NASA/TM—2009-215500

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February 2009

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Level of Review: This material has been technically reviewed by technical management.

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Summary

Future lunar surface missions supporting the NASA Vision for Space Exploration will rely on wireless networks to transmit voice and data. The ad hoc network architecture is of particular interest since it does not require a complex infrastructure. In this report, we looked at data performance over an ad hoc network with varying distances between Apple AirPort wireless cards. We developed a testing program to transmit data packets at precise times and then monitored the receive time to characterize connection delay, packet loss, and data rate. Best results were received for wireless links of less than 75 ft, and marginally acceptable (25-percent) packet loss was received at 150 ft. It is likely that better results will be obtained on the lunar surface because of reduced radiofrequency interference; however, higher power transmitters or receivers will be needed for significant performance gains.

Introduction

The availability of robust, lightweight voice and data communication is critical to the success of lunar surface missions supporting the NASA Vision for Space Exploration. The development of wireless surface networks integrating computing and data storage, as well as sensor network interfaces and controls, will be essential for future exploration missions (Refs. 1 and 2). Wireless architectures offer human and robotic explorers all the benefits of a wired network without the restrictions of wires. Ad hoc mesh networks, in particular, take a straightforward approach to data communication among rovers, habitats, and astronauts because they do not rely on complex infrastructure. These networks also provide greater scalability since configurations can be changed easily to support a dynamic number of interfaces.

The fault tolerance, reliability, and expandability of ad hoc wireless networks must be evaluated if they are to be considered for applications in the core exploration architecture. In this report, we investigate the data flow performance of an ad hoc networking configuration based on the IEEE 802.11g wireless standard. We examine the characteristics of data packet delay and packet loss. We also look at the observed data rate relative to the transmitted data rate. The measurement data will help to determine an approximate range at which a standard laptop 802.11g transceiver could be used for lunar surface area communications.

802.11 Wireless Communication

The IEEE 802.11g protocol was developed to specify an over-the-air interface between a wireless user and an access point in infrastructure mode, or between two wireless users in an ad hoc setup. Data communication is accomplished by encoding packets and then transmitting them serially over the physical medium to a remote station. The ad hoc architecture configuration shown in Figure 1 allows two nodes equipped with 802.11g wireless adapter cards to set up an independent network when they are within range of one another. A node could be a computer, as in our analysis, or another electronic device, like a sensor.

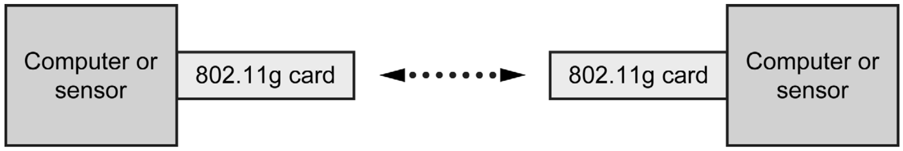

Figure 1.—Wireless ad hoc network architecture.

Table I shows the specifications for the various IEEE 802.11 wireless protocols. The 802.11g approach specifies a burst rate of 54 megabits per second (Mbps) using orthogonal frequency division multiplexing in the 2.4-GHz Industrial, Scientific, and Medical (ISM) unlicensed band. This frequency range is shared with other wireless systems, and thus, it must operate in a noninterfering fashion (i.e., through collision-avoidance and carrier-sensing mechanisms). The IEEE 802.11g and 802.11a protocols theoretically can transfer data five times faster than 802.11b. However, because of protocol and packet processing overhead, actual network data rates typically are lower than the nominal maximum rate. In addition, wireless networks tend to experience interference that results in erosion of throughput.

TABLE I.—SPECIFICATIONS FOR IEEE 802.11 WIRELESS PROTOCOLS
[Ref. 3.]

	Specification		
	WiFi[a] IEEE 802.11a	WiFi IEEE 802.11b	WiFi IEEE 802.11g
Standard approval	July 1999	July 1999	June 2003
Maximum data rate, Mbps	54	11	54
Modulation	OFDM[b]	CCK[c]	OFDM, CCK
Supported data rates, Mbps	6, 9, 12, 18, 24, 36, 48, 54	1, 2, 5.5, 11	CCK: 1, 2, 5.5, 11 OFDM: 6, 9, 12, 18, 24, 36, 48, 54
Frequencies, GHz	5.15 to 5.35 5.425 to 5.675 5.725 to 5.875	2.4 to 2.497	2.4 to 2.497
Approximate theoretical range, ft (Mbps)	40 (54) 125 (11) 150 (2)	170 (11) 260 (2)	65 (54) 180 (11) 260 (2)

[a]Certification of the Wi-Fi Alliance that is based on the IEEE 802.11 standards and that ensures interoperability between wireless devices.
[b]Orthogonal frequency division multiplexing.
[c]Complementary Code Keying.

Testing Configuration

The in-house packet transceiver program in Figure 2 was written for the wireless evaluations. Existing network performance testing toolkits can perform similar tasks, but often it is not possible to characterize any added instruction overhead. Instead, simplistic code was developed to minimize processing delays.

The testing program was split into two major parts: a controller and node. The controller is the central interface for network testing, responsible for instructing specific nodes to transmit information to other nodes. The node program, therefore, handles both transmit and receive functionality. By default, a node listens constantly for commands and data. A separate instance of the node program, called a child process, is created when a node receives a command to transmit packets. This allows simultaneous data flows to originate from a single node. Meanwhile, the node continues to listen for test data on its local receive port. Statistics are updated as each data packet arrives on the proper port.

Several implementation decisions were made to reduce the complexity of the testing architecture. A single laptop acted as both the controller and the transmitter, to allow for a smaller mobile system size. Minimal network overhead was added because of communication between the two programs on the same system; the local loopback protocol was used to deliver the initial transmit command. The packet payload size was set at 982 bytes in order to pad the entire packet to 1024 bytes when considering the standard

```
control {
        1. Create sockets pointing at each of the transmit nodes.
        2. Continuously poll the command line for user commands.
                a) "quit" : Tell each node to display statistics and terminate.
                b) "help" : Print usage information for available commands.
                c) "transmit" : Send a 'transmit' command to the desired node.
}

node {
        1. Listen for control messages (port 5000) and data packets (port 5001).
        2. Reset packet size, packet number, and error counters; open a log file.
        3. Continuously poll for data on all ports, non-blocking, until 'break'.
                If (test data is received)
                        a) Record receive time for the first and most recent packet.
                        b) Increment the byte counter.
                        c) Parse the packet number; check to see if the packet is sequential.
                Else if (control data is received)
                        a) "quit": Break out of continuous polling mode.
                        b) "transmit": Call p_transmit() to send packets.
        4. Print the number of bytes received and calculate a data rate.
}

p_transmit {
        1. Create a UDP/IP socket pointing to the remote node.
        2. Create an independent child process and terminate the p_transmit() parent process.
        3. Construct a UDP/IP/Ethernet packet, and fill a 982-byte payload with 0xFF.
        4. Transmit the desired number of packets.
                a) Fill bytes 0 and 1 of the packet with a sequential packet number.
                b) Transmit the single packet over the socket to the destination host.
                c) Delay for a number of milliseconds.
}
```

Figure 2.—Custom packet transceiver program for performing packet data analysis. UDP, User Datagram Protocol; IP, Internet Protocol.

8-byte User Datagram Protocol (UDP) header, 20-byte Internet Protocol (IP) header, and 14-byte Ethernet header. In addition, a 16-bit packet number was appended to the beginning of the payload to help determine whether arriving packets were sequential.

Both UDP and IP have characteristics that make them adept at performance testing (Ref. 4). UDP is a connectionless, stateless protocol, which reduces packet timing overhead by eliminating items such as congestion control, throttling, and handshaking procedures. In addition, UDP does not provide error correction: lost packets are not retransmitted, and corrupt packets are either delivered as-is or are dropped, depending on the implementation. IP provides minimal interference in the transmission process. A checksum is computed over the IP header, but otherwise no error correction or retransmission takes place at the network layer.

The testing environment for the wired and wireless systems is shown in Figure 3, parts (a) and (b), respectively. All tests were conducted using the same transmit and receive programs, laptops, and UDP/IP configuration parameters. The UDP port and IP address were chosen arbitrarily, and the Media Access Control (MAC) address was defined by the network card. Since the network hub used for the wired testing is limited to around 10-Mbps throughput, the theoretical testing data rates were kept far below this threshold.

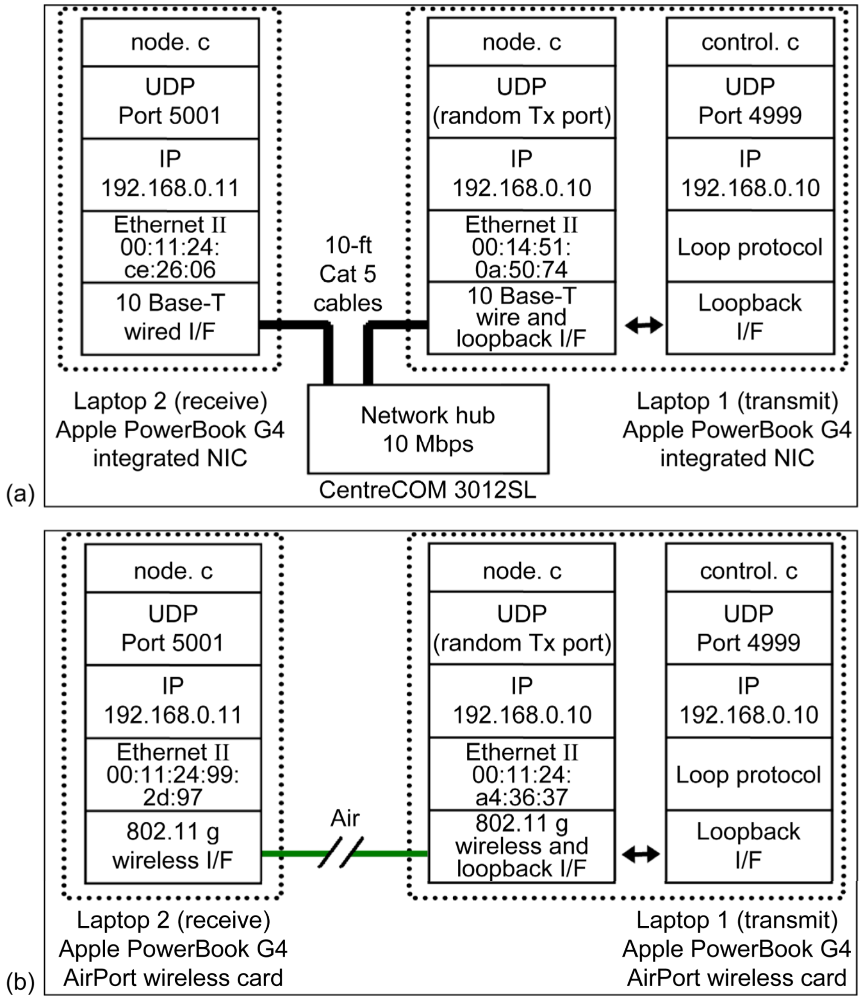

Figure 3.—Testing environment. UDP, User Datagram Protocol; IP, Internet Protocol; NIC, network interface card; I/F, interface. (a) Wired systems. (b) Wireless systems.

Testing and Results

For each test, 1000 packets were transmitted to the receiver with a timed delay of 100 ms between each packet. Wireless tests were conducted outdoors using a line-of-sight link; however, the test area contained several trees that could contribute to radiofrequency scattering effects. Figure 4(a) shows measurement results for observed packet delay in the wired testing environment. Results for the wireless testing environment are exhibited in Figures 4(b) to 4(e), with distances between the transmitter and receiver of 1, 75, 150, and 200 ft, respectively.

Table II shows packet transmission characteristics for the wired and wireless tests. The number of packets transmitted but never received increased up to 27.1 percent as the distance between the transmitter and receiver reached 150 ft. When the distance was extended to 200 ft, only 0.5 percent of the packets were received from the transmitter. Data rate refers to the average calculated throughput from the time that the first packet was received until the time that the last packet was received. The highest data rate was seen for a wireless range of 1 ft; however, no test showed a remarkable drop in throughput. A high data rate would have been possible despite large packet loss if all the received packets arrived in a compact group.

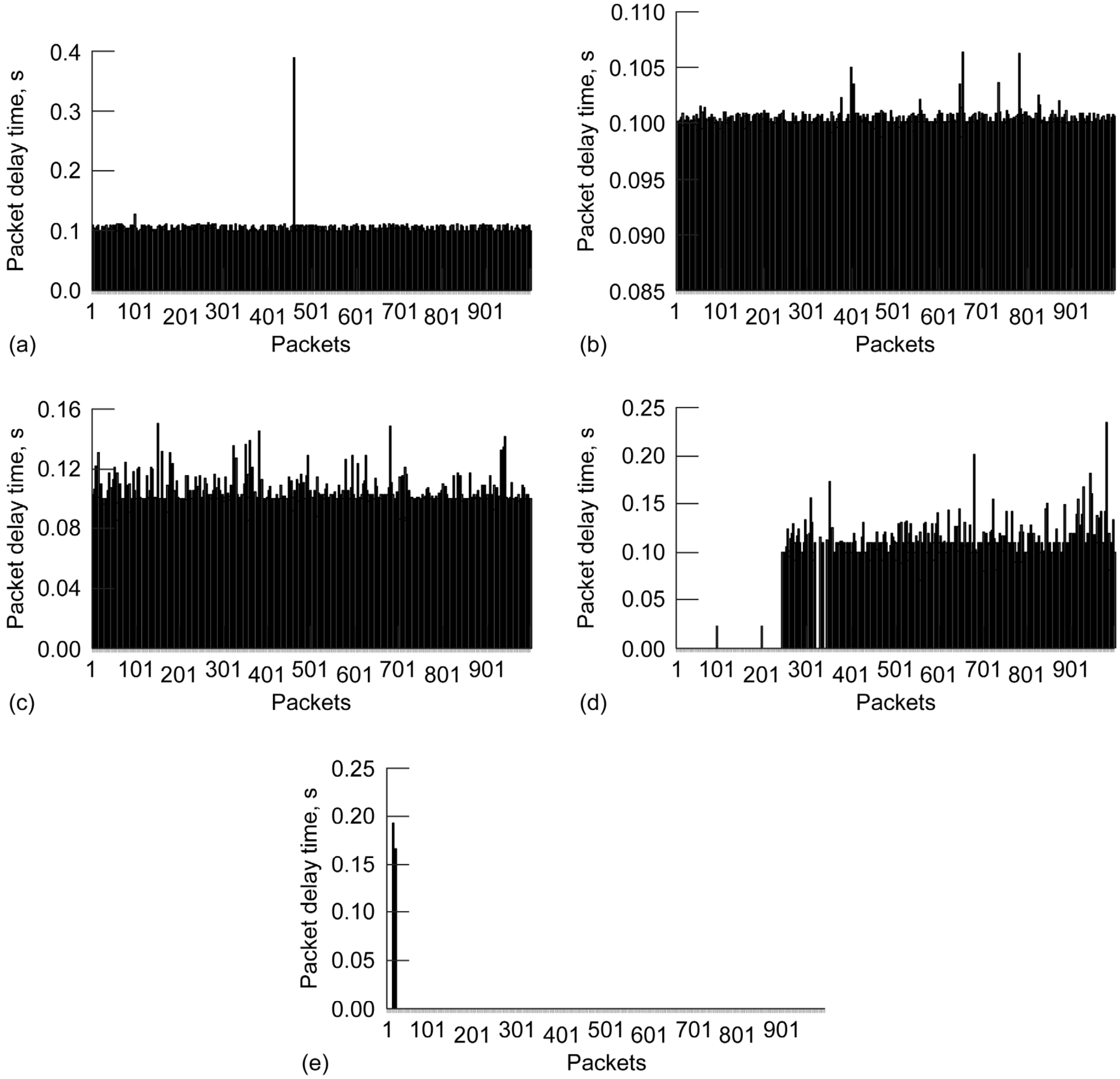

Figure 4.—Measurement results for observed packet delay. (a) Wired connection. (b) Wireless connection (1 ft). (c) Wireless connection (75 ft). (d) Wireless connection (150 ft). (e) Wireless connection (200 ft).

TABLE II.—PACKET TRANSMISSION CHARACTERISTICS FOR WIRED AND WIRELESS TESTS

Network type (distance transmitted)	Average delay, ms	Standard deviation, ms	Packet loss, percent	Data rate, bytes/s
Ideal transmitted	100	0	0.0	10240.0
Wired	100	11	.0	9939.7
Wireless (1 ft)	100	0.6	.0	10238.3
Wireless (75 ft)	100	15	.4	10198.4
Wireless (150 ft)	105	76	27.1	9811.5
Wireless (200 ft)	(a)	(a)	99.5	8722.3

[a]Could not be computed because of excessive packet loss.

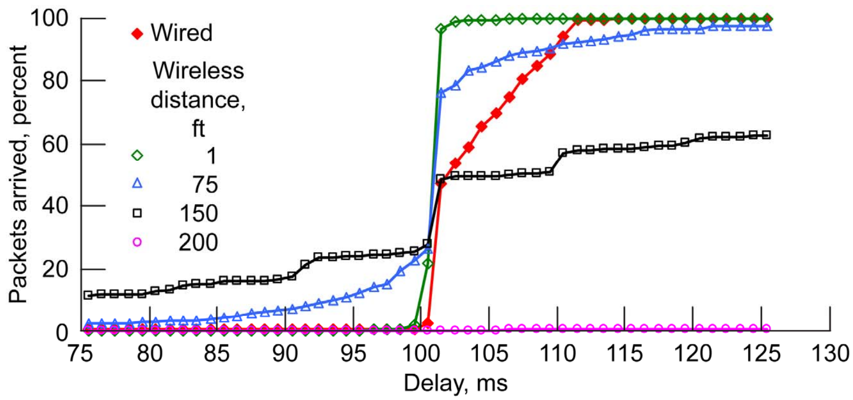

Figure 5.—Cumulative packets arrived by time for wired and wireless tests. Total 1000 packets sent; 1000-ms desired delay.

Figure 5 shows the amount of cumulative packets arrived versus time for wired and wireless network tests. The best results are indicated by a sharp increase around the 100-ms mark. In general, the delay time required to reach 100-percent packet arrival became larger as the distance between the transmitter and receiver increased.

Discussion

The data in Table II show a clear trend toward less reliable wireless communication as the distance between the transmitter and receiver increases. It appears that the 802.11g card evaluated in this test can cover effectively a range of about 75 ft with minimal packet loss. A majority of the packets still arrived at 150 ft; however, approximately 25 percent of the packets were lost, which may not be acceptable for some real-time applications like voice or streaming video. Communication was lost almost completely when the transmitter and receiver were separated by 200 ft, with only 5 out of 1000 packets being received at this distance between the transmitter and receiver.

We expected that the wired network test would provide a result close to the ideal performance level; however, the results demonstrate that this was not the case. Figure 5 shows that approximately half of the packets arrived very close to the transmitted 100-ms delay and that the remainder arrived by around 112 ms. We do not think that the network hub reduced system performance, because a hub is a passive device and all packets would be delayed equally. Therefore, since IP and UDP do not provide congestion control, it is likely that the Ethernet card or the driver involved in the test provided some type of packet buffering.

Figure 5 shows that a number of packets from the wireless tests arrived well before the 100-ms mark. We observed that, as distance increased, packets tended to be more clustered. A significantly delayed packet was often followed quickly by the subsequent packet. This could be due to the multipath effects of the testing environment or to error-correcting retransmission algorithms within the wireless network card. It is possible that the 802.11g firmware contains error detection and correction functionality that was not controllable within the test environment.

Conclusions

The 802.11g wireless performance test showed that a standard wireless network card provides best performance up to approximately 75 ft. Tests beyond that distance resulted in increased packet loss and slower data rates.

IEEE 802.11g communication is subject to interference by a number of terrestrial technologies, including cordless phones and Bluetooth devices operating at 2.4 GHz. However, it is unlikely that a communication network operating on the lunar surface will see the same adverse effects to the extent reflected in our data.

The advantage of using the ad hoc network architecture presented in this report is that it requires no administration or preconfiguration. However, the drawback is that communication is limited to a very short range. Because of this restriction, on the lunar surface the ad hoc network likely is more suited for data communication among astronauts within close proximity.

Future Work

We identified additional areas of research on this topic. Because of the uncertainties in error correction associated with the network cards used in the project, it would be useful to study the performance of a pure 802.11g implementation on a field-programmable gate array platform. It would also be helpful to observe the effects of adding amplifiers or high-gain antennas to the study. Further research could be performed to draw comparisons to similar terrestrial communication standards, such as 802.16e (mobile WiMAX) or cellular protocols.

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REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
01-02-2009	Technical Memorandum	

4. TITLE AND SUBTITLE
Assessment of the 802.11g Wireless Protocol for Lunar Surface Communications

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Chelmins, David, T.; Nguyen, Hung, D.; Foore, Lawrence, R.

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
WBS 903184.04.03.02.02

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field
Cleveland, Ohio 44135-3191

8. PERFORMING ORGANIZATION REPORT NUMBER
E-16820

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSORING/MONITORS ACRONYM(S)
NASA

11. SPONSORING/MONITORING REPORT NUMBER
NASA/TM-2009-215500

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified-Unlimited
Subject Category: 17
Available electronically at http://gltrs.grc.nasa.gov
This publication is available from the NASA Center for AeroSpace Information, 301-621-0390

13. SUPPLEMENTARY NOTES

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15. SUBJECT TERMS
Wireless communication; Lunar surface; Data transmission; Frequency division multiplexing

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			STI Help Desk (email:help@sti.nasa.gov)
U	U	U	UU	13	**19b. TELEPHONE NUMBER** *(include area code)* 301-621-0390

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Prescribed by ANSI Std. Z39-18