distances between nodes (access points or wireless clients) imply weaker communication links, and lower throughput.

Many experiments had to be narrowed in scope or abbreviated, in the interest of time and limited funding. For expediency, Jperf (a Java graphical front end for easy configuration of the Iperf utility) was used for traffic generation. *Because of packet loss rates preventing effective TCP connections, experiments were performed using the User Datagram Protocol (UDP).*

3.1 Results of Experiment 1: Failover at IAP with Mobile Client

The intent of this experiment was to find out, from the client perspective, what happens to an IAP that loses wired connectivity. The investigators were interested in finding out whether the IAP drops any clients associated to it and if the IAP shuts down or turns (effectively) into an MWR.

At 35 seconds into the communication test, the wired connection was removed between the IAP with which the client was associated, and the wired network. 255 seconds later the network reformed, with the disconnected IAP appearing as an MWR in the WMN. The data throughput prior to disconnecting the IAP from the wired network, was about 1 Mbps. Once the network reformed and came back into equilibrium, the throughput was about 505 Kbps. This is close to the performance expected for a two hop (client-MWR-IAP) wireless network. This data is shown in Figures 18 and 19 for the test using the 3 dBi antenna.

The experiment was repeated using an antenna with a gain of 8 dB. Similar results were obtained. Once the network reformed, the throughput very quickly stabilized at approximately 400 Kbps, as shown in Figure 20.

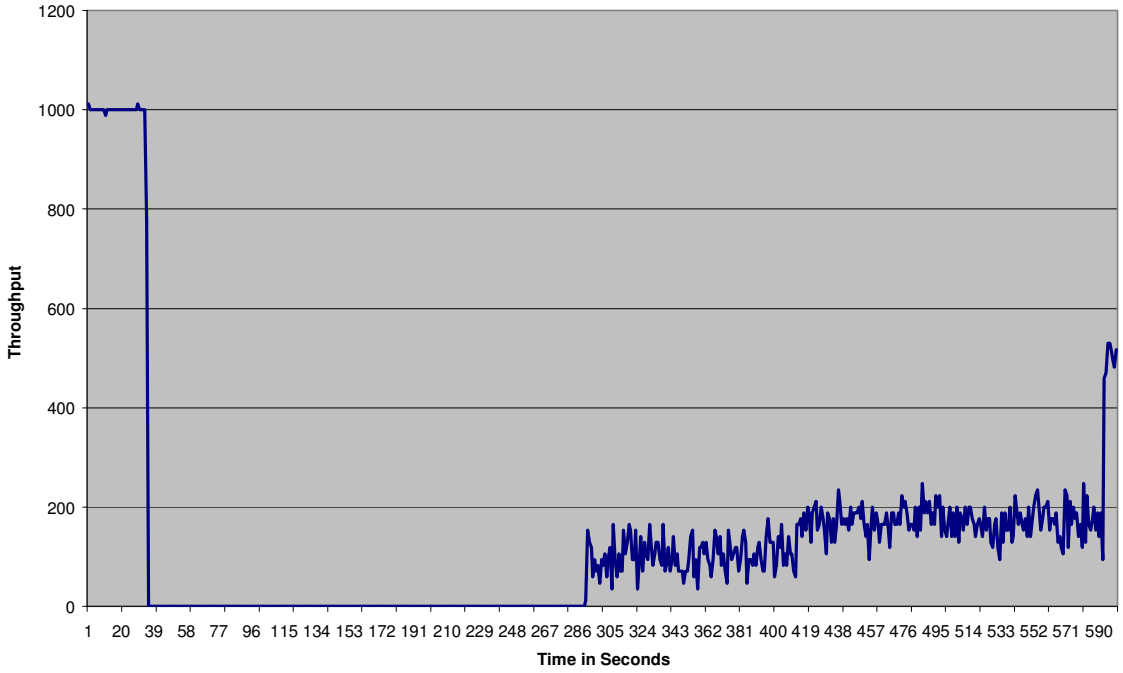


Figure 18. Throughput with 3 dB Gain Antenna (Kbits/sec)

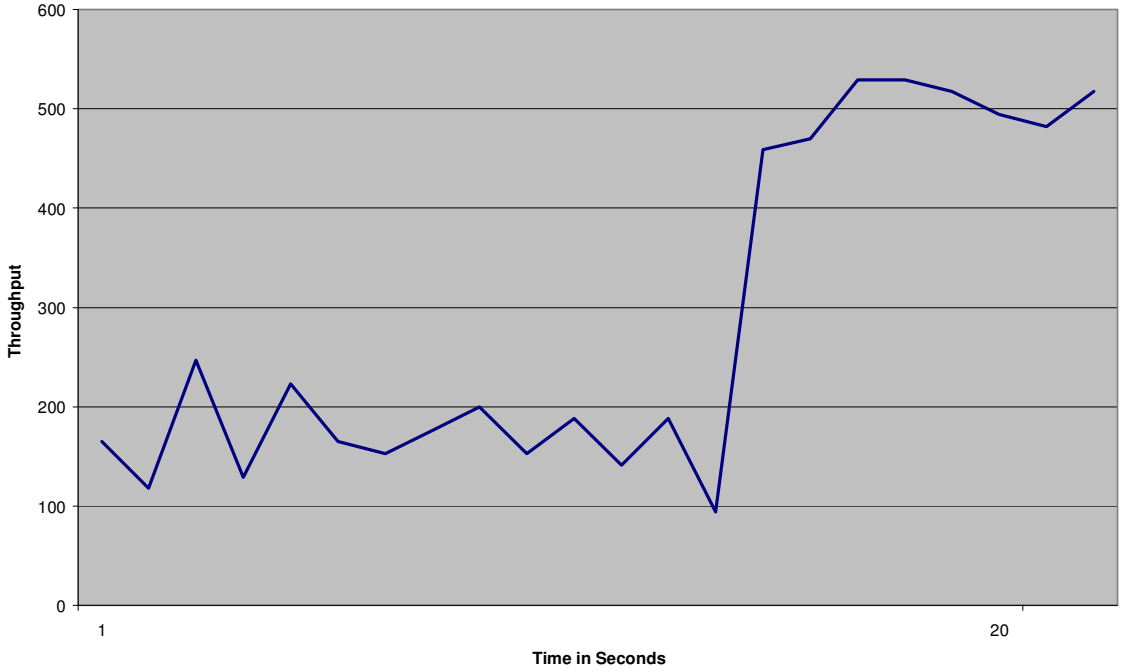


Figure 19. Exploded view of data points at time 578 (seconds) through 599 (seconds)

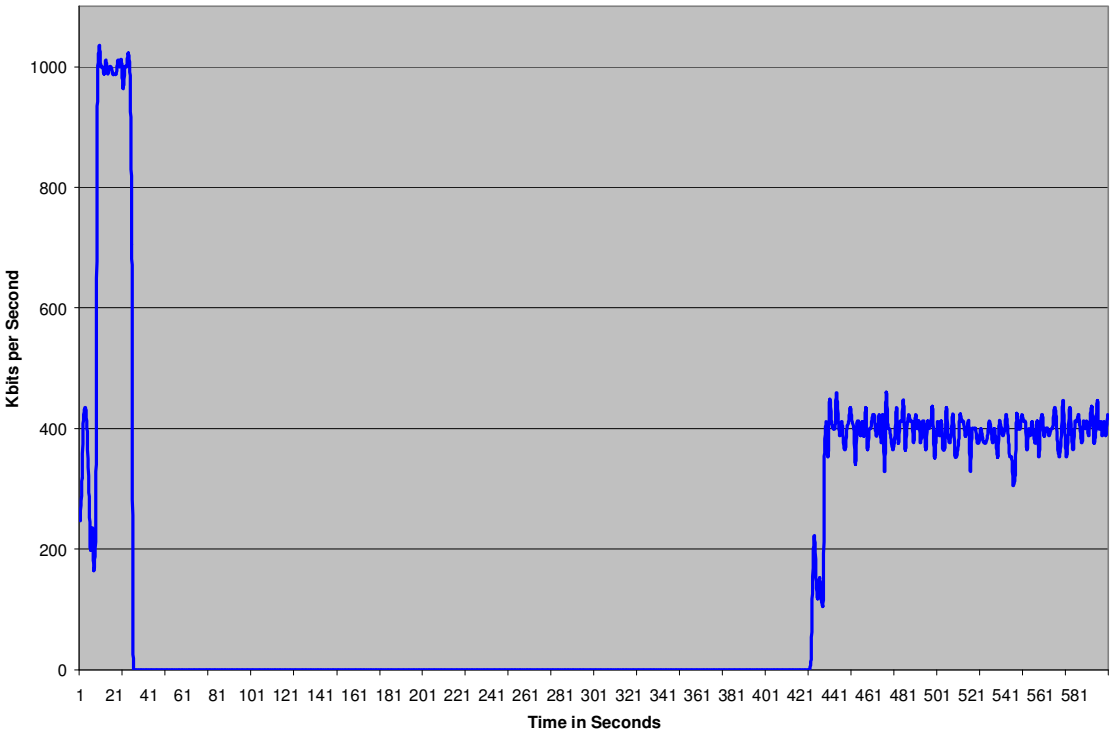


Figure 20. Throughput with 8 dB Gain Antenna (Kbits/sec)

3.2 Results of Experiment 2: Failover at IAP with Mesh Wireless Router

The intent of this experiment was to find out, from an MWR perspective, what happens to an IAP that loses wired connectivity. This test is essentially a repeat of Experiment 1, but an MWR replaces the mobile client. (A mobile client is still needed to generate network traffic, but the mobile client is now associated to an MWR, which in turn has a wireless connection to an IAP.) The investigators were interested in learning whether the IAP would just go off-line, forcing the MWR to communicate elsewhere, or if the IAP would effectively turn into another MWR and route the traffic on through the network.

At 31 seconds into the communication test, the wired connection was removed between the IAP with which the MWR was communicating, and the wired network. 79 seconds later the network reformed, with the disconnected IAP appearing as another MWR in the WMN. The data throughput prior to disconnecting the IAP from the wired network, was about 170 Kbps. Once the network reformed and came back into equilibrium, the throughput was about 220 Kbps (Figure 21). This is close to the performance expected for a three hop (client-MWR-MWR-IAP) wireless network. The reader may find it strange that the throughput increased when another hop was added. A potential explanation for this is as follows.

It is a possible that the experimenters should have waited a longer period of time for the data to become more stable before disconnecting the IAP. At 31 seconds into the test, it may not have been in equilibrium with respect to routes and such. There may have been higher two hop performance (closer to 400-500Kbps throughput) before disconnecting the IAP from the wired portion, if the network was into a more 'steady state.'

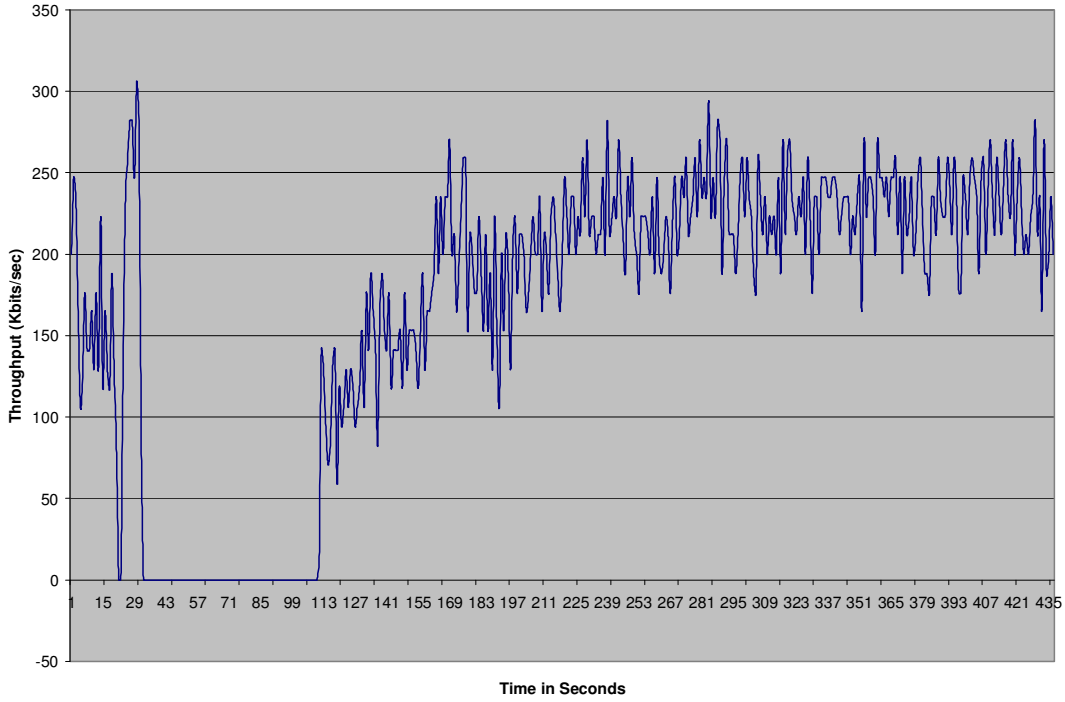


Figure 21. IAP Failover to MWR

3.3 Results of Experiment 3: Single IAP with Mesh at Speeds >30 mph

The intent was to find out, using only a single IAP with no handoffs involved, whether there was throughput degradation of MEA links at speeds above or below 30 mph. This test involved driving past an IAP at 10, 20, 30, 40, and 50 mph and gauging throughput performance in terms of bits per second for UDP. The investigators tried to repeat this experiment on the driven route at the stated speeds to gauge performance with TCP, but could not maintain a usable TCP connection long enough to collect meaningful data. This is understandable in light of the findings of Bergamo, et al. [4] regarding packet loss rates greater than 1% while using TCP.

The route chosen for this experiment and Experiment 4 was picked for where the experimenters could obtain wireless connectivity and could drive at the speeds selected for the experiments, not for the amount of multipath interference that might be available. Unfortunately the route is fairly flat and open. There were only a few obstacles that would be likely to cause multipath interference on our test course.

Our route included approximately 7200 feet of usable connectivity, once the vehicle was up to speed. The vehicle's closest approach to the wireless access point was about 1500 feet and the maximum distance from the access point to the vehicle on the route was about 4200 feet. Connected to the VMM, we used an omnidirectional antenna with a 3 dB gain, mounted on the roof of the client vehicle.

To discount outlying data points when calculating average throughput in this experiment and the next, we computed the average and standard deviation over each data set and discarded samples whose throughput fell more than one standard deviation away from the average. This eliminated anomalous high points and samples where no data got through. (We would like to have eliminated all outliers beyond two standard deviations but the 802.11 data was so variable – thus generating such large standard deviations – that in many cases this would not have filtered out any outlying data points.) Once the outlying data samples (with respect to throughput) were filtered out, we computed the new average throughput and standard deviation over the remaining samples

The MEA throughput did not vary significantly over the speed range tested. Both the raw data and the processed data are shown in Figures 22-41 for the five tested vehicle speeds in both directions of the course.

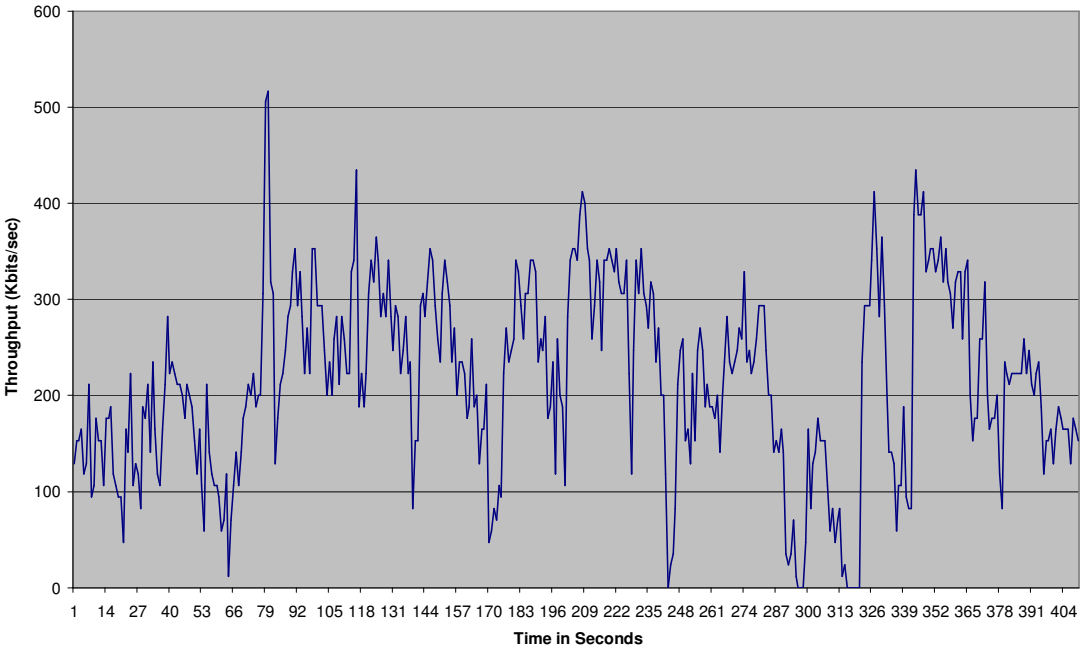


Figure 22. 10 mph north-to-south raw data for MEA

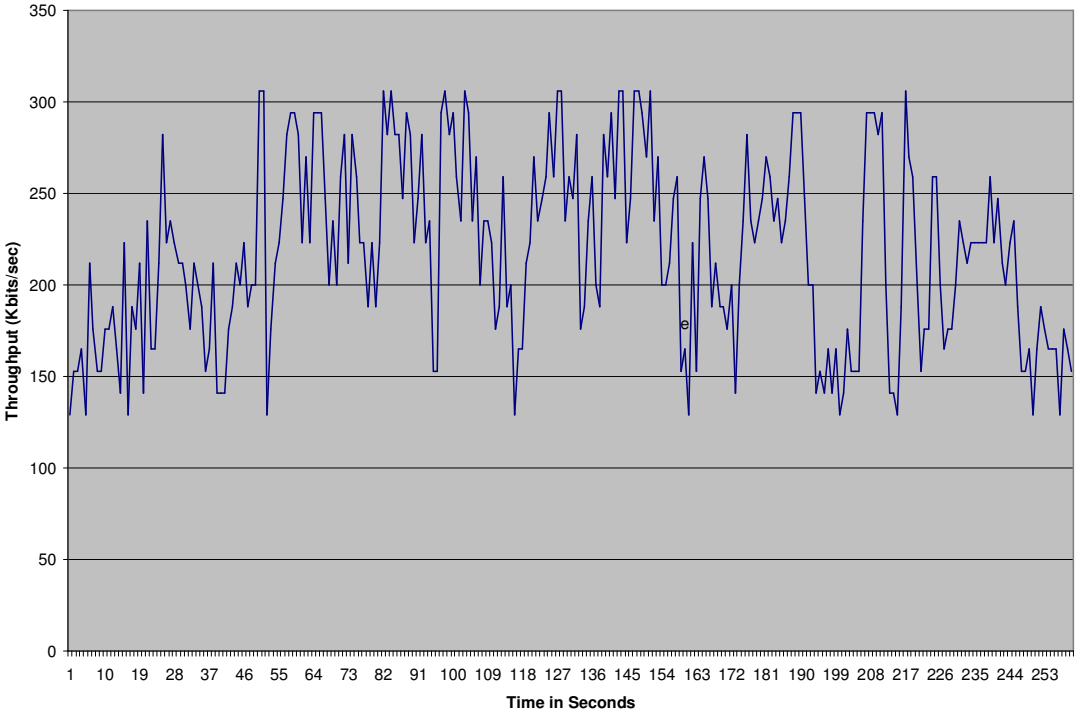


Figure 23. 10 mph north-to-south processed data for MEA

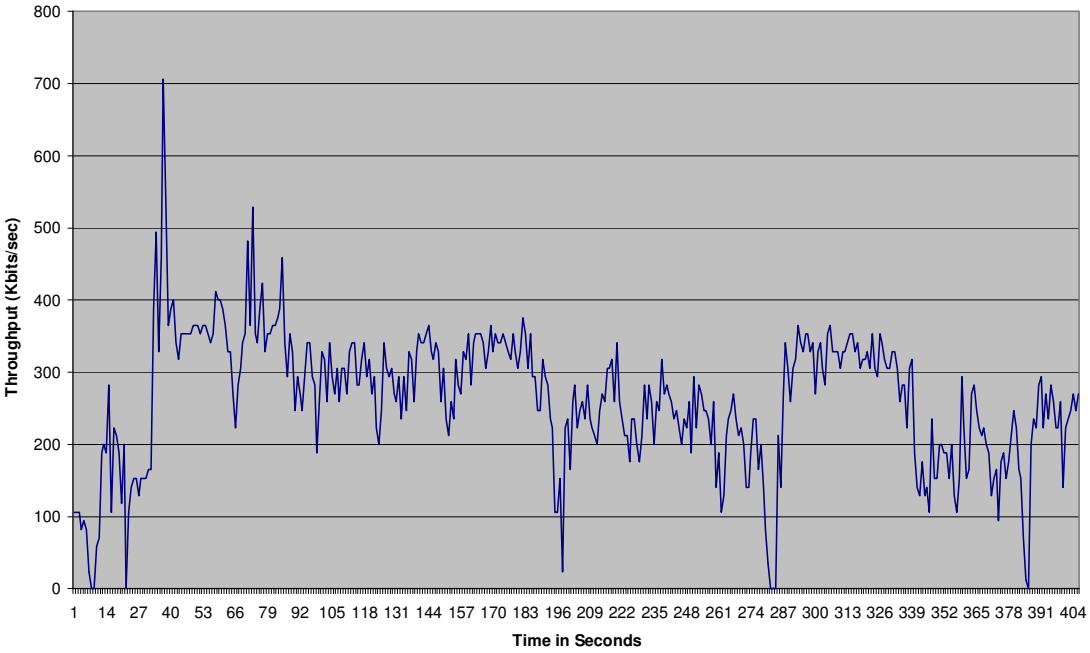


Figure 24. 10 mph south-to-north raw data for MEA

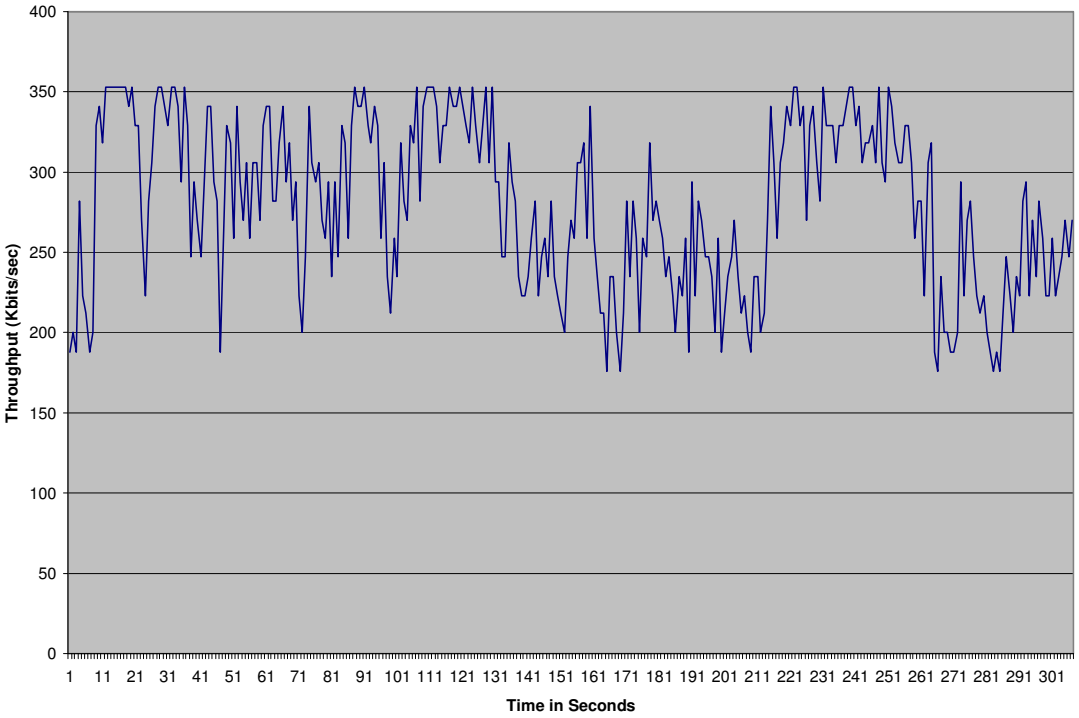


Figure 25. 10 mph south-to-north processed data for MEA

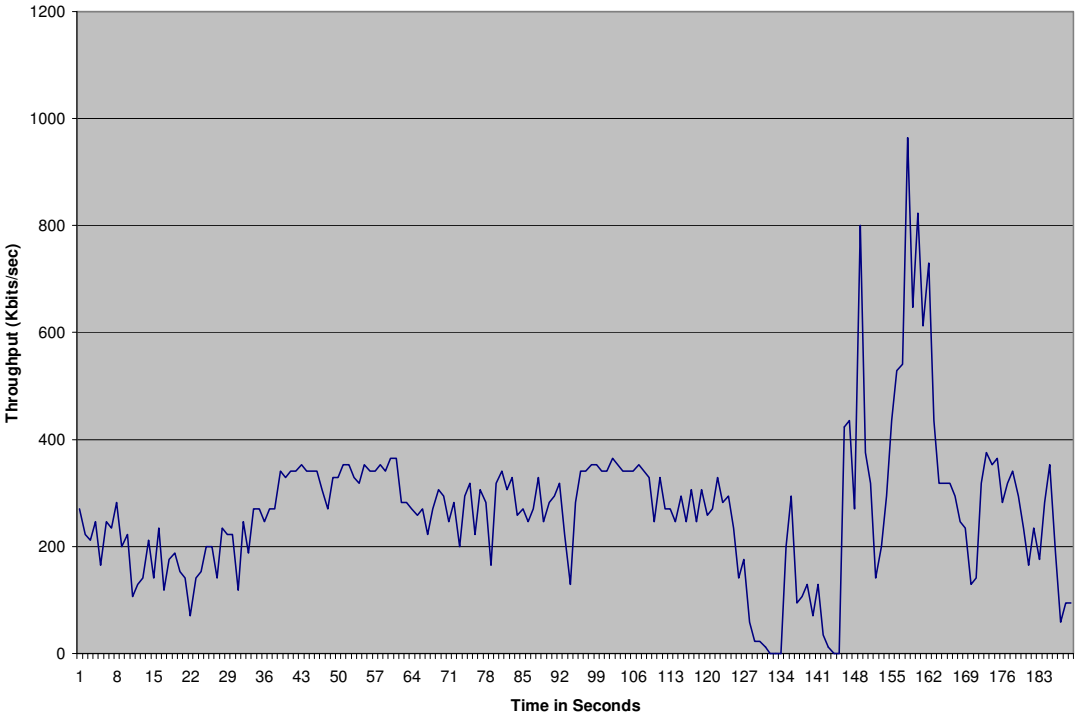


Figure 26. 20 mph north-to-south raw data for MEA

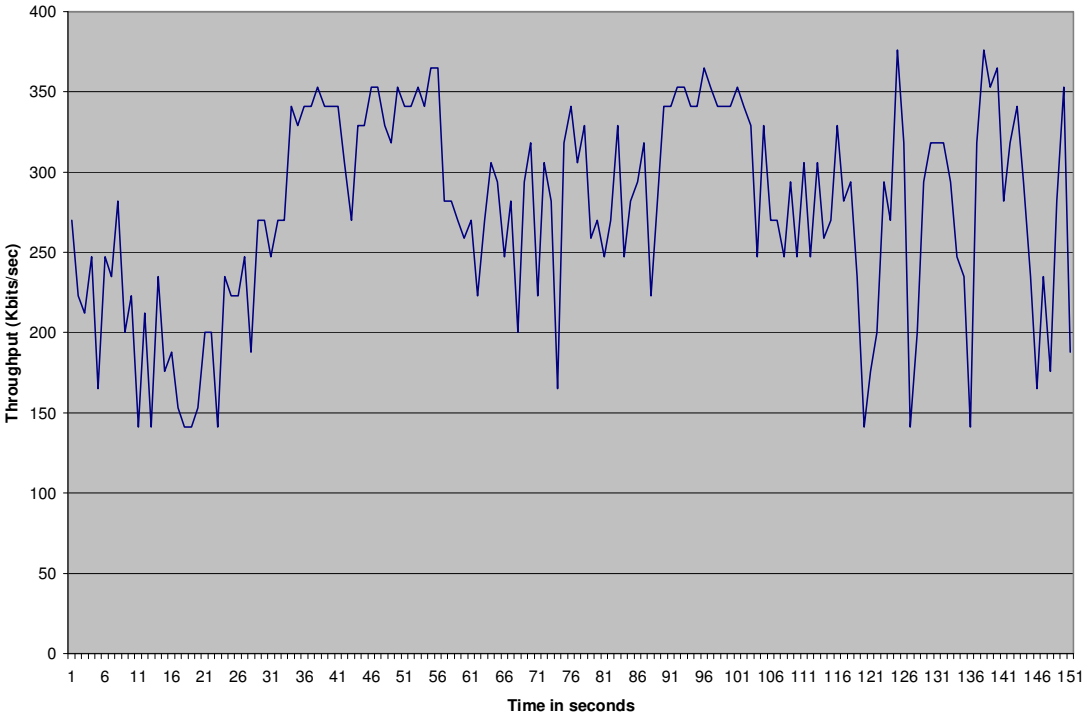


Figure 27. 20 mph north-to-south processed data for MEA

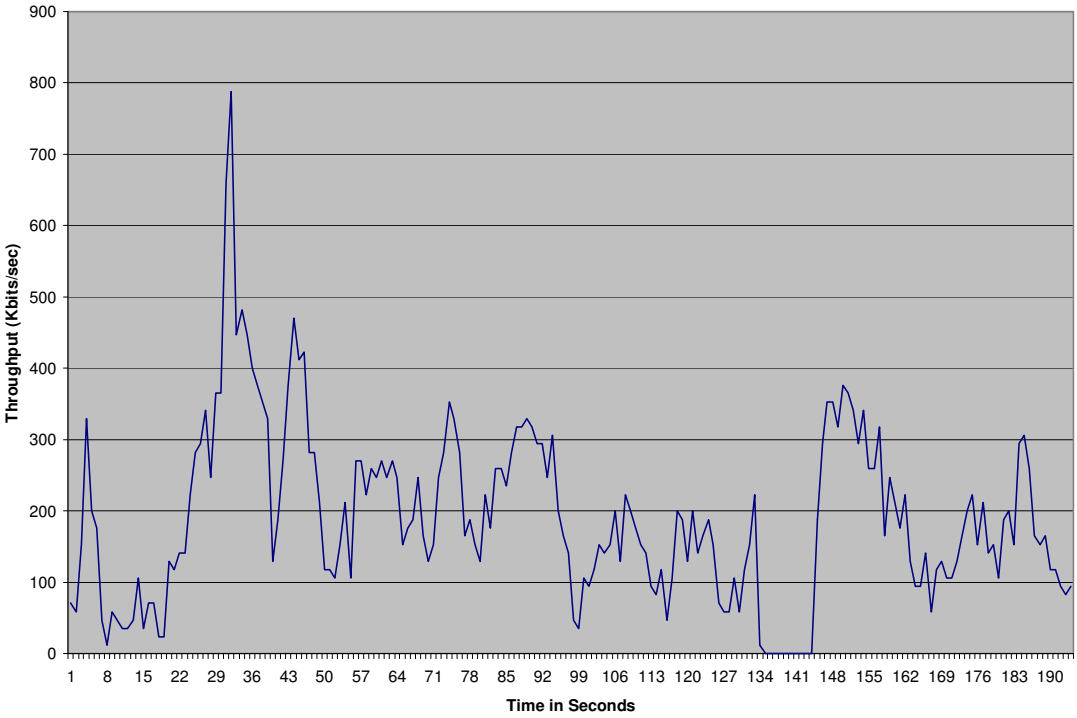


Figure 28. 20 mph south-to-north raw data for MEA

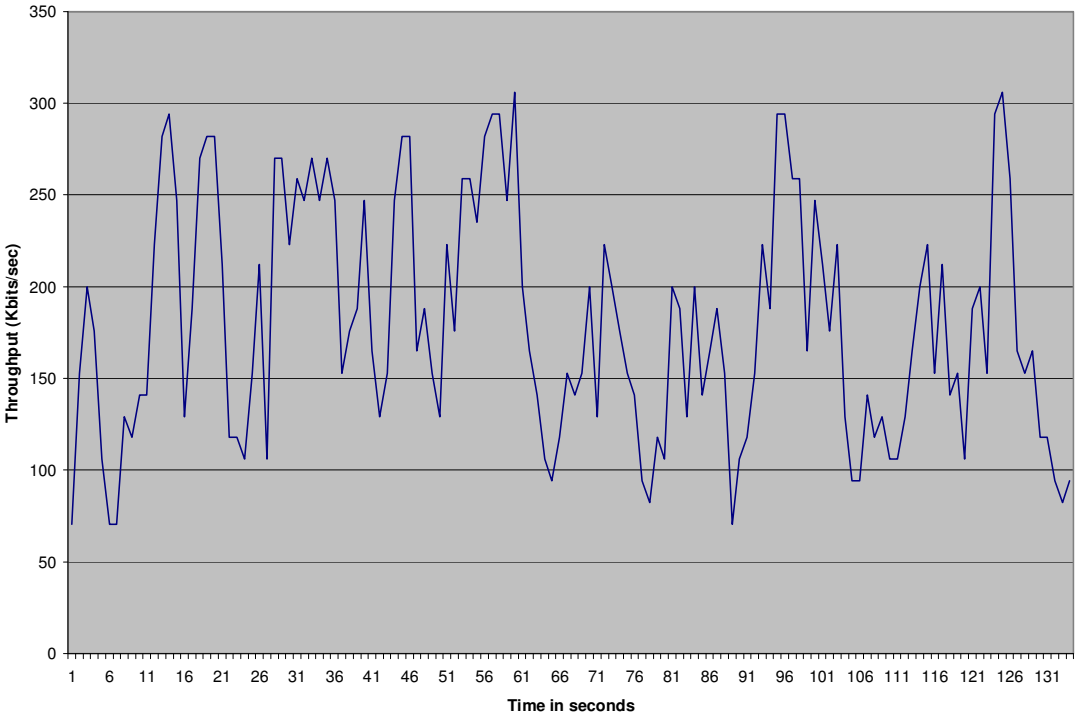


Figure 29. 20 mph south-to-north processed data for MEA

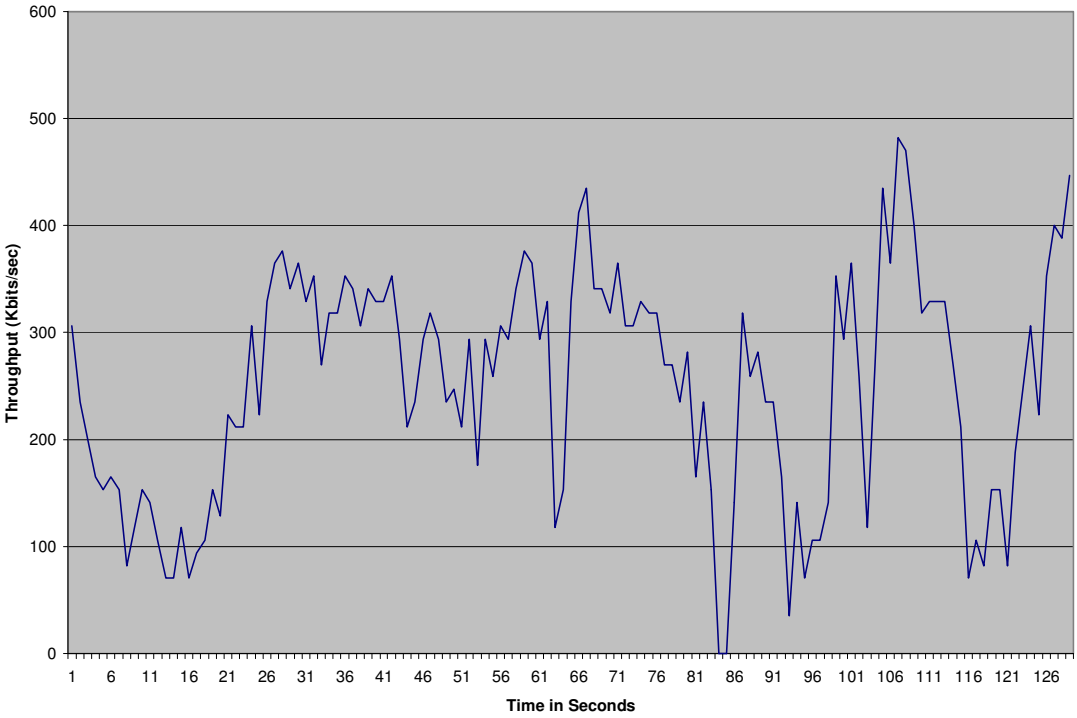


Figure 30. 30 mph north-to-south raw data for MEA

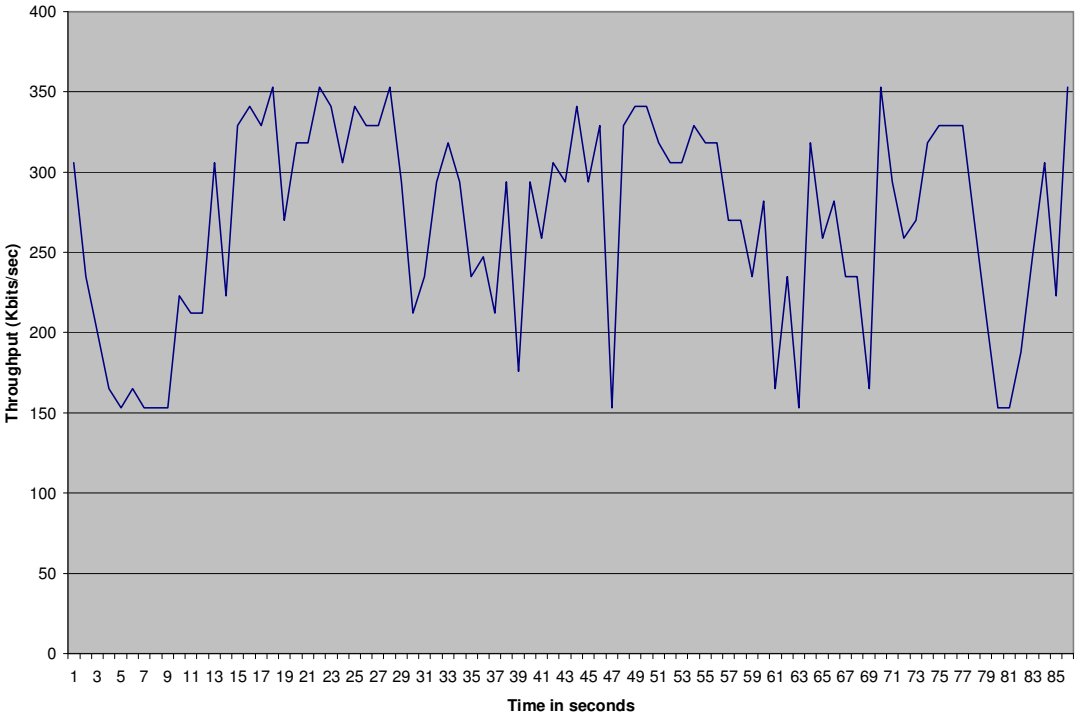


Figure 31. 30 mph north-to-south processed data for MEA

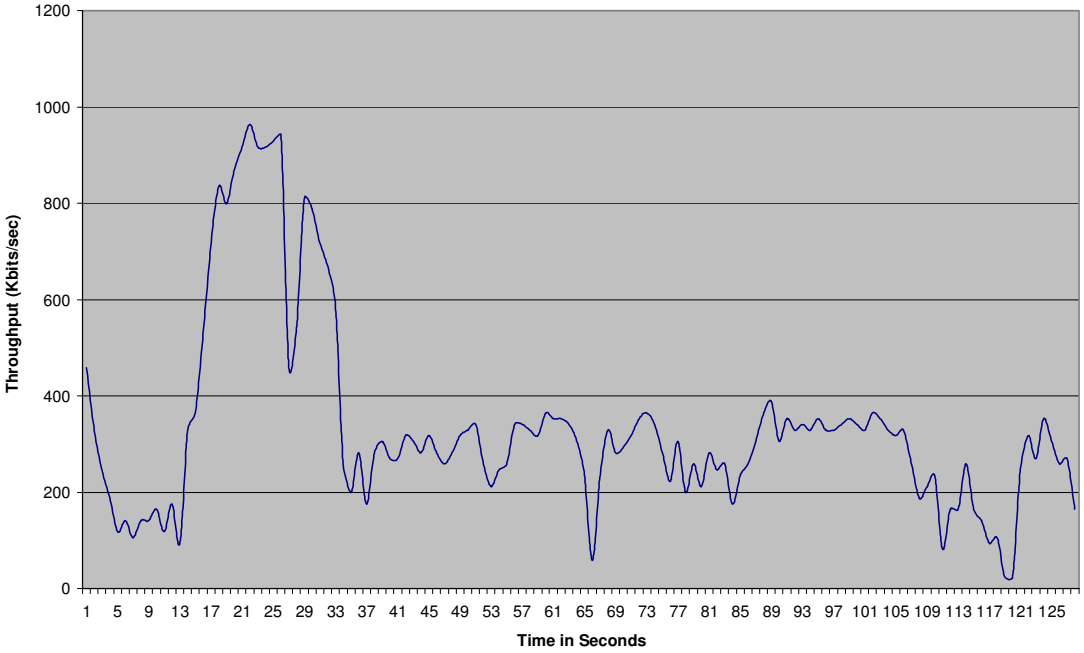


Figure 32. 30 mph south-to-north raw data for MEA

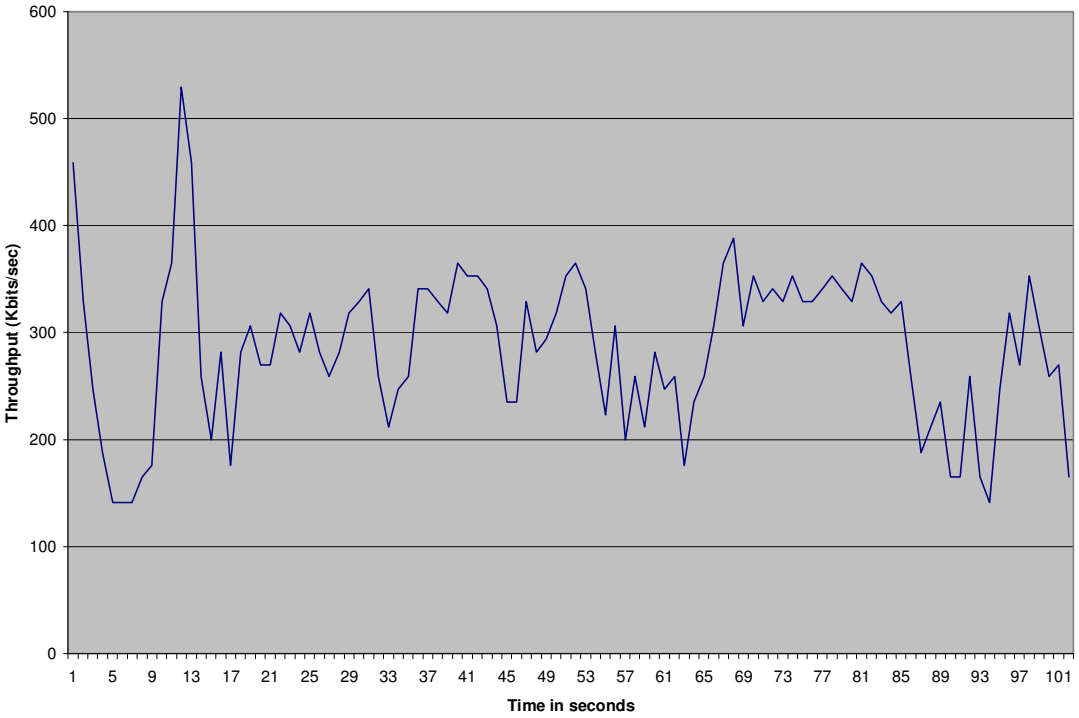


Figure 33. 30 mph south-to-north processed data for MEA

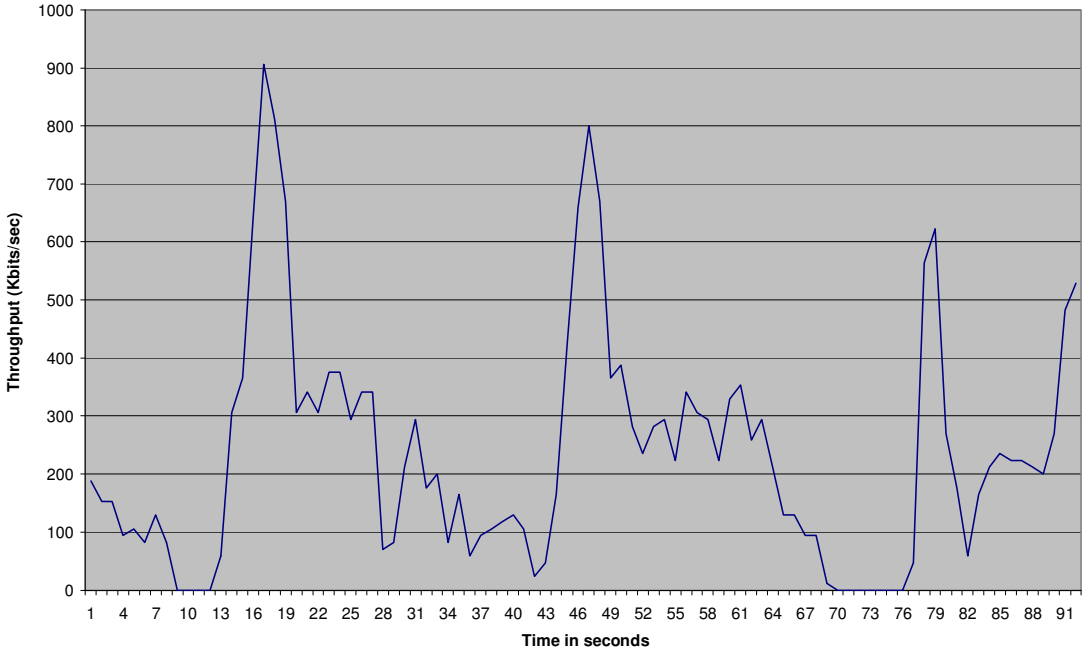


Figure 34. 40 mph north-to-south raw data for MEA

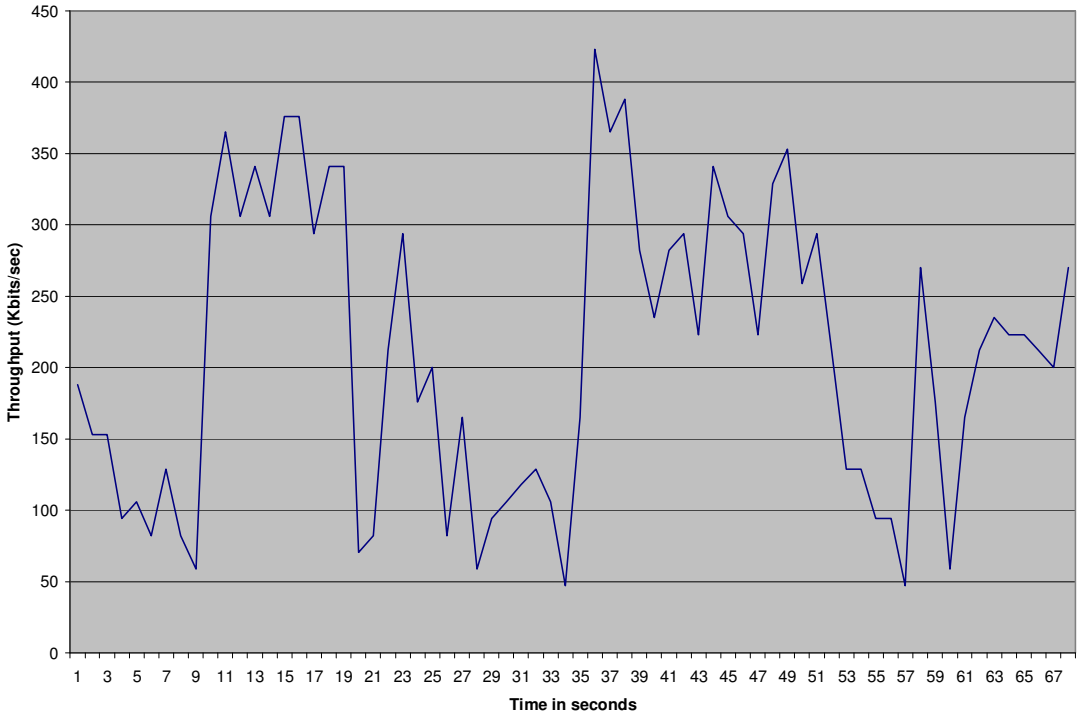


Figure 35. 40 mph north-to-south processed data for MEA

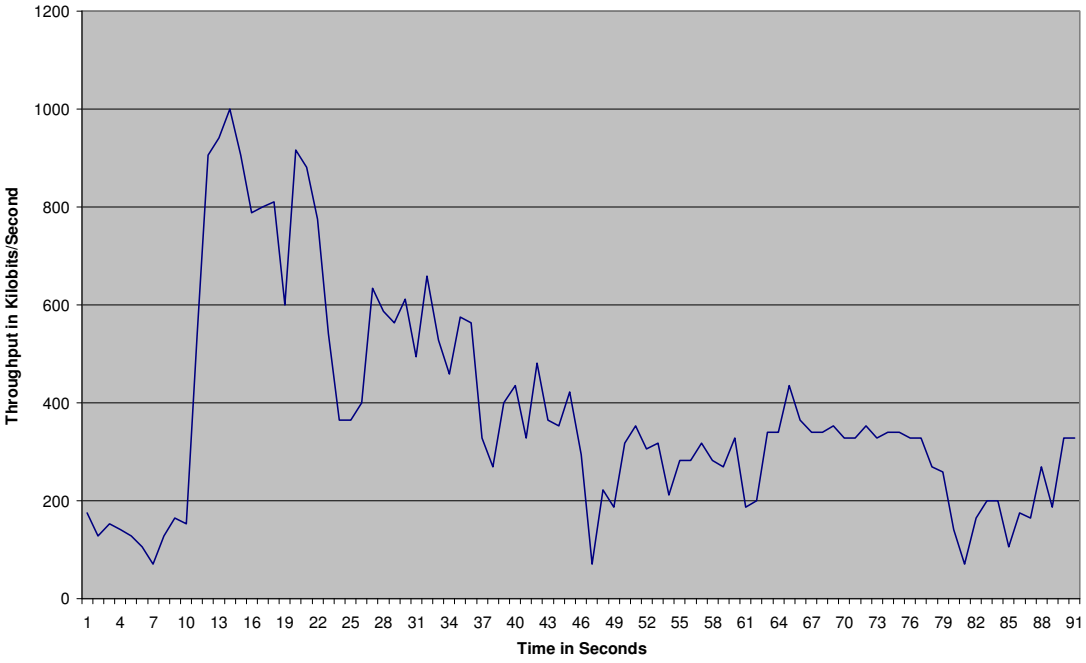


Figure 36. 40 mph south-to-north raw data for MEA

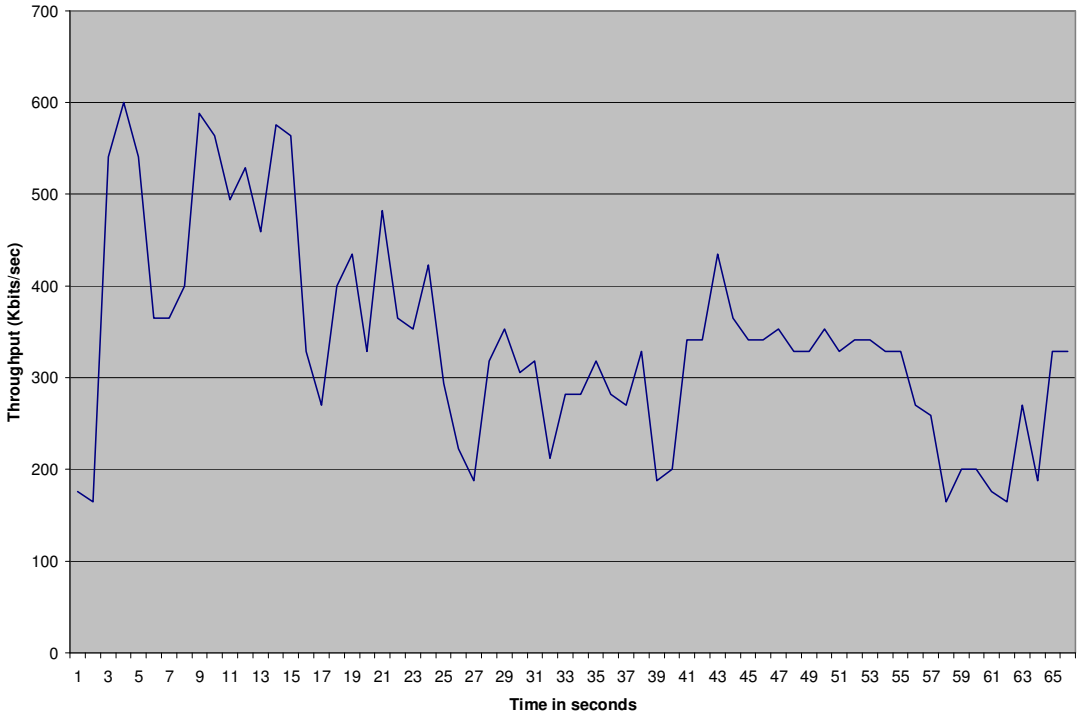


Figure 37. 40 mph south-to-north processed data for MEA

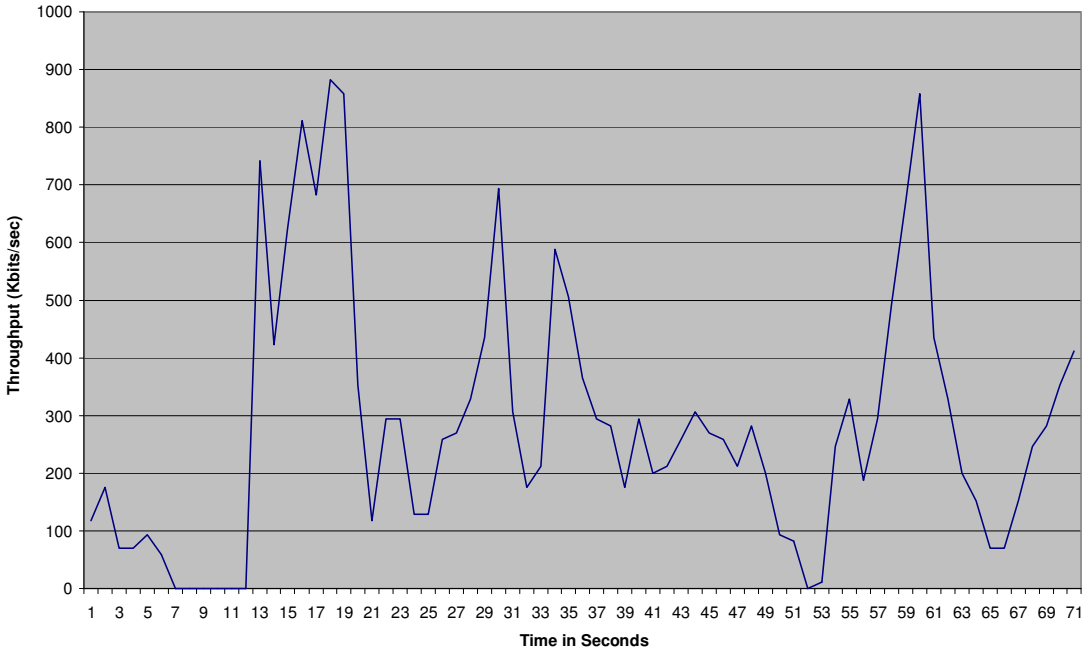


Figure 38. 50 mph north-to-south raw data for MEA

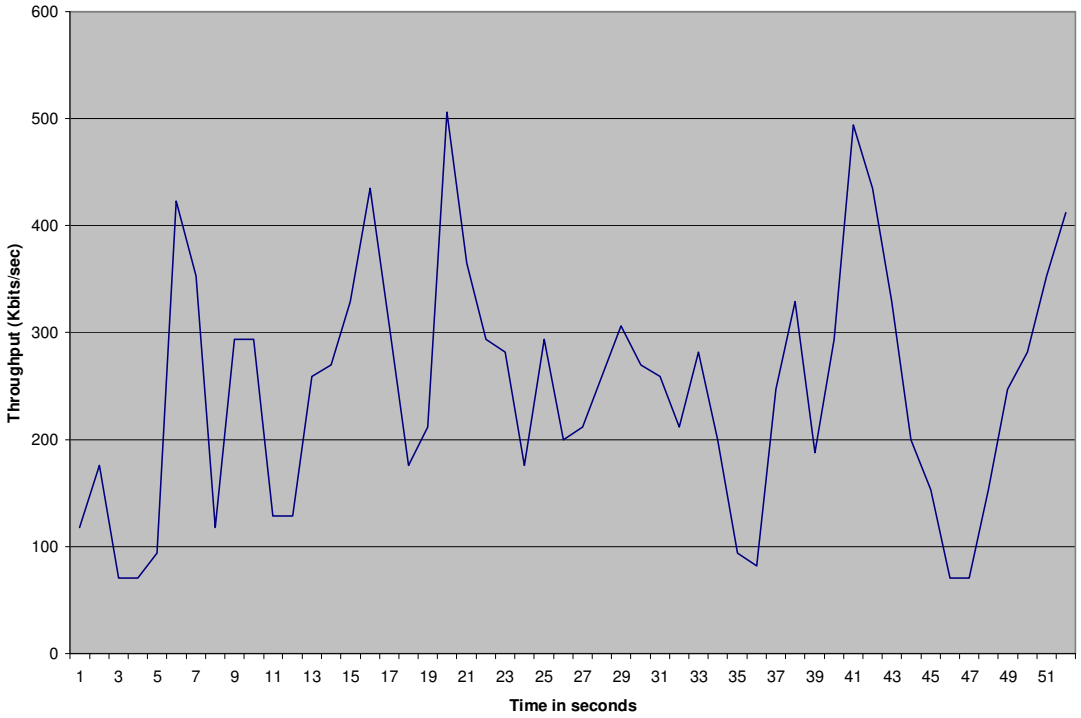


Figure 39. 50 mph north-to-south processed data for MEA

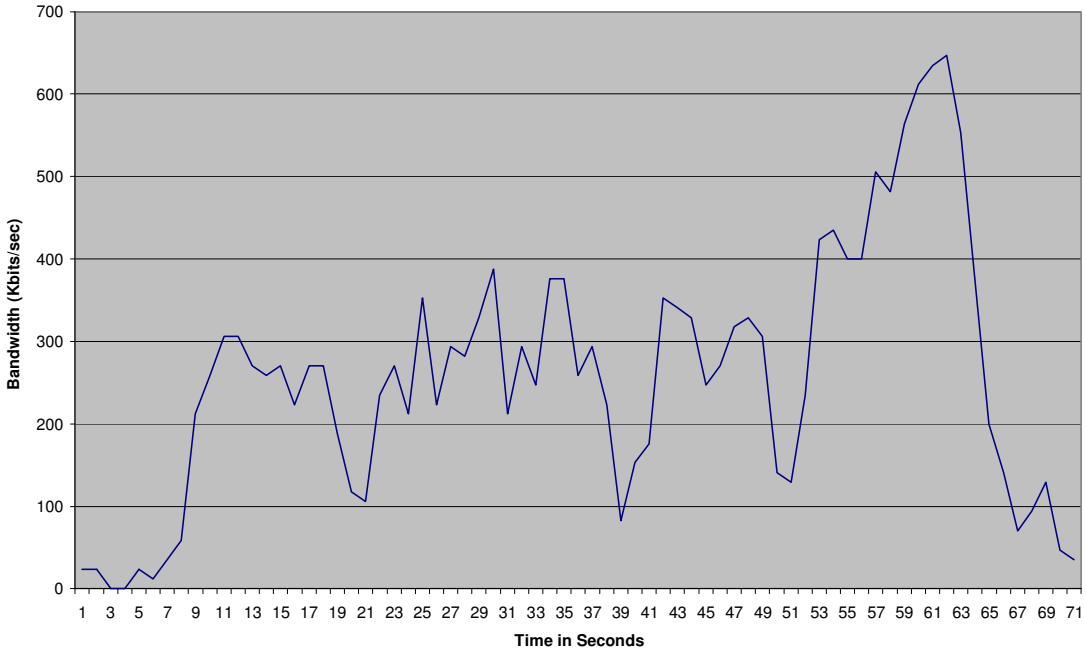


Figure 40. 50 mph south-to-north raw data for MEA

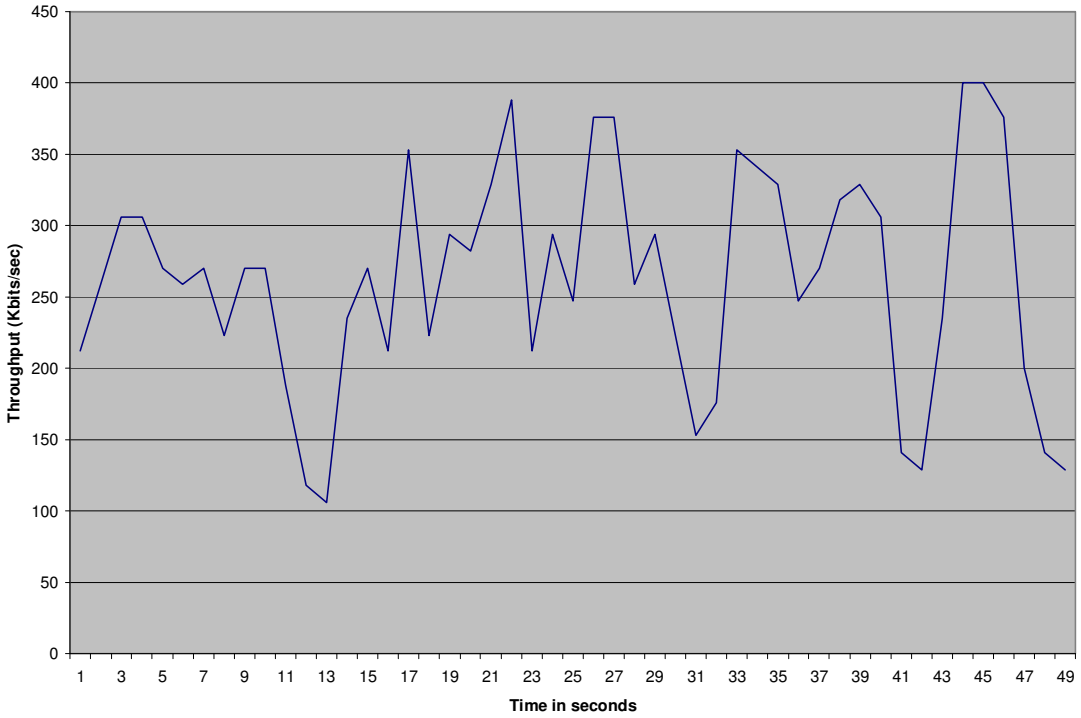


Figure 41. 50 mph south-to-north processed data for MEA

3.4 Results of Experiment 4: Single IAP with 802.11 at Speeds >30 mph

This test was essentially a repeat of Experiment 3 but with an 802.11 access point. The intent was to find out, using only a single access point where no handoffs were involved, whether there was throughput degradation of 802.11 links at speeds above 30 mph. This test involved driving past an IAP whose 802.11 radio was configured for client access rather than backbone connectivity, at 10, 20, 30, 40, and 50 mph and gauging throughput performance in terms of bits per second for UDP. The investigators tried to repeat this experiment on the driven route at the stated speeds to gauge performance with TCP, but, like with the MEA experiments, could not maintain a usable TCP connection long enough to collect meaningful data. (Again, see reference [4].)

This experiment used the same route as for Experiment 3, with approximately 7200 feet of usable connectivity, once the vehicle was up to speed. As in Experiment 3, the vehicle's closest approach to the wireless access point was about 1500 feet and the maximum distance from the access point to the vehicle on the route was about 4200 feet.

When processing the data, we again computed the average and standard deviation over each data set and discarded samples whose throughput fell more than one standard deviation away from the average. This eliminated outlying high points and samples where no data got through. Once the outlying data samples (with respect to throughput) were filtered out, we computed the new average throughput and standard deviation over the remaining samples

The investigators attempted this experiment using the 802.11g radio in the Motomesh IAP. The transmit power was 125 mW feeding an 8 dBi omnidirectional antenna. The RF interface to the laptop in the vehicle was a Proxim ORiNOCO 8470, 802.11b/g PC card operating at about 60 mW, connected to an external omnidirectional antenna with a gain of 3 dB, mounted on the roof of the vehicle. Using this setup, the experimenters could not get a connection to the access point while on the route. A linear amplifier (with a receive pre-amp) was then connected into the circuit between the ORiNOCO card and the external antenna, boosting the output that fed the antenna to 3 watts. At this point the experimenters could successfully get a connection and made runs in both directions (N-S, S-N) at 10, 20, 30, 40, and 50 mph. Unfortunately, this was not a close comparison to the MEA experiments, as the amplified 802.11 signals were much stronger than the MEA signals. It basically introduced another variable (the linear amplifier), rendering the data unusable in direct comparison to the MEA data.

To obtain a closer comparison to the MEA experiments, the investigators tried to obtain effective radiating power levels for the 802.11g equipment that were similar to the levels used in the MEA experiments. The experimenters continued to use the same setup at the access point (125 mW, feeding an 8 dBi Omni), and at the vehicle used the same ORiNOCO 8470 PC card (transmitting at about 60 mW), but this time used an 8 dBi external omnidirectional antenna without a linear amplifier. On the IAP to vehicle link, this put the operating margin about 2 dB higher than the MEA experiments. For the vehicle to IAP link, the operating margin was about 1 dB less than in the MEA experiments.

Examining the average throughput data, the investigators observed higher throughputs on every speed (averaged over the North-to-South and South-to-North runs) for 802.11 verses MEA. The investigators also observed that for every speed, the 802.11 throughput data had a much greater standard deviation – usually by a factor of 1.6 or more and sometimes by a factor greater than 2 – than the MEA data. This indicates a much higher variability in the throughput data for 802.11 than for MEA. This variability also indicates a higher rate of jitter, which could be problematic when using real-time video and Voice over IP (VoIP) applications transferring data to or from a moving vehicle via 802.11.

The average throughputs, when using the linear amplifier, were generally lower (and just as variable) than when not using the linear amplifier. This is consistent with the results of a complementary study performed on Motorola MEA equipment, which included bench tests in a controlled laboratory environment [10]. That study found, for the MEA equipment, that increasing transmitter power will mitigate receiver performance degradation resulting from path loss, but not from multipath interference.

Both the raw data and the processed data for the unamplified 802.11 experiments are shown in Figures 42-61 for the five tested vehicle speeds in both directions of the course.

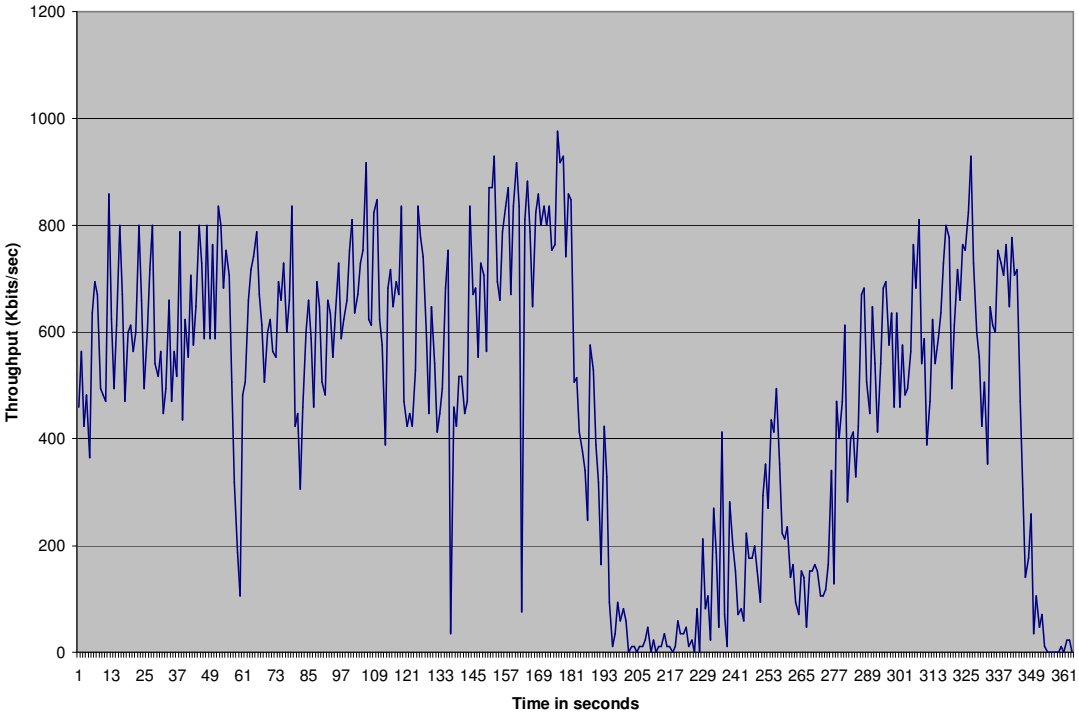


Figure 42. 10 mph north-to-south raw data for 802.11

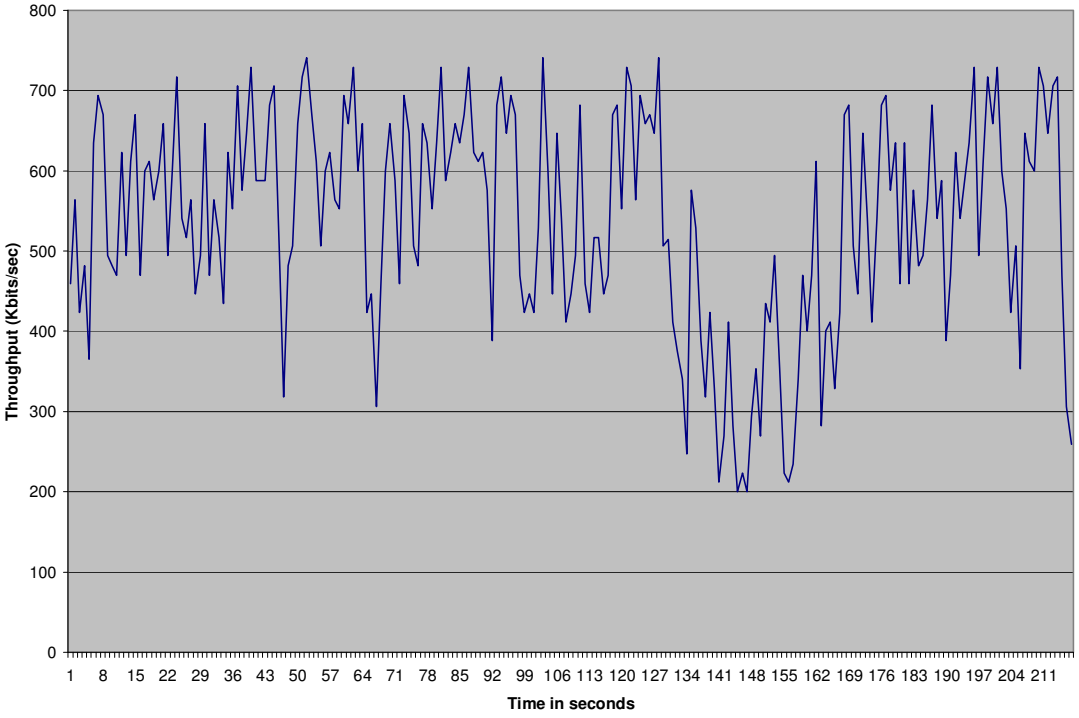


Figure 43. 10 mph north-to-south processed data for 802.11

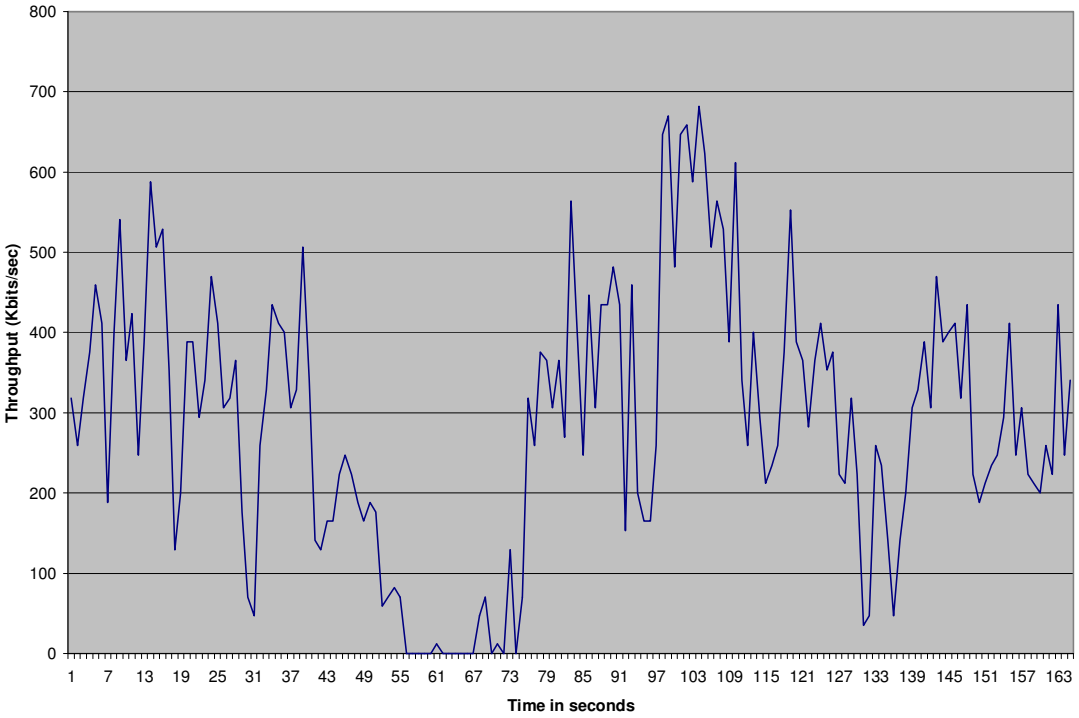


Figure 44. 10 mph south-to-north raw data for 802.11

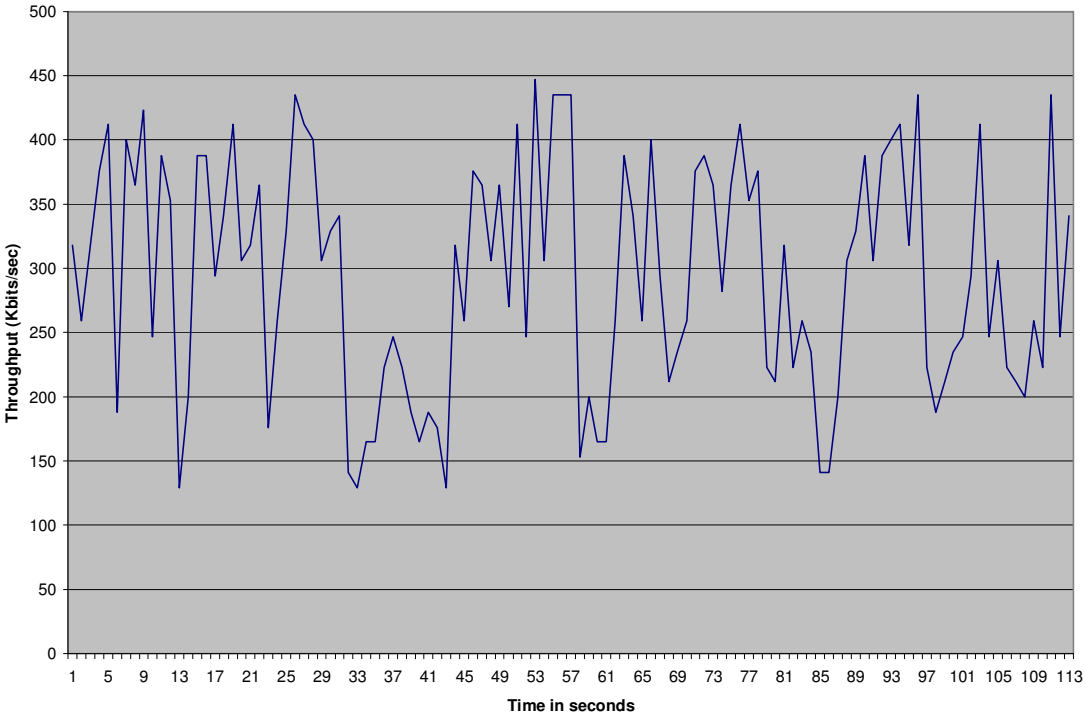


Figure 45. 10 mph south-to-north processed data for 802.11

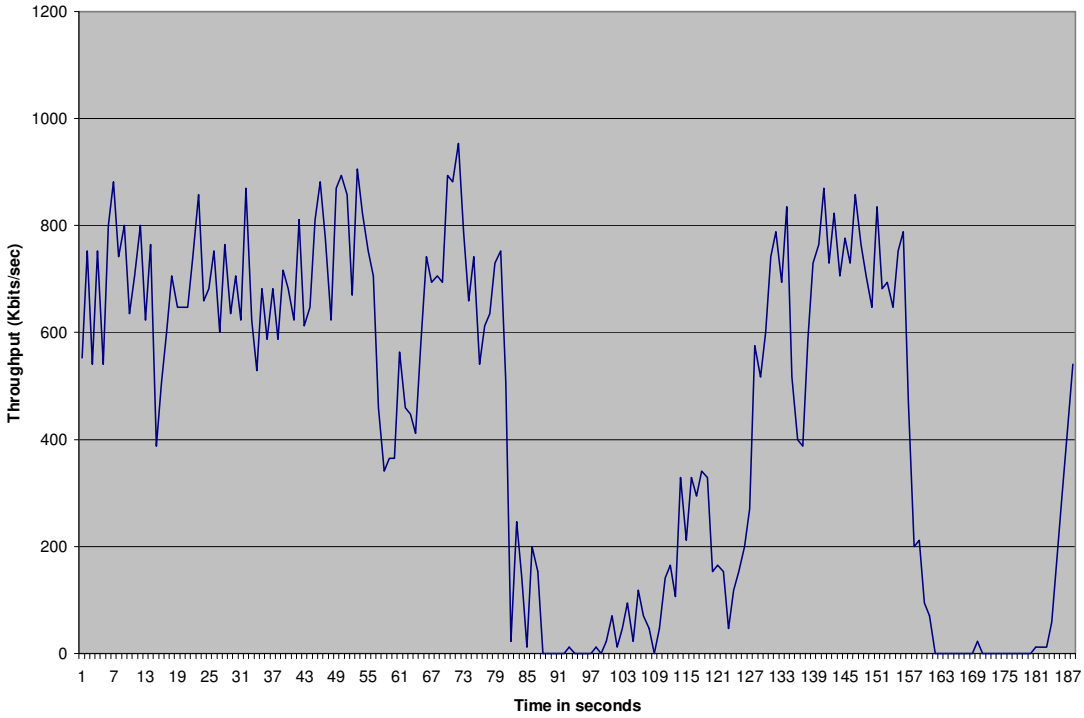


Figure 46. 20 mph north-to-south raw data for 802.11

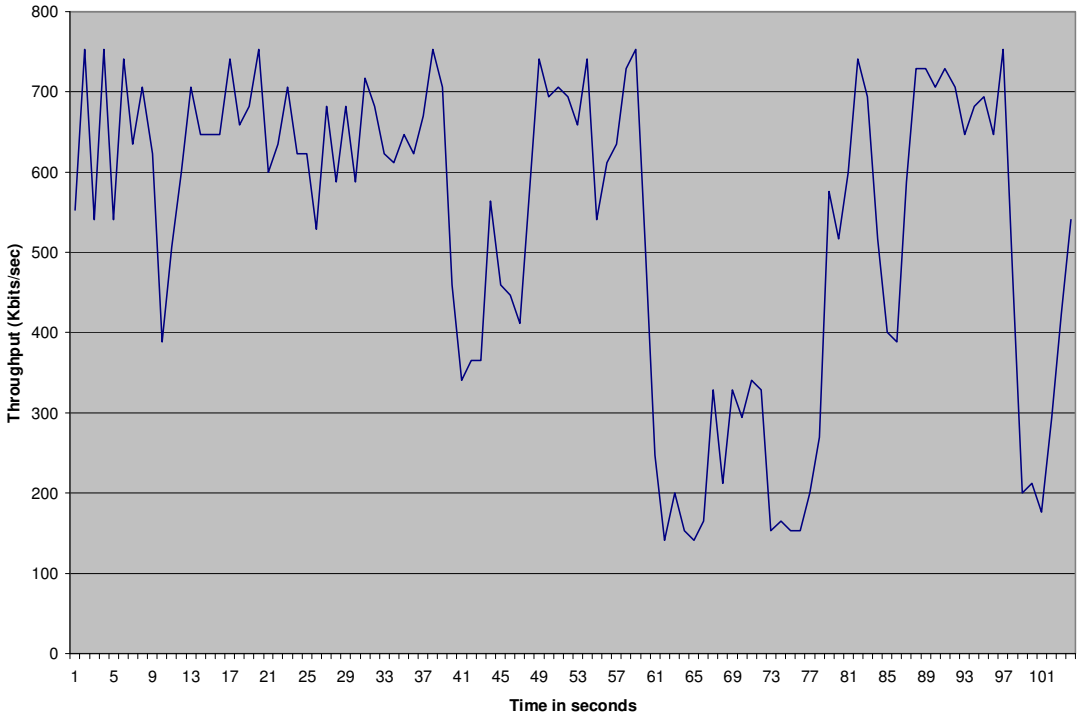


Figure 47. 20 mph north-to-south processed data for 802.11

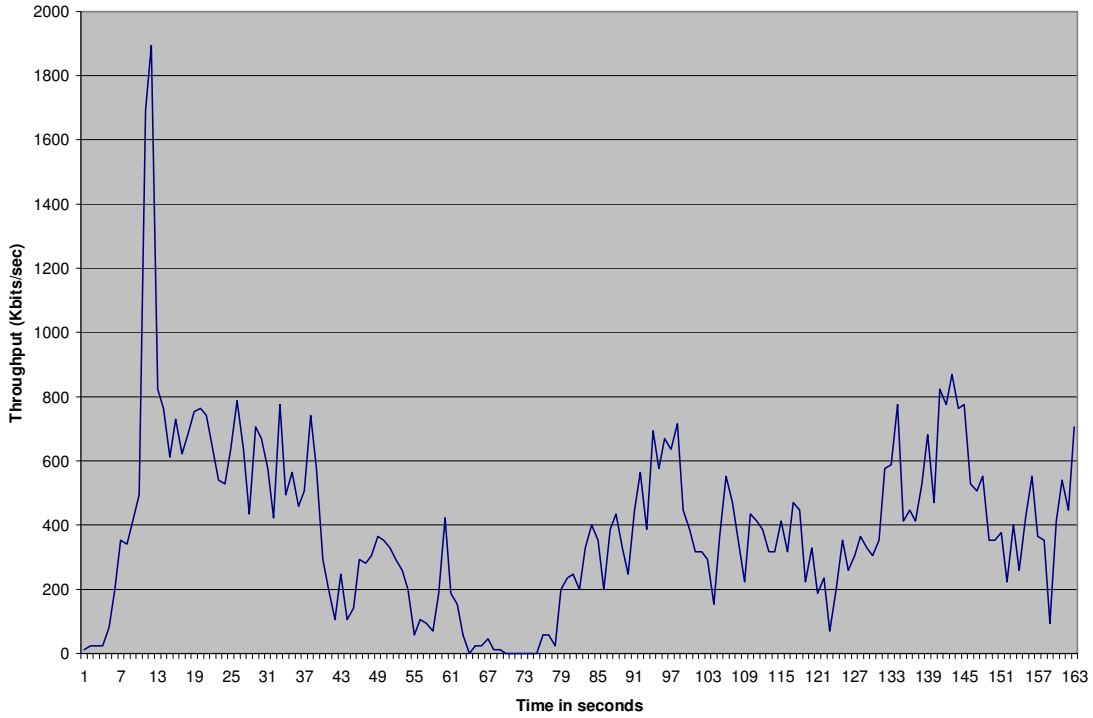


Figure 48. 20 mph south-to-north raw data for 802.11

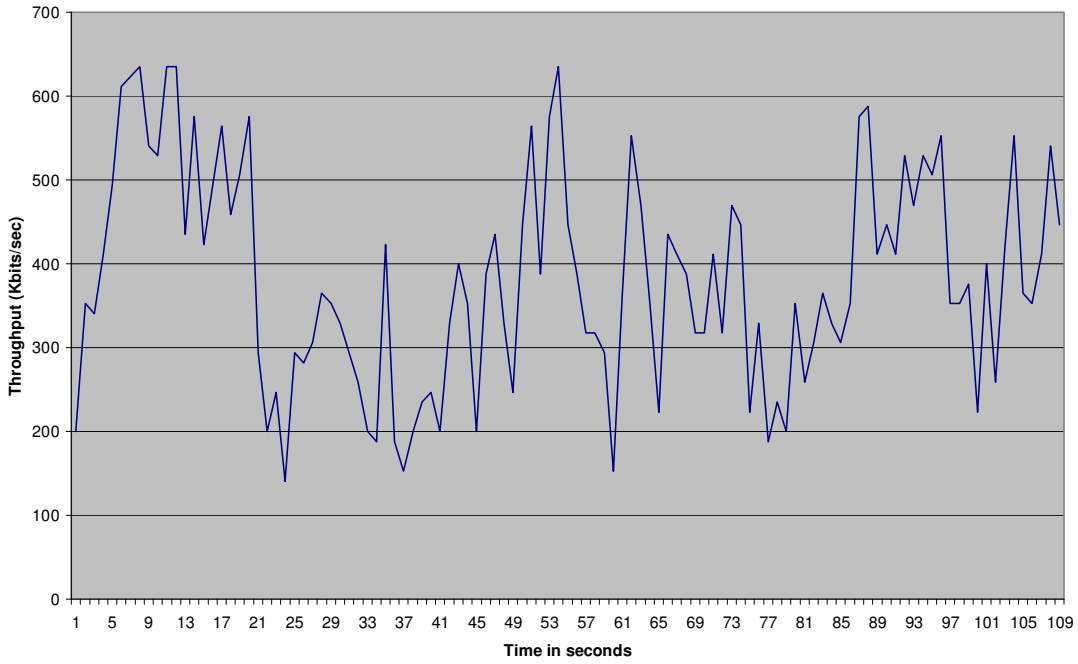


Figure 49. 20 mph south-to-north processed data for 802.11

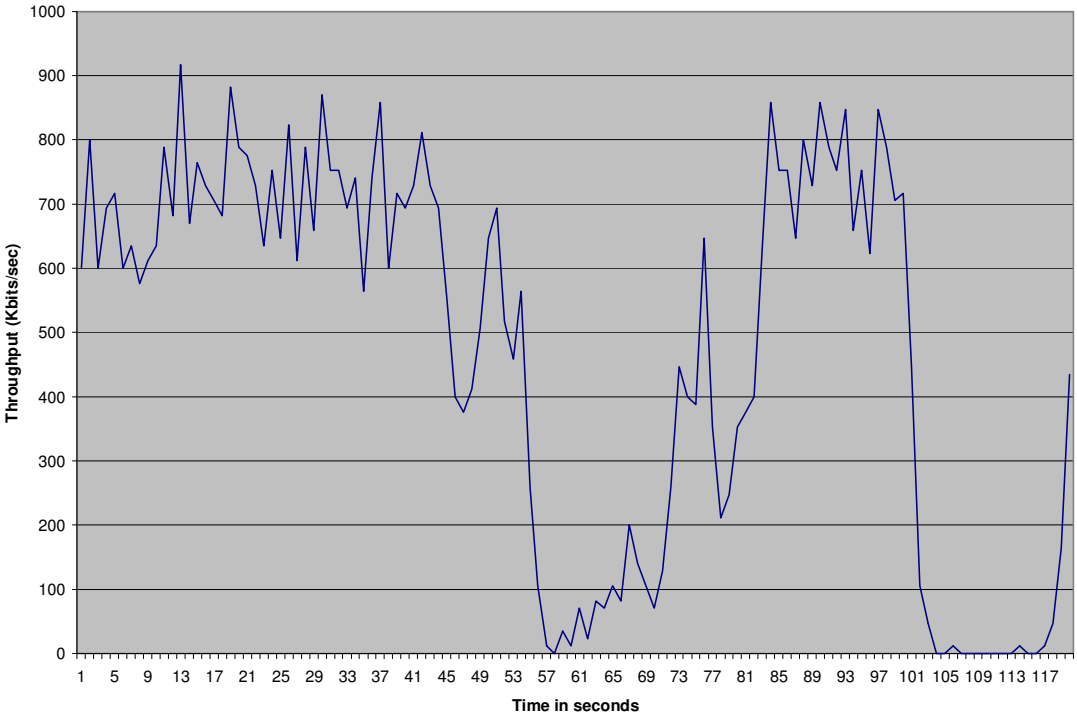


Figure 50. 30 mph north-to-south raw data for 802.11

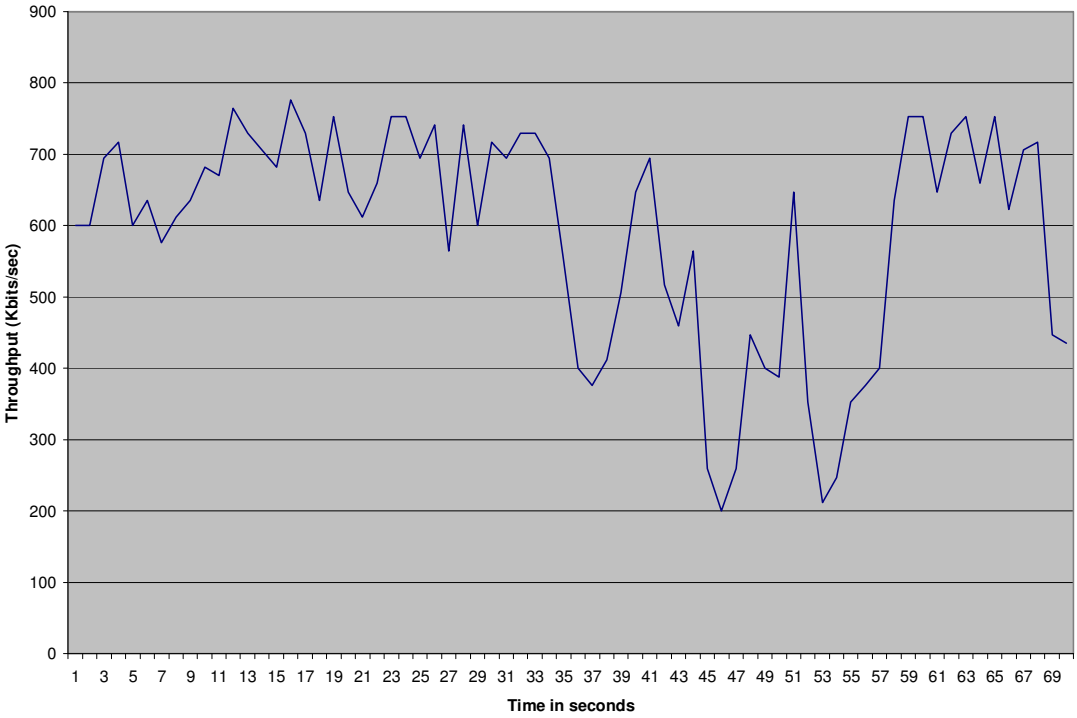


Figure 51. 30 mph north-to-south processed data for 802.11

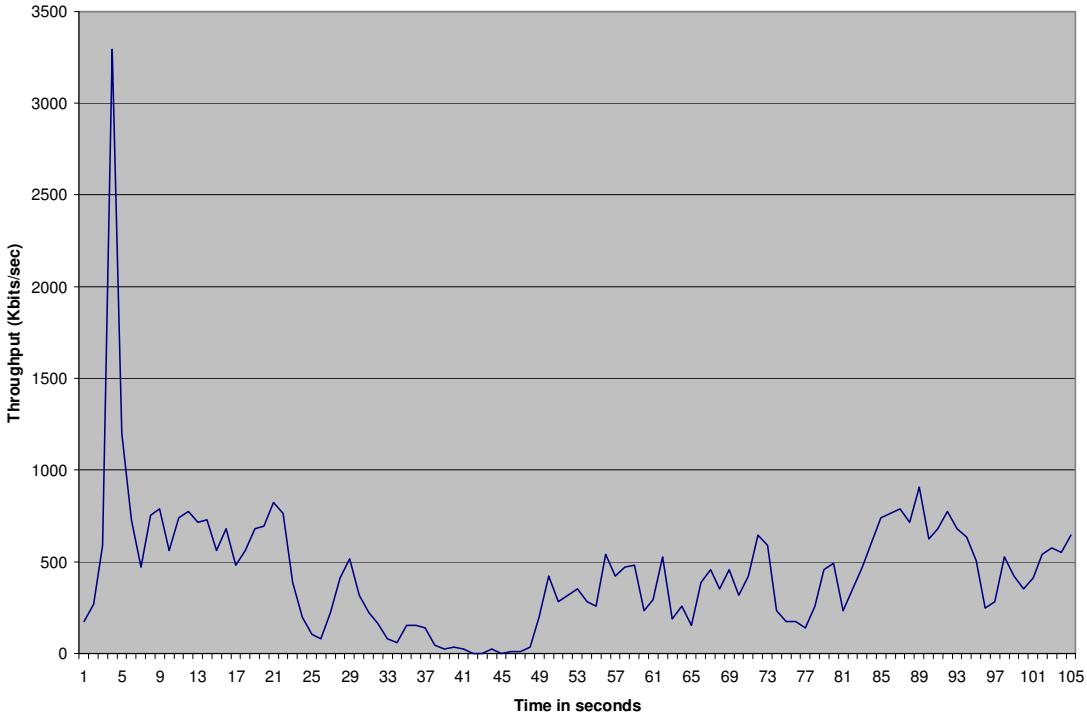


Figure 52. 30 mph south-to-north raw data for 802.11

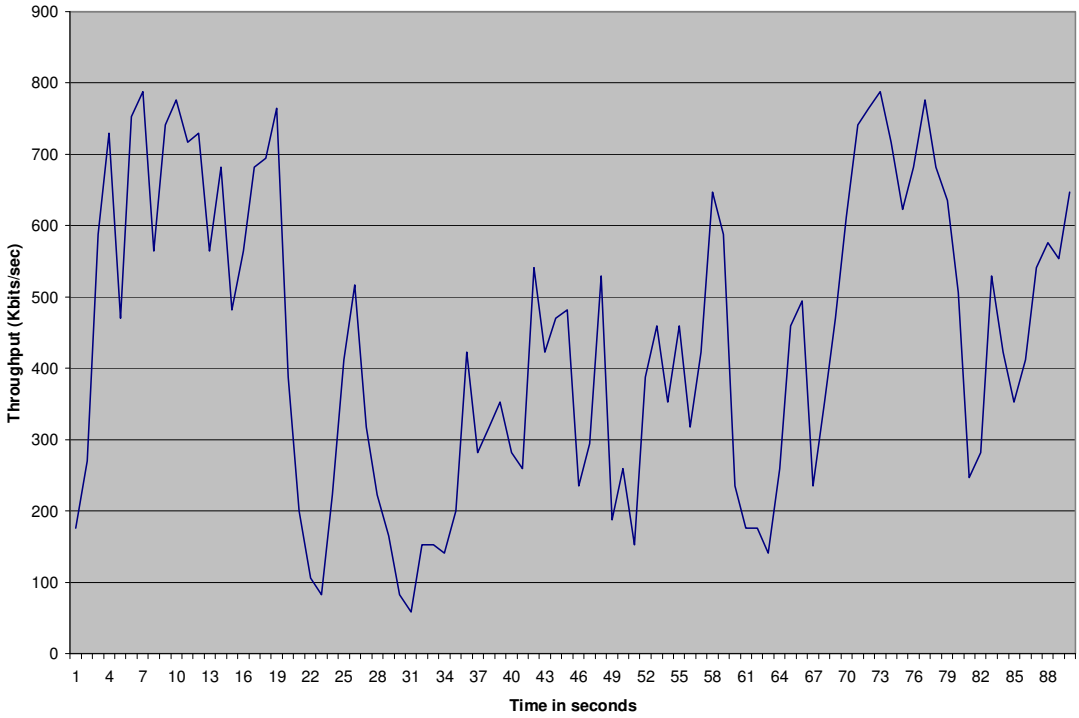


Figure 53. 30 mph south-to-north processed data for 802.11

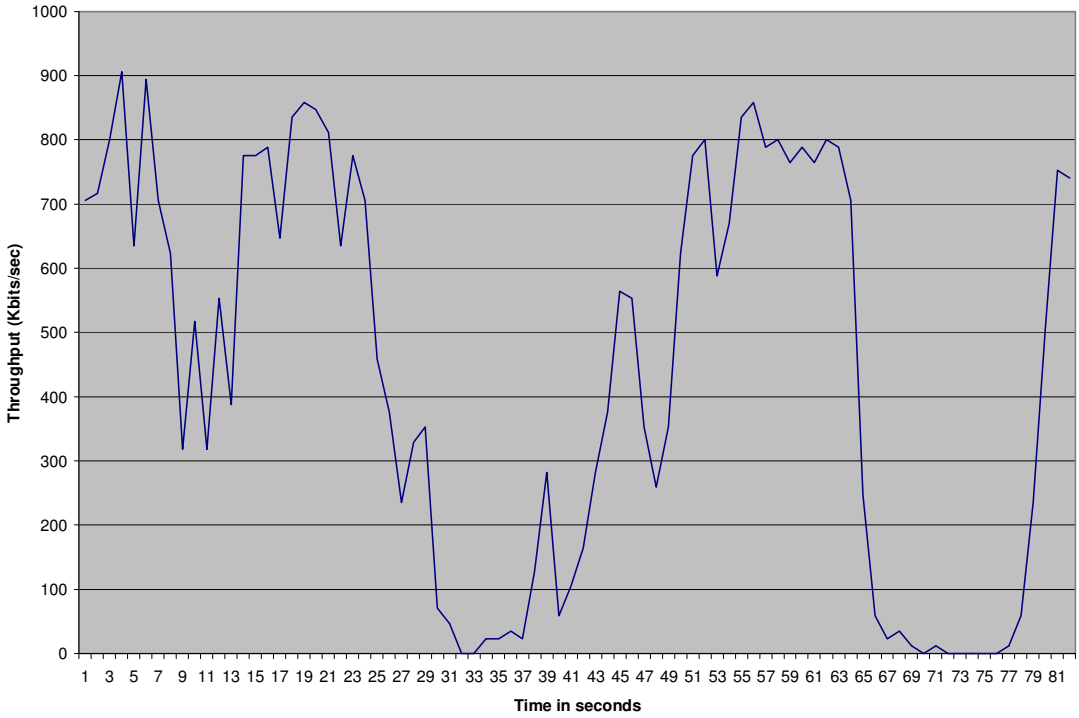


Figure 54. 40 mph north-to-south raw data for 802.11

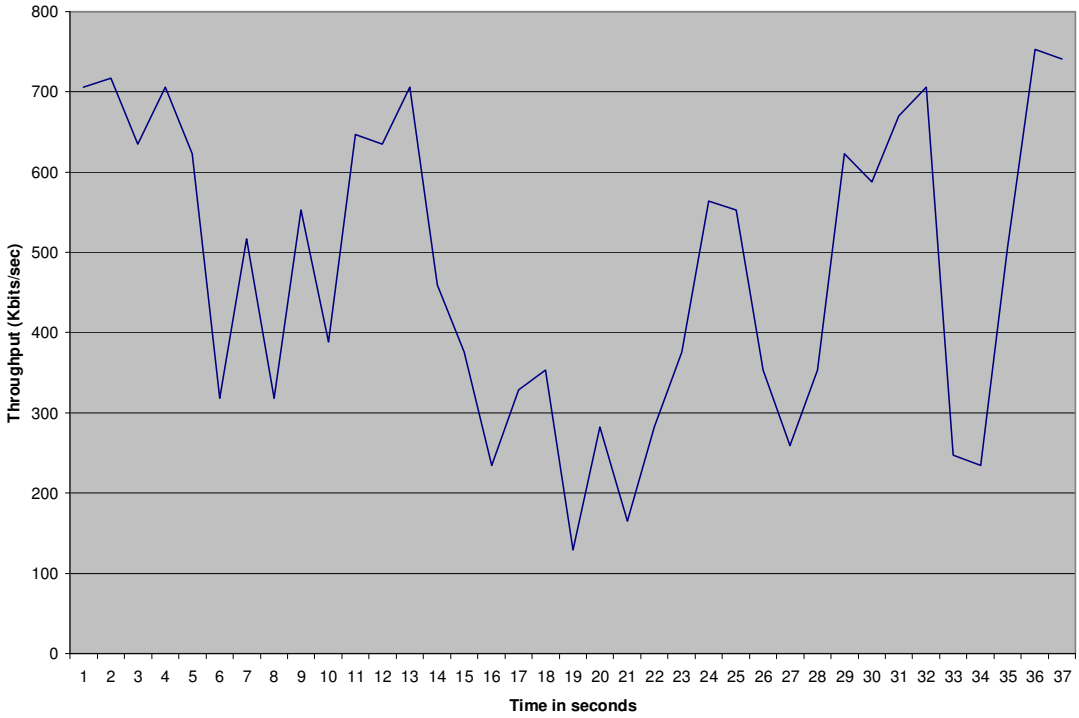


Figure 55. 40 mph north-to-south processed data for 802.11

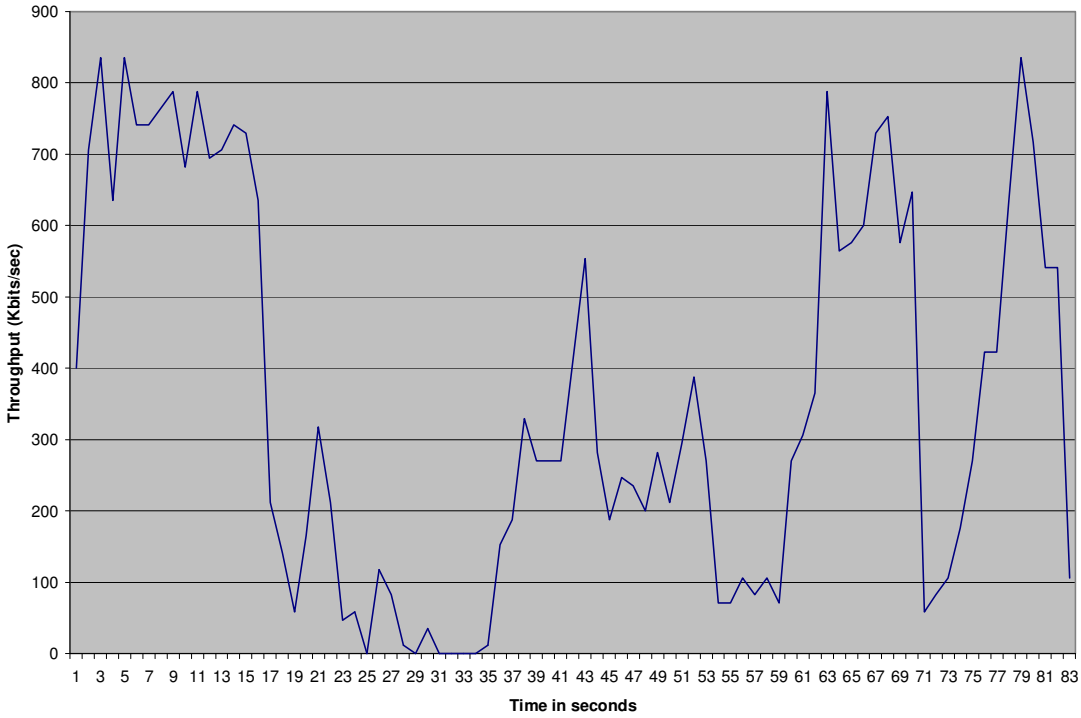


Figure 56. 40 mph south-to-north raw data for 802.11

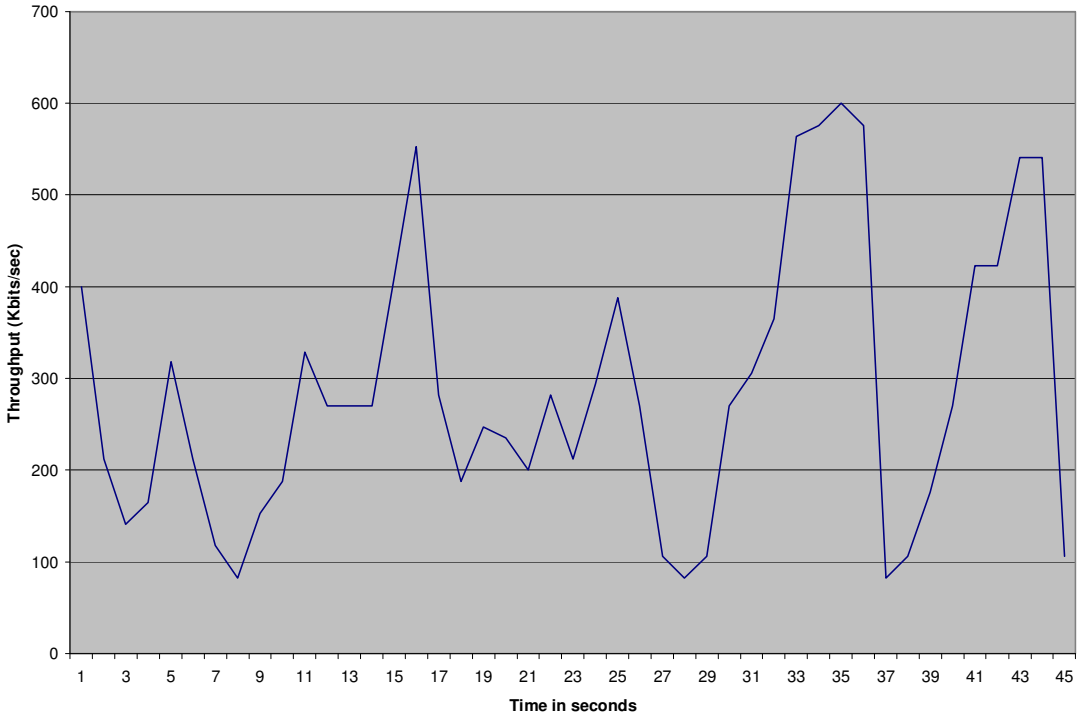


Figure 57. 40 mph south-to-north processed data for 802.11

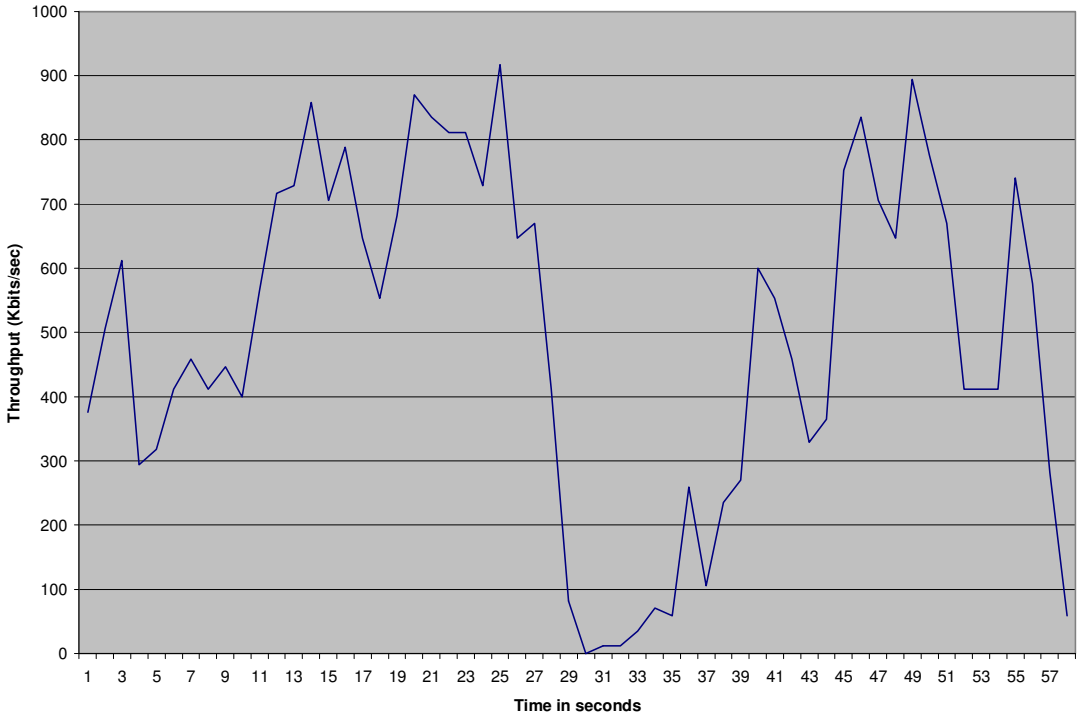


Figure 58. 50 mph north-to-south raw data for 802.11

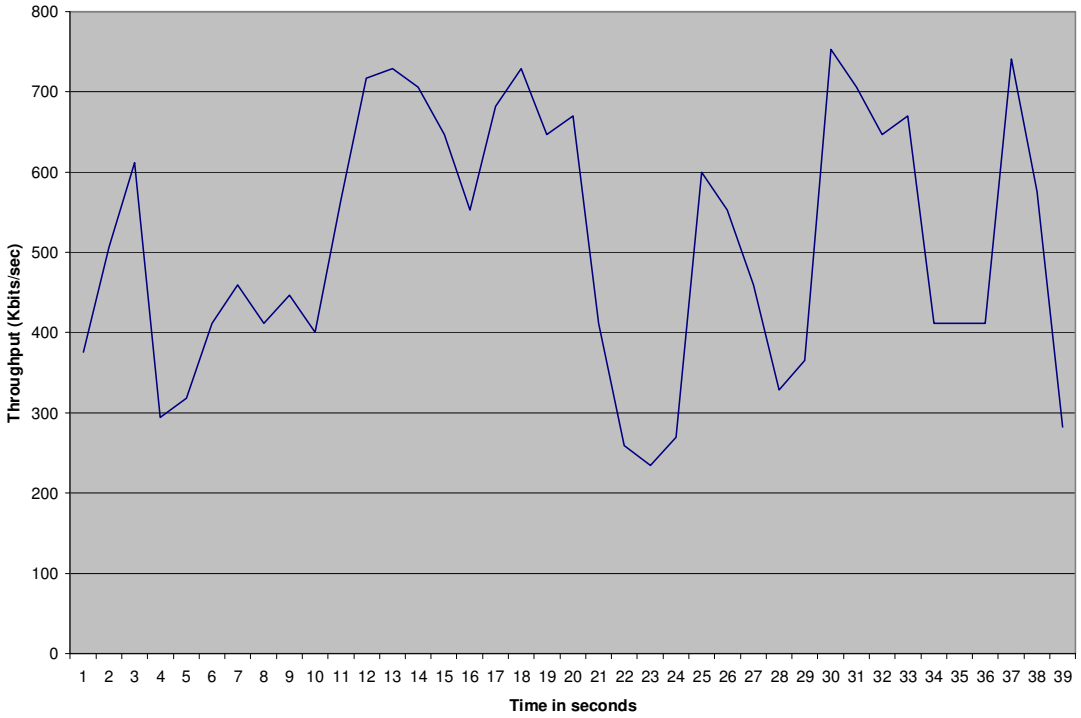


Figure 59. 50 mph north-to-south processed data for 802.11

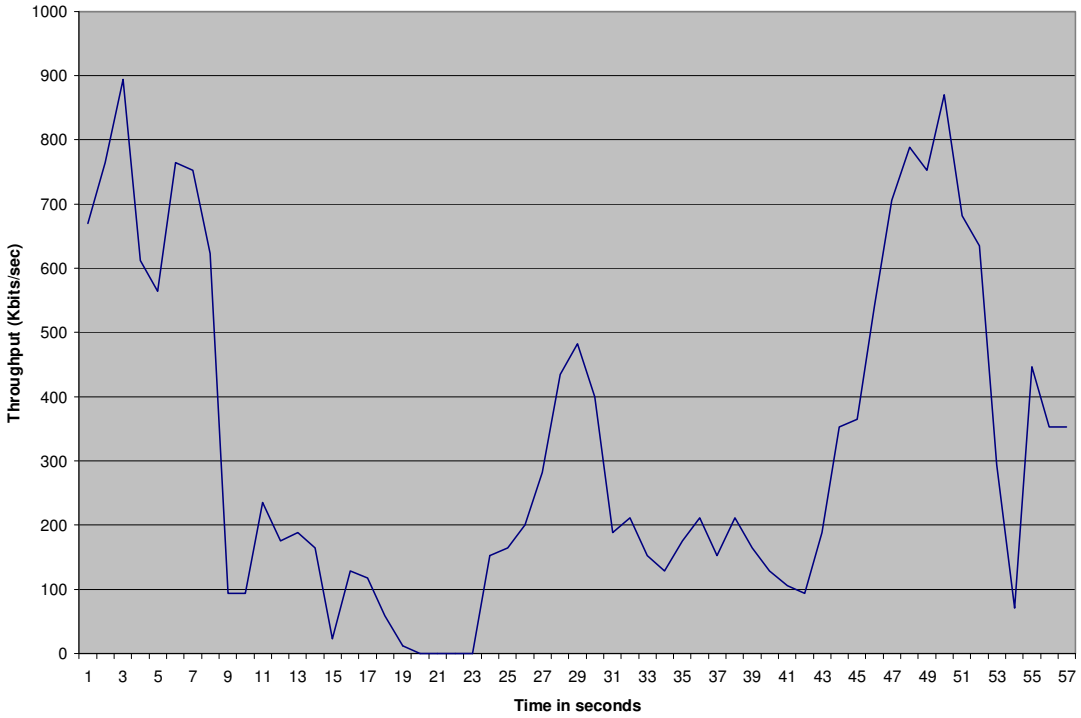


Figure 60. 50 mph south-to-north raw data for 802.11

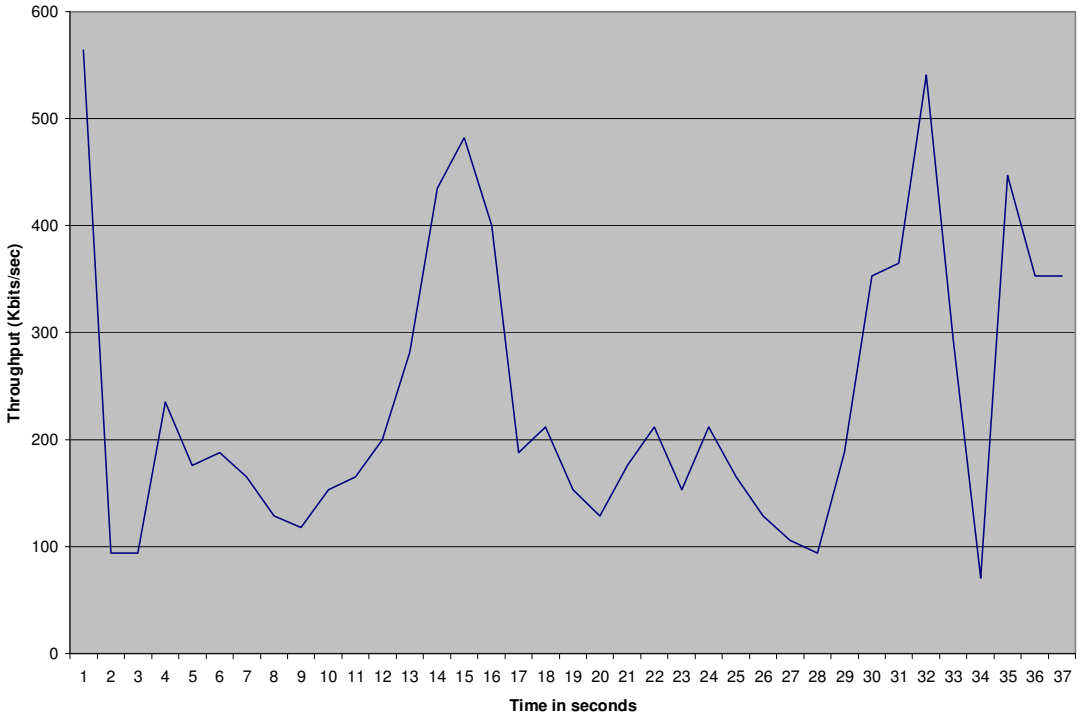


Figure 61. 50 mph south-to-north processed data for 802.11

3.5 Results of Experiment 5: Handoff with Mesh at Speeds >30 mph

The intent here was, incorporating handoffs, to measure any throughput degradation of MEA links at speeds above 30 mph. Investigators used two or three IAPs in a rough line with overlapping coverage areas (Figure 14). (Note that investigators also considered 802.11 access in Experiment 6.) While driving, investigators checked continuity and how many seconds the client remained in the target area or zone of connectivity. After establishing a route that could be repeated, with accurately measured start/stop points, the investigators drove past the IAPs at 10, 20, 30, 40, and 50 mph, and gauged performance in terms of throughput for UDP. Based on experience in previous experiments (Sections 3.3 and 3.4), investigators did not attempt to repeat the tests for TCP.

There were problems with this set of tests, caused by ambiguity in which access points the mobile client was associated at what times. Salvaging some data from this experiment, the investigators observed throughputs ranging from 108 Kbps to 203 Kbps. The results are summarized in Table 1.

Table 1. Summary results for Experiment 5.

Speed (mph)	Throughput (Kbps)
20	139
30	177
40	125
50	179

3.6 Results of Experiment 6: Handoff with 802.11 at Speeds >30 mph

The intent here was, incorporating handoffs, to measure any throughput degradation of 802.11 links at speeds above 30 mph. This test was a repeat of Experiment 5 with 802.11 access points (Figure 16).

Since this set of tests was conducted with the 3 watt linear amplifier in place, the results cannot be compared to those recorded in Experiment 5. This experiment should have been re-done without the linear amplifier, but with a higher gain (8 dBi) antenna. Due to funding and time constraints, this did not occur.

The data that was collected, with the linear amplifier in place, was nearly useless, being very irregular and bursty. The collected data for these tests ranged from 12 Kbps to 22 Kbps, and did not vary significantly with the speed of the client vehicle. The average throughput was about 15.5 Kbps.

3.7 Results of Experiment 7: Determine Performance Difference with Mesh and 802.11 as Backbone

The intent of this experiment was to determine the performance difference, if any, between using 802.11 as the backbone that connects the infrastructure devices and using MEA as the backbone. Investigators were to use both radios (MEA, 802.11) on the 2.4 GHz band in each wireless infrastructure device (IAPs, MWRs) (Figure 17). The MEA radios would provide client connectivity and the 802.11 radios provide the backbone connection between wireless infrastructure devices. Investigators were to then associate a client to an IAP and measure throughput for both protocol types, UDP and TCP back to a server on the wired network. Investigators were to then reconfigure the network with only the 2.4 GHz MEA radio activated in each IAP and MWR. Thus, the MEA radios would provide both the client connectivity and the backbone communications between infrastructure devices. Investigators were to again associate to the selected IAP and measure throughput for UDP and TCP back to the server on the wired network.

Experiment 7 was poorly designed and its objective was not clearly communicated to the investigators conducting the experiment. Hence, this experiment was done incorrectly and due to funding and time constraints, was not repeated correctly.

4 Summary and Conclusions

From Experiments 1 and 2, we were able to determine that when an IAP loses its connection to the wired network, it will eventually fail-over and appear as an MWR in the network, without dropping associated clients or MWRs. The throughput performance of a client communicating over the network (and through the severed IAP, now behaving like an MWR) was consistent with what we expected to see in 2-hop and 3-hop communication paths in a mesh network. This is significant for network robustness and redundancy.

Experiments 3 and 4 were very useful. Both the 802.11 network and the MEA network, operating in the 2.4 GHz band, allowed usable connections at all tested speeds, with UDP packets. We had great difficulty maintaining a connection on either network when using TCP packets, and were unable to gather meaningful TCP throughput data. At the distances we were operating from the access points (and hence the fraction of dropped packets), this is consistent with the findings of [4] regarding the use of TCP with high packet loss rates (greater than 1%).

The 802.11g technology has a higher link speed than the MEA technology (54 M bits per second [bps] vs. 6 Mbps). This means that even with greater packet loss rates, 802.11 can show higher throughputs than MEA, because of the higher transmission rates. This is what we saw.

We observed on the 802.11 network, that the throughput was higher, but much more variable (less predictable) from a mobile client to the wired network, than on the MEA network. Although the MEA had a lower average throughput, it was much more consistent than the 802.11 network for mobile client to wired network tests, at any of our tested vehicle speeds. This could make MEA mobile networks appropriate for transmission of real time video and VoIP to and from moving vehicles.

There may have been some degradation in throughput on the 802.11 network at vehicle velocities above 30 mph, but this was difficult to determine conclusively due to the high variability of the throughput data. The MEA throughput did not vary significantly over the speed range tested.

Processed throughput and packet loss data for both MEA and 802.11, gathered from Experiments 3 and 4, are summarized in Tables 2 and 3.

The MEA throughput was not as sensitive to velocity (as the 802.11), averaging 257 Kbps and staying in a range of 228-278 Kbps (average over both directions) throughput for the tested vehicle speeds. 802.11 throughput varied through the range of velocity tests, from (averaged over both directions) 375 Kbps to 514 Kbps, averaging overall about 429 Kbps. It can be observed from Tables 2 and 3 that the average throughput for MEA, when examined across the relevant vehicle speeds, had a much tighter standard deviation (45 Kbps) than the comparable 802.11 data (Std. Dev. of almost 123 Kbps).

As stated in Chapter 3, we were working with a sparse testbed where the closest approach to an access point in Experiments 3 and 4 was about 1500 feet. The best 802.11 throughput values we saw in Experiment 4 were consistent with what other researchers have reported at their maximum working distances. The report authors feel that in a deployment with denser infrastructure (a maximum of 1000-1500 feet between IAPs/MWRs and a maximum of 500-800 feet between clients and access points), higher throughputs would be seen for the MEA equipment and possibly the 802.11 equipment, due to higher signal strengths over the reduced distances.

To examine packet loss, the raw data was processed in a different manner than when analyzing throughput. For data samples that showed zero packets lost out of zero packets transmitted, 100% (lost packets) was substituted for the division by zero error. This was justifiable because, since no packets got through for several consecutive intervals, Jperf/Iperf did not know how many packet transmissions were attempted and so reported no packets transmitted. Average packet loss percentages and standard deviations of the packet loss percentages were comparable between the 802.11 and MEA networks.

Table 2. Summary of MEA data for Experiment 3.

		MEA					
Speed (mph)	Direction	New Ave. Throughput (bps)	Std. Dev. of Throughput (bps)	Average Packet Loss (%)	Std. Dev. of Packet Loss (%)	Minimum (non-zero) Throughput	Maximum Throughput
10	N-S	218.41	97.13	21.38	26.34	11.8	517
10	S-N	279.91	93.25	10.98	21.1	11.8	706
20	N-S	275.89	136.93	13.6	25.61	11.8	964
20	S-N	180.35	122.51	30.52	30.88	11.8	788
30	N-S	269.14	106.72	16.19	24.71	35.3	482
30	S-N	286.55	203.15	9.54	18.34	23.5	964
40	N-S	210.96	201.29	29.74	35.94	11.8	906
40	S-N	339.76	222.77	9.52	17.09	70.6	1000
50	N-S	246.29	226.52	23.48	32.77	11.8	882
50	S-N	263.2	155.85	21.03	31.29	11.8	647
Average =		257.05	156.61	18.60	26.41	21.20	785.60
Std. Dev. =		45.20	52.72	7.87	6.31	19.04	189.53

Table 3. Summary of 802.11 data for Experiment 4.

		802.11					
Speed (mph)	Direction	New Ave. Throughput (bps)	Std. Dev. of Throughput (bps)	Average Packet Loss (%)	Std. Dev. of Packet Loss (%)	Minimum (non-zero) Throughput	Maximum Throughput
10	N-S	538.35	272.64	14.41	22.49	11.8	976
10	S-N	294.47	169.09	14.31	29.05	11.8	682
20	N-S	533.12	317.68	25.91	35.13	11.8	953
20	S-N	382.18	275.77	14.02	21.91	11.8	1893
30	N-S	591.44	304.39	20.15	30.46	11.8	917
30	S-N	437.27	378.97	12.65	19.75	11.8	3293
40	N-S	475.84	320.56	20.47	30.99	11.8	906
40	S-N	286.91	274.02	20.45	26.23	11.8	835
50	N-S	512.13	264.88	13.76	17.32	11.8	917
50	S-N	237.13	262.36	20.07	26.18	11.8	894
Average =		428.88	284.04	17.62	25.95	11.80	1226.60
Std. Dev. =		122.77	54.00	4.36	5.59	0.00	796.30

Our test course had only a few obstacles that would be likely to cause multipath interference. Near the South end of the course there were some structures and other items that could contribute to multipath interference issues. From the throughput data plots, we observed degradation in this area for both 802.11 and MEA technologies. The effect of these obstacles can be seen in the raw 802.11 data, noting similar patterns but reversed, when traversing the route in the opposite direction. (i.e, A degradation in the data may appear about three quarters of the way through a north-to-south plot, with a corresponding data degradation about one quarter of the way through a south-to-north data plot for the same vehicular speed.) This effect is well defined at 10, 20, and 30 mph (refer back to Figures 42 and 44, 46 and 48, 50 and 52, respectively, in the previous chapter) and still evident at 40 and 50 mph (Figures 54 and 56, 58 and 60 in Chapter 3).

Although the raw data plots indicated throughput degradation in this area for both tested network technologies, 802.11 suffered a much more pronounced reduction in throughput than the MEA technology, presumably caused by multipath interference. An example of this can be seen by comparing Figures 50 and 52 to Figures 30 and 32 in Chapter 3.

Raw, unprocessed data from using the linear amplifier in Experiment 4 is summarized in Table 4. The observations on the use of a linear amplifier to boost the 802.11 signal were

consistent with laboratory bench test results of the study of MEA equipment [10]. The authors experimentally confirmed that increasing the effective radiating power is not helpful for mitigating throughput degradation resulting from multipath interference.

Table 4. Summary of 802.11 data using a linear amplifier in Experiment 4.

		802.1 w/ Linear Amp. (Raw)	
Speed (mph)	Direction	Ave. Throughput (Kbps)	Std. Dev. of Throughput (Kbps)
10	N-S	161.56	201.28
10	S-N		
20	N-S	388.69	217.36
20	S-N	262.47	82.37
30	N-S	490.99	231.34
30	S-N	259.93	215.49
40	N-S	353.61	223.36
40	S-N	245.90	262.70
50	N-S	519.18	246.86
50	S-N	212.30	209.21
Average =		321.63	210.00
Std. Dev. =		124.42	51.50

Experiment 4, 802.11 in motion at vehicular speeds conducted with a single access point, confirmed findings of [4] and [6] with respect to performance in environments free of, or with minimal, multipath interference. (Bergamo, et al. [4] also observed problems with metal obstructions, which may be similar to the phenomena we were seeing toward the South end of our test course.) In the portion of our test route where more multipath interference was inferred to be present, we saw degraded performance that could be expected based on the work of Alexander, et al. [3], Matolak [9], Cheng, et al. [5], and Giustiniano, et al. [7]. In either case, the high variability of the 802.11 throughput could be a problem for real-world applications. The MEA technology appears to be more consistent and resilient in the presence of multipath interference.

Because Experiments 5 and 6 were faulty, not much useful information was gained from them. In Experiment 5 (MEA radios, with handoffs between infrastructure nodes), the investigators did observe lower throughputs than when dealing with a single IAP. This is likely caused, at least in part, by the handoff between IAPs. Also contributing to the reduced throughput may be the difference in terrain because of the longer route. Experiment 6 (802.11 radios, with handoffs between IAPs), conducted with a linear

amplifier at the client end (in the vehicle), exhibited very poor throughput performance, even when compared to the single IAP results using a linear amplifier in Experiment 4. It also reinforced the notion that increasing the power is not effective in improving throughput performance in high multipath interference environments.

Even though Experiment 7 was flawed, the investigators did observe that in a lightly loaded, sparse network, the MEA backbone yielded higher throughput results than the 802.11 backbone. The authors would expect that in a network with a greater density of infrastructure nodes meshing together (resulting in higher speed backbone communication links facilitated by stronger signal-to-noise ratios from geographically closer nodes), that as more MEA clients are added to the network, increasing the MEA traffic, an 802.11 backbone would then give better throughput performance.

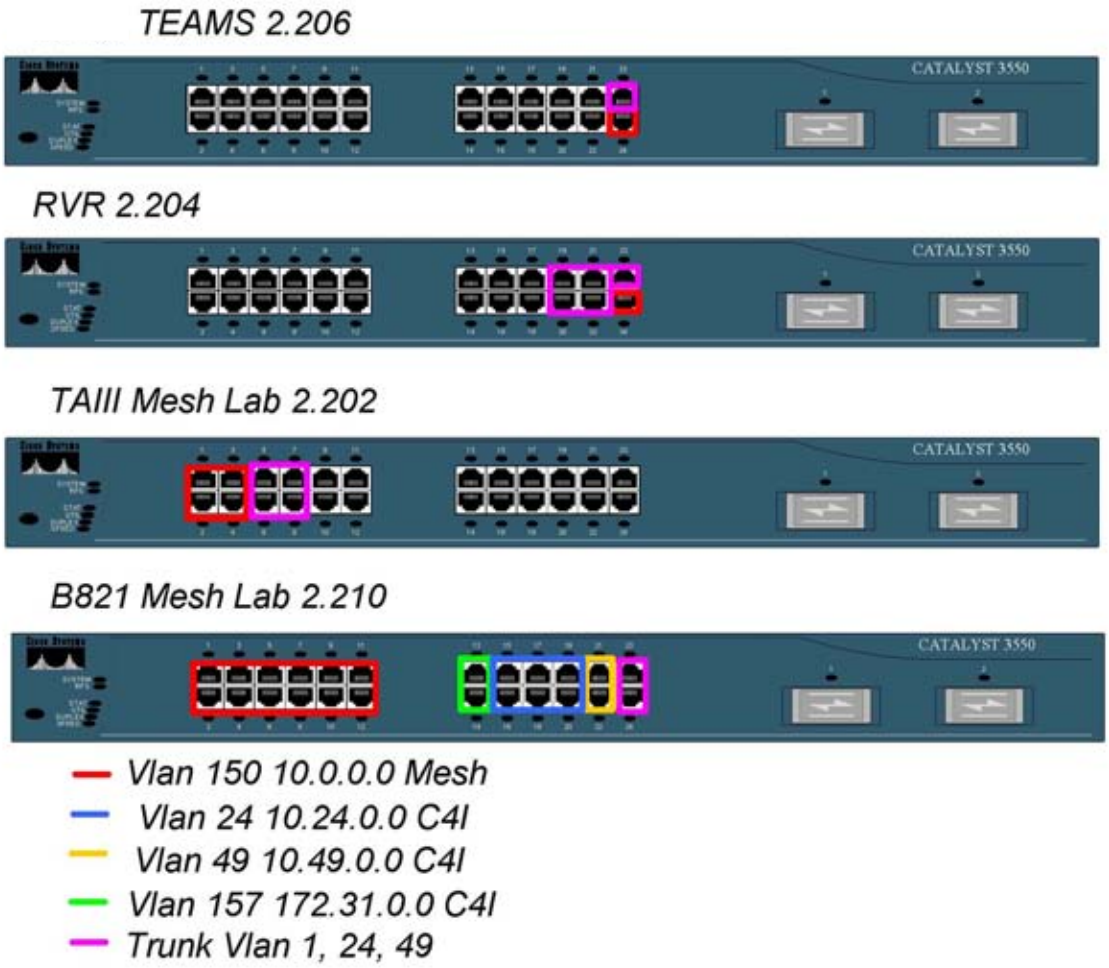
On a general note, the authors were also interested in the ratio of MWRs to IAPs in a wireless mesh network. Conventional wisdom from Motorola and one of its equipment resellers/installers, dictates a ratio of 4 to 8 MWRs per each IAP, giving a ratio of between 4:1 and 8:1. The authors were interested in whether any issues (such as excessive mesh network management/maintenance traffic between IAPs) would arise if this ratio were reduced to 2:1, 1:1, or even lower.

By lowering the ratio of MWRs to IAPs in a wireless mesh network, the data has more places to get off of the wireless network onto the wired network; thereby increasing the aggregate throughput the wireless network is capable of supporting. The lower number of MWRs in a network – using them only when necessary, due to lack of wired infrastructure availability – also minimizes the hop count on the wireless links, hence improving throughput with respect to a path containing more wireless hops.

In this network, the investigators used ratios of MWRs to IAPs that varied between 2/3 : 1 and 1/3 : 1. The investigators did not see any adverse effects induced by this very low ratio of MWRs to IAPs. It seems, that as long as the overall density of IAPs and MWRs is not too great (where power density limits are exceeded or clients keep re-associating between infrastructure nodes because all paths are of approximately equal strength), the mix between IAPs and MWRs does not affect functionality. Performance can be affected by not having enough connections to the wired network, if there are too many MWRs per IAP. Having more IAPs in favor of fewer MWRs in the wireless network, seems to not only increase the aggregate network traffic capacity of the wireless network, but also make the network more robust and more tolerant of wired communication line failures (such as 'backhoe errors').

Appendix A Switch Configuration for Testbed Setup

Shown below are the port configurations for the communications switches in the wireless testbed.



Appendix B Acronyms and Abbreviations

Area III	Sandia National Laboratories Technical Area III
dB	decibel
dBi	decibel (isotropic)
GPS	global positioning system
IAP	Intelligent Access Point
IP	Internet protocol
Kbits	Kilo bits
LOS	line of sight
MEA	mesh enabled architecture
mph	miles per hour
mW	milliwatt
MWR	Mesh Wireless Router
QDMA	quadrature division multiple access
RF	radio frequency
RVR	robotic vehicle range
TCP	transmission control protocol
UDP	user datagram protocol
VMM	Vehicle-mounted Modem
VoIP	voice over IP (voice over Internet protocol)
WMN	wireless mesh network

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