Evaluation of IEEE 802.11g and 802.16 for Lunar Surface Exploration Missions Using MACHETE Simulations

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In this paper, we investigated the suitability of terrestrial wireless networking technologies for lunar surface exploration missions. Specifically, the scenario we considered consisted of two teams of collaborating astronauts, one base station and one rover, where the base station and the rover have the capability of acting as relays. We focused on the evaluation of IEEE 802.11g and IEEE 802.16 protocols, simulating homogeneous 802.11g network, homogeneous 802.16 network, and heterogeneous network using both 802.11g and 802.16. A mix of traffic flows were simulated, including telemetry, caution and warning, voice, command and file transfer. Each traffic type had its own distribution profile, data volume, and priority. We analyzed the loss and delay trade-offs of these wireless protocols with various link-layer options. We observed that 802.16 network managed the channel better than an 802.11g network due to controlled infrastructure and centralized scheduling. However, due to the centralized scheduling, 802.16 also had a longer delay. The heterogeneous (hybrid) of 802.11/802.16 achieved a better balance of performance in terms of data loss and delay compared to using 802.11 or 802.16 alone.

Nomenclature

CCSDS = Consultative Committee for Space Data Systems
EVA = Extra Vehicular Activity
IEEE = Institute of Electrical and Electronics Engineers
IRTF = Internet Research Task Force
LEO = Low Earth Orbit
MAC = Medium Access Control
MACHETE = JPL's Multi-mission Advanced Communications Hybrid Environment for Test and Evaluation
OFDM = Orthogonal Frequency-Division Multiplexing
TDD = Time Division Duplex
TOAST = JPL's Telecom/Orbital Analysis Tool
VSE = U.S. Vision for Space Exploration

I. Introduction

Under the Vision for Space Exploration, presented by then U.S. President George W. Bush, NASA will return to and "gain a new foothold on the moon" by 2020 "with the goal of living and working there for increasingly extended periods of time." While previous lunar surface exploration missions used custom communication systems, the rapidly developing field of terrestrial wireless communications (e.g., WiFi, WiMAX, 3G, etc) offers the potential use of Commercial Off The Shelf (COTS) communication systems for future lunar surface exploration missions. However, terrestrial telecommunication systems are designed with terrestrial constraints in mind, so NASA must perform analysis and simulations to understand the trade-offs and identify shortfalls and risks of using COTS communication systems.

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In addition to the lunar surface network, simulations should consider data return to the Earth. The communication may be direct-to-Earth from lunar surface assets or through lunar communications and navigation relay satellite(s). The integration of COTS communications systems with custom communication systems needs careful evaluation due to the challenges posed by the lunar environment. The resources such as base-stations and relay satellites are limited. There are also very few nodes on the lunar surface (e.g. EVAs, rovers) compared to terrestrial networks; fewer nodes can act as relays. Additionally, due to the sparse network structure, communications links may be disruptive due to nodes moving beyond communication range, relay satellite(s) occultation, or terrain obstruction. One must also consider the trade-off of using lower power radios and adding more relay nodes or using higher power radios and needing to resolve interference.

The moon's surface curvature also poses a challenge and increases the need of repeaters at relatively short distances. At a distance of roughly 2.3 km, communicating entities will lose line-of-sight communication and must rely on repeaters. Other considerations concern the weight constraint of the Extra Vehicular Activity (EVA) suits. Weight constraints imply the need for lightweight low power radios. Optimizing (minimize) power use in the radios can negatively affect communication range and data rates. Simulations can be used to characterize the effects these changes have on protocol behavior.

The goal of this study was to determine the suitability of COTS protocols for lunar missions as a step towards future Mars missions. This study was performed under the Software Avionics Integration Office (SAVIO). SAVIO in turn supports the Systems Engineering and Integration (SE&I) group for NASA's Constellation Program (CxP). The Constellation Program is the organization responsible for implementing the vision of the Exploration Systems Mission Directorate (ESMD), which leads NASA's new Vision for Space Exploration initiative. The Constellation Program is responsible for building and operating NASA's new space vehicles that will return humans to the moon and then eventually enable further exploration to Mars.

This study focused on the evaluation of IEEE 802.11g and IEEE 802.16 protocols for lunar exploration missions. In this work, we used JPL's Multi-mission Advanced Communications Hybrid Environment for Test and Evaluation (MACHETE)[1] tool for the evaluation and analysis of end-to-end wireless technologies. MACHETE is built on a COTS discrete event simulator and contains additional custom-built models for space-based networking. For example, MACHETE contains protocol models for IRTF delay-/disruption-tolerant networking and CCSDS space data link protocols like CFDP, Proximity-1 and Telecommand/Telemetry. Results showed advantages and disadvantages for homogeneous and heterogeneous 802.11 and 802.16 networks for lunar surface exploration.

The rest of this paper is organized as follows. Section II provides an overview of the physical nodes and connectivity for lunar surface operations. Section III describes the protocols modeled and application traffic simulated. Section IV presents the simulation analysis and results. Section V summarizes the results and discusses follow on work.

II. Lunar Surface Scenario

While the Vision for Space Exploration starts in low earth orbit, goes to the moon and then to Mars, this study focused only on the lunar surface operations. We focused on nominal operations and defer consideration of relay links and links from or to Earth to future studies. Also we did not address tracking and navigation needs for lunar surface elements.

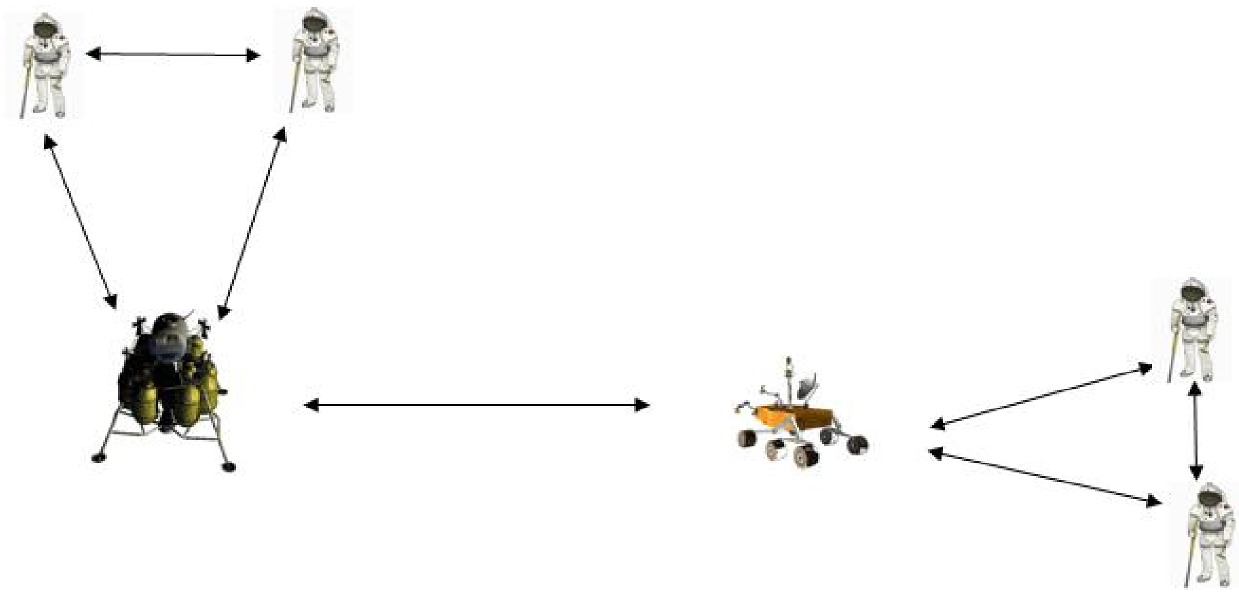


Figure 1. Lunar Surface Scenario Example.

The scenario's physical topology was based on an early lunar surface network design (shown in Figure 1) with two EVA teams external to the Altair station. One of the EVA teams is performing science investigations close to Altair's location and can communicate with Altair directly. The other EVA team is out farther and should use a rover to relay communication with Altair; the EVA members of this team can tele-operate the rover. The rover is situated within the communication vicinity of Altair to allow direct communication with Altair. EVA crewmembers in the same team should also be capable of communicating with each other directly. This basic scenario is used to evaluate the feasibility of various radio types as well as determining protocol capabilities. Data traffics simulated include voice, command, telemetry, caution and warning, and file transfer. Video traffic was analyzed in a separate study[2].

III. Simulation Description

A number of wireless communications protocols have been established as international standards and are in commercial use. The protocols selected and simulated in this study were the IEEE 802.11g wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications and the IEEE 802.16 Air Interface for Fixed Broadband Wireless Access Systems. We focused on 802.11g and 802.16e protocols because of the commonality in the physical layer for Orthogonal Frequency-Division Multiplexing (OFDM). The simulation scenario (shown in Figure 1) involved two teams of EVAs, one rover and the Altair base-station. The EVAs, rover and Altair were located within an area bounded by 650 meters by 550 meters, and mobility was not modeled. We modeled expected traffic patterns from NASA data traffic studies in which there were five traffic types: caution and warning, voice, command, telemetry and file transfer. Among these traffic types, caution and warning has the highest priority and voice has the next highest priority. Command and telemetry share the next highest priority level, and file transfer operations have the lowest priority.

We simulated one-hour surface scenarios with four alternative link protocol combinations: Homogeneous 802.11g with and without link-layer retransmissions, homogeneous 802.16, and heterogeneous 802.16/802.11g. We assumed a two-ray path loss model. The channel topology for homogeneous 802.11 and 802.16 is shown in figure 2. The heterogeneous 802.11/802.16 topology is shown in figure 3This study focused exclusively on link protocols. Neither 802.11g nor 802.16 specify network routing protocols so dynamic/adaptive routing was not included. Using 802.11g without dynamic routing reduced the operations range by the most constrained radio (carried by EVA), but, notably, allowed the desired point-to-point capability for EVA to EVA communications.

A. Homogeneous 802.11g Network

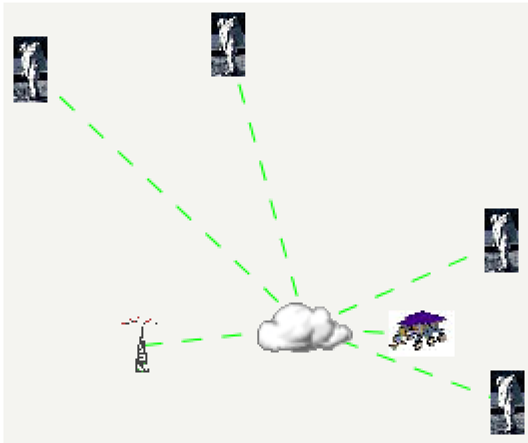


Figure 2. Network Topology for Homogeneous Network (802.11, or 802.16).

802.11g settings: To disable/enable link-layer retransmission the short and long packet transmit limits were alternated from 1 (no link retransmissions) to 11 (up to 10 retransmissions). The 802.11g network topology is shown in Figure 2 (ad-hoc mode).

B. Homogeneous 802.16 Network

802.16e settings: we modeled 802.16e allowing automated modulation switching to maximize on the data rate. Altair was configured as the base station.

The homogeneous 802.16 topology is also shown in Figure 2. Altair was used as a base station while the rover and all the other assets are subscriber stations. Wireless connectivity between two base stations is not a part of the 802.16 standard and subscriber to subscriber cross-communication is not defined. Thus, even though 802.16 provided reliable data transfer, there was a loss of the essential point-to-point EVA to EVA communication capabilities.

C. Heterogeneous 802.11g/802.16 Network

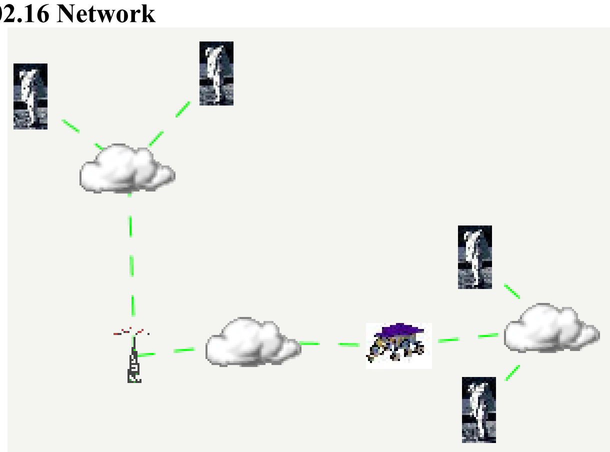


Figure 3. Network Topology for Mixed/Hybrid Network (802.11 and 802.16).

In the heterogeneous network, the long-haul link (Altair-Rover) uses 802.16, and short-range networks use 802.11g. We modeled separate channels for 802.11 and 802.16 so they did not interfere with each other. In order to allow internetwork communication a static route entry was added between the 802.16 and 802.11 LANs. All other model parameters were identical to the homogeneous scenarios discussed above.

IV. Analysis of Design and Results

The following section presents results for simulated VOIP, Caution and Warning, Command, Telemetry, and Tele-Operate traffic and signal errors. The results help us to understand the loss and delay trade-offs of COTS wireless protocols with various link-layer options for a lunar surface exploration network.

In either homogeneous network (802.11 only and 802.16 only) without adaptive routing the network was not able to use the rover as the relay for the EVA team. This reduced the range of operations for the 802.11 network by the most constrained link which is the EVA to EVA link if all surface assets are assumed to be a part of the same 802.11 network but allowed the point-to-point link capability essential for EVA to EVA communications. Likewise, wireless connectivity between two base stations is not a part of the 802.16 standard. Thus even though 802.16 network provides reliable data transfer, there was a loss of the essential direct EVA to EVA communications.

We observed that with the predicted traffic patterns a homogeneous 802.16 network managed the channel better than an 802.11g network due to the controlled infrastructure nature as compared to the ad-hoc nature of the 802.11g network. This reliability on the 802.16 network came with longer delay due to the centralized scheduling of the links as well as requiring all data transferring through the base station (Altair). 802.16 even without link-layer retransmissions resulted in almost no lost application messages though with the aforementioned loss of direct EVA to EVA communication capabilities.

Finally, the heterogeneous 802.11/802.16 scenario benefited from channel separation. This design not only reduced the data loss and delay of the network as compared to homogeneous 802.11g and 802.16e, it also provided additional benefits increasing the range of the Rover-EVA team and providing point-to-point connectivity between EVA crew members.

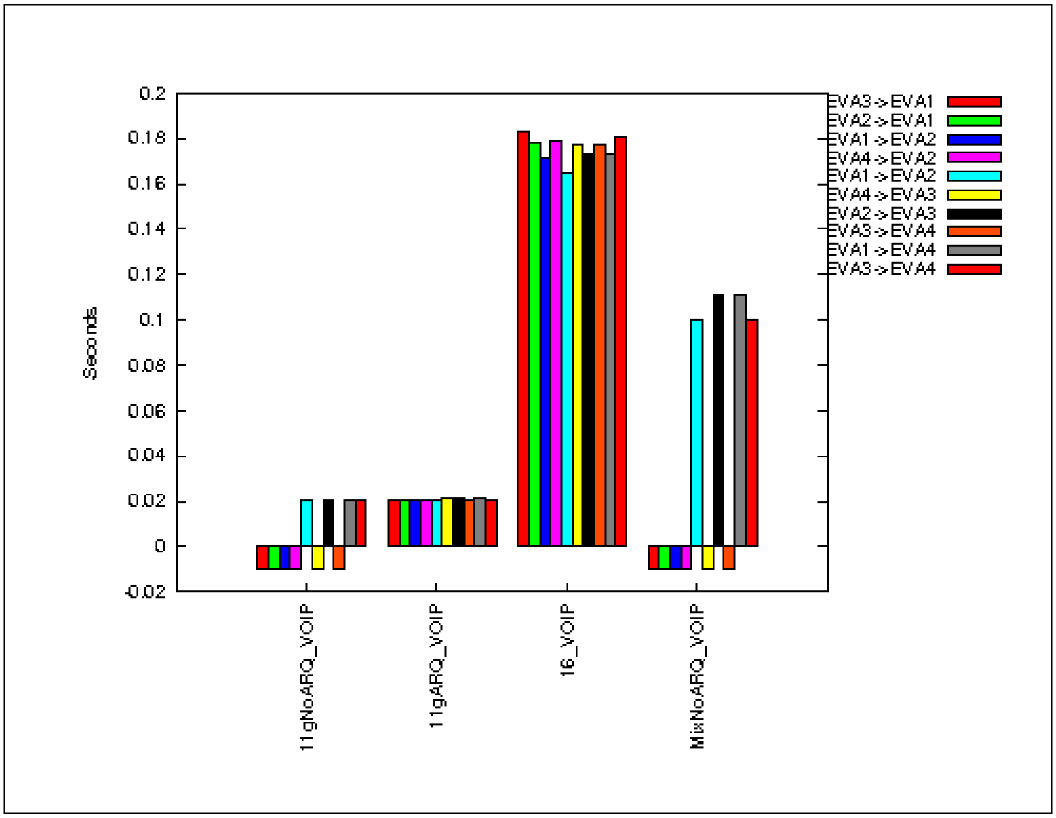
The following sections describe the results for each traffic type.

A. Voice over IP (VoIP)

For VoIP, most notably, the centralized-scheduling architecture of 802.16 significantly increased delay and jitter, by requiring all traffic to pass through the base station as seen in the both plots in figure 4, but had much less data loss (Figure 5) compared to the 802.11g network.

Typical terrestrial VoIP systems desire less than 100ms delay, less than 20ms jitter and less than 1% loss rates. During simulation both the homogeneous 802.11g (without link retransmission) and heterogeneous 11g/16 networks had calls fail to establish due to collisions. Additionally, the homogeneous 802.16 scenario had an average delay of 180ms and jitter of 70ms.

So these preliminary simulations showed 802.11g (with ARQ) as the only scenario capable of satisfying typical terrestrial VOIP requirements in a lunar surface network. But one should note that these simulations used default settings for the 802.16 model and further simulation will be required to investigate link-layer parameter tuning which could improve VoIP characteristics while running over 802.16 similar to discussions in[2] .



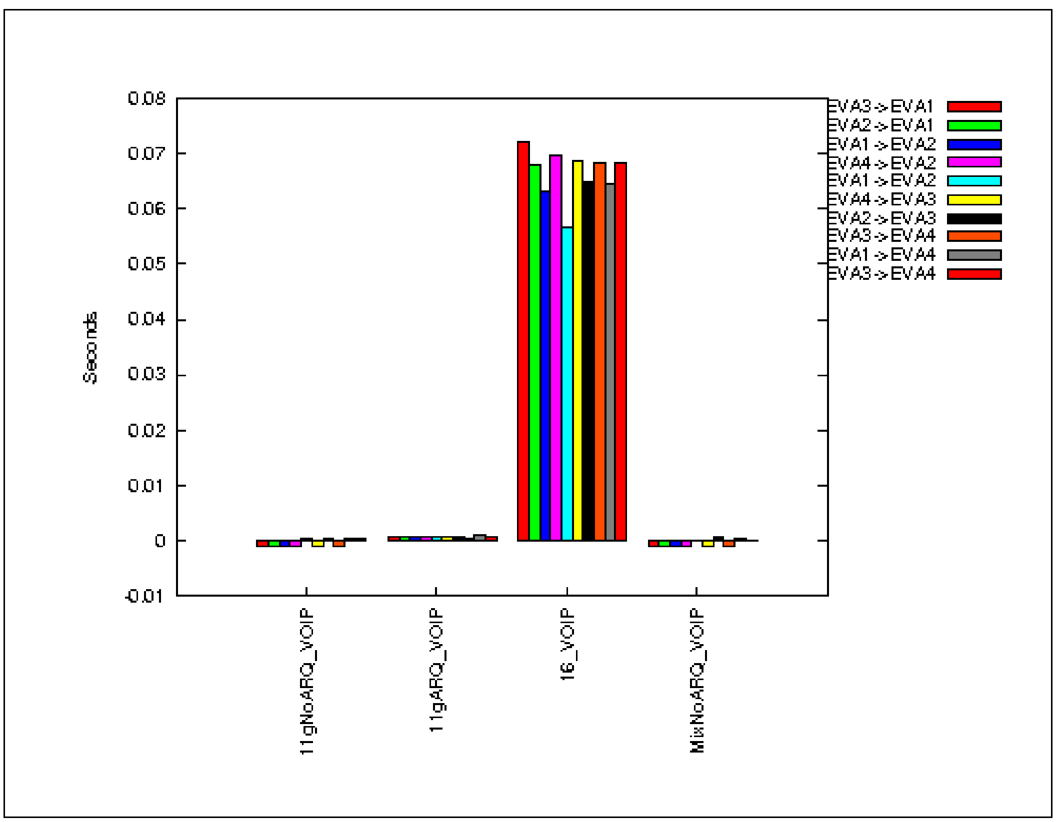


Figure 4. (Top) **VoIP delay** and (Bottom) **VoiP jitter**. Negative values indicate failed calls. Each bar represents a different conversation.

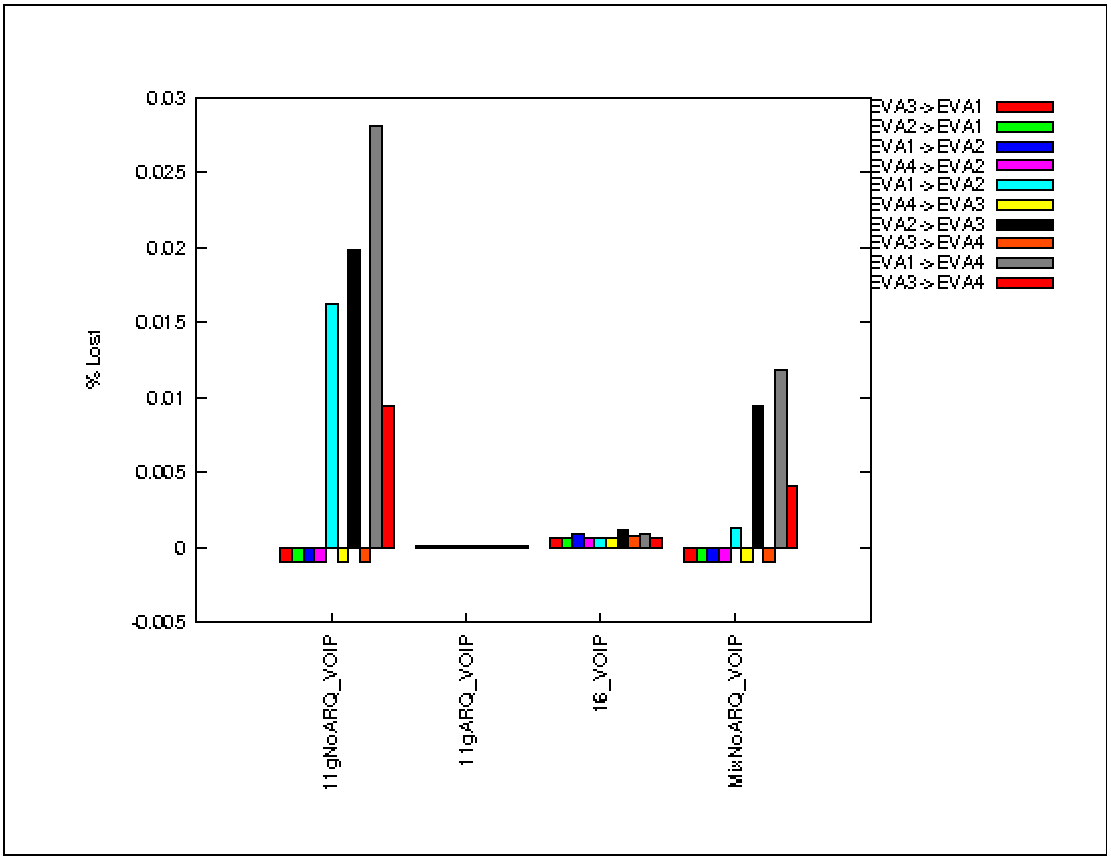


Figure 5. VoIP Loss Percentage. Negative values indicate failed calls.

B. Caution & Warning, Command, and Telemetry

In general, the centralized architecture and Time Division Duplex (TDD) of 802.16 significantly increased the delay (figures 4 and 6) relative to 802.11g's distributed architecture.

Application traffic flows were different for voice applications and caution & warning. While voice calls were only from EVA to EVA, all Caution & Warning traffic either originated at or was destined for Altair. Simulation results showed that the traffic on the uplink from subscriber stations (EVA or rover) to base station (Altair) suffered longer delay (on 802.16 network) and higher packet loss (on 802.11 network) as compared to the downlink traffic (Altair to EVA or rover).

Furthermore, even with the channel separation the homogeneous 802.11g network outperformed the heterogeneous 802.11/802.16 network with respect to delay and jitter. Disabling link-layer retransmissions (ARQ) on 802.11g further improved delay performance but allowed errors to be visible at the application layer. This trade-off is notable if caution & warning applications are built on reliable transport protocols. However, without link retransmission, caution & warning never experienced more than 0.05% loss. Command and Telemetry showed similar behavior so the graphs were excluded.

In summary, all scenarios gave acceptable performance for caution & warning traffic assuming retransmission is handled above the link-layer. With link-layer retransmission, the 802.11g and 802.16 still performed well enough given the high tolerance for delay of caution & warning traffic, although this tolerance is subject to future constraining.

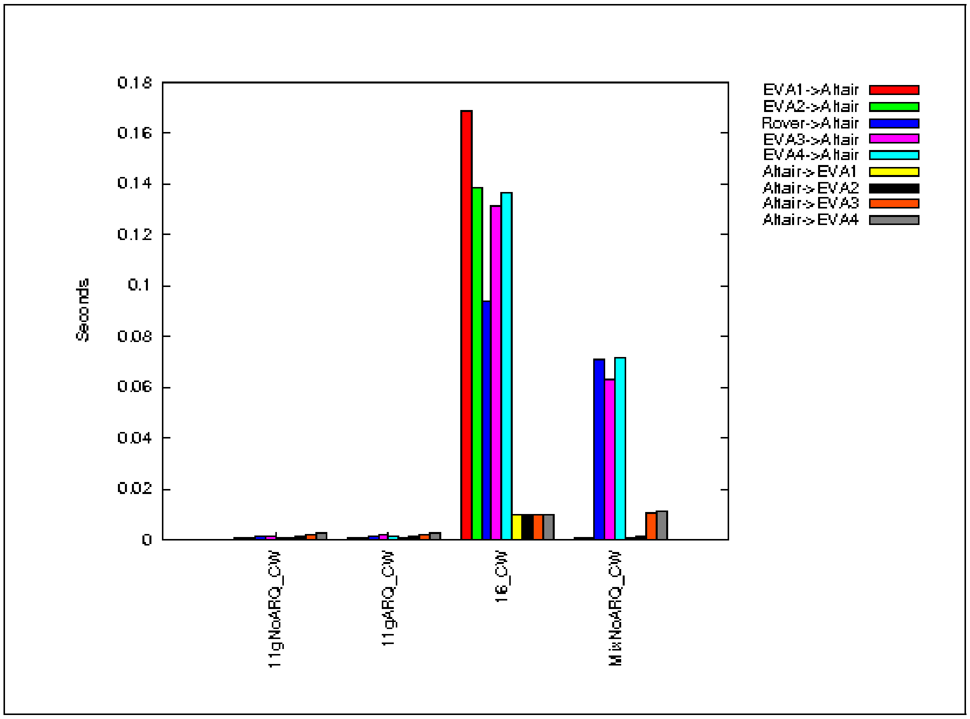


Figure 6. Caution & Warning Delay. The distributed scheduling of 802.11g (ad-hoc mode) resulted in better latency performance than the centralized scheduling and Time Division Duplex of 802.16.

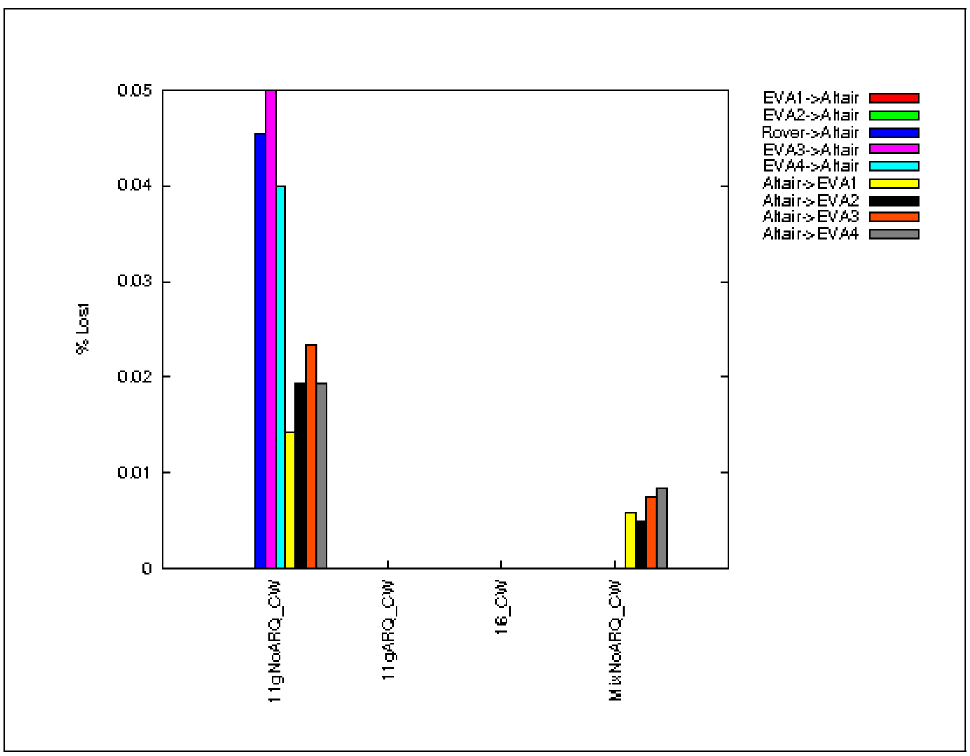


Figure 7. Caution & Warning Loss Percentage. Loss was seen when using 802.11g without link-layer retransmissions in the homogeneous 802.11g and heterogeneous 802.11g/802.16 scenarios.

C. Channel

Overall at the channel layer (figure 8) 802.16 benefited from centralized scheduling and Time Division Duplex showing the least number of signal errors and, conceivably, the most potential for robustness as the network load increases. However, this improvement came at a cost of increasing delay as shown in figures 4 and 6.

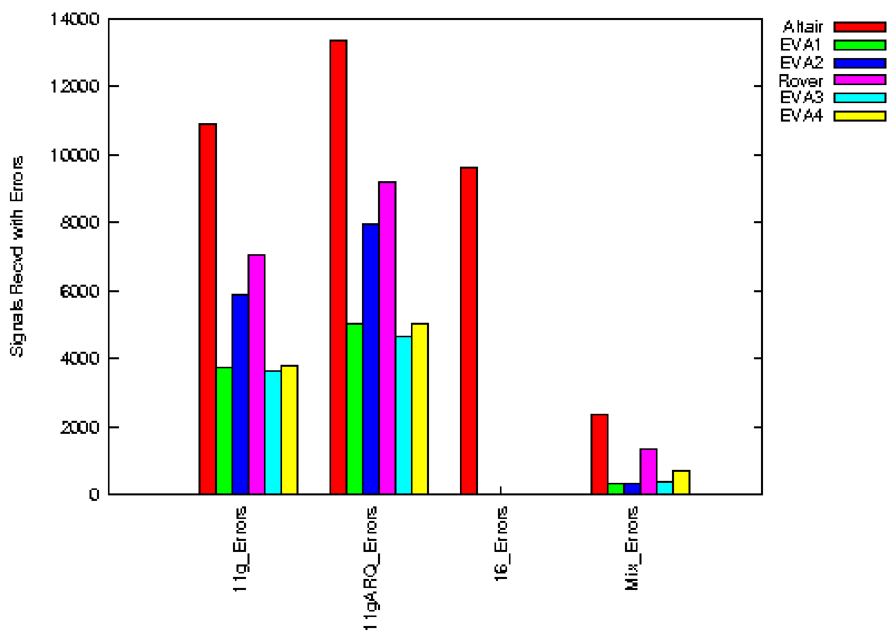


Figure 8. **Errors observed at the link layer for each receiver.**

In the above figure, distributed scheduling of 802.11g links resulted in collisions; centralized scheduling of 802.16 resulted in no collisions observed at subscriber stations, while collisions still occurred for control messages sent to the Altair base station.

V. Conclusion and Future Work

These simulations provide preliminary results on the performance of the 802.11g network, 802.16 network and combined 802.11/802.16 network. While these results provide some preliminary understanding of how the lunar surface network can operate and what communication functionality can be assumed for surface operations, more work needs to be done to evaluate performance tuning and other options such as sub-channelization of the 802.11g network, using physical repeaters, and characterizing high volume traffic such as video and file transfer. At the completion of this work, there was no quantification of acceptable delay, loss or jitter for Caution & Warning, Command, Telemetry, or Tele-Operate. Further work will be needed with the mission planners to define performance requirements.

In either homogeneous network (802.11g only and 802.16 only) the network was not able to use rover as the relay for the EVA team; 802.11g because of the non-defined network routing, and 802.11g because of the centralized nature requiring all traffic transferred through the base station.

The heterogeneous network scenario benefited from channel divisions, which not only reduced the data loss and delay of the network as compared to homogeneous 802.11g and 802.16e networks, but also provided additional benefits (initially intended during design) of increasing the range of the Rover-EVA team and also providing the essential point-to-point connectivity between each EVA crew member.

Future simulations will consider Delay/Disruption Tolerant Networking (DTN), 802.11n and 3G/4G protocols. Additionally terrain, mobility, relay satellite's orbit, and Earth's rotation will be examined in follow on work. Lunar terrain impact on RF loss should also be considered, perhaps with JPL's TOAST simulation tool, which uses GSSR data to evaluate effects of terrain on RF loss. Lastly, further simulations and analyses will investigate protocol parameter tuning for the homogeneous 802.16 and heterogeneous 16/11g networks and characterize the distribution of loss over a longer simulation time period with more conversations and increased network load.

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