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

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Introduction

- Space Exploration Mission
  - Returning humans to the surface of moon
  - Need to evaluate alternatives for lunar surface communications network
- Lunar surface network scenarios
  - Two teams of astronauts, one base-station, one rover
  - Network solutions using terrestrial wireless protocols
    - 802.11g ad-hoc network
    - 802.16e infrastructure based network
    - Inter-mix of 802.16e and 802.11g
- Simulations to analyze:
  - Physical Layer behavior and performance
  - End-to-End simulations addressing MAC-layer issues
    - Analyze various variants of the 802.11 and 802.16 protocols to identify impacts of delay, loss and jitter to higher layers

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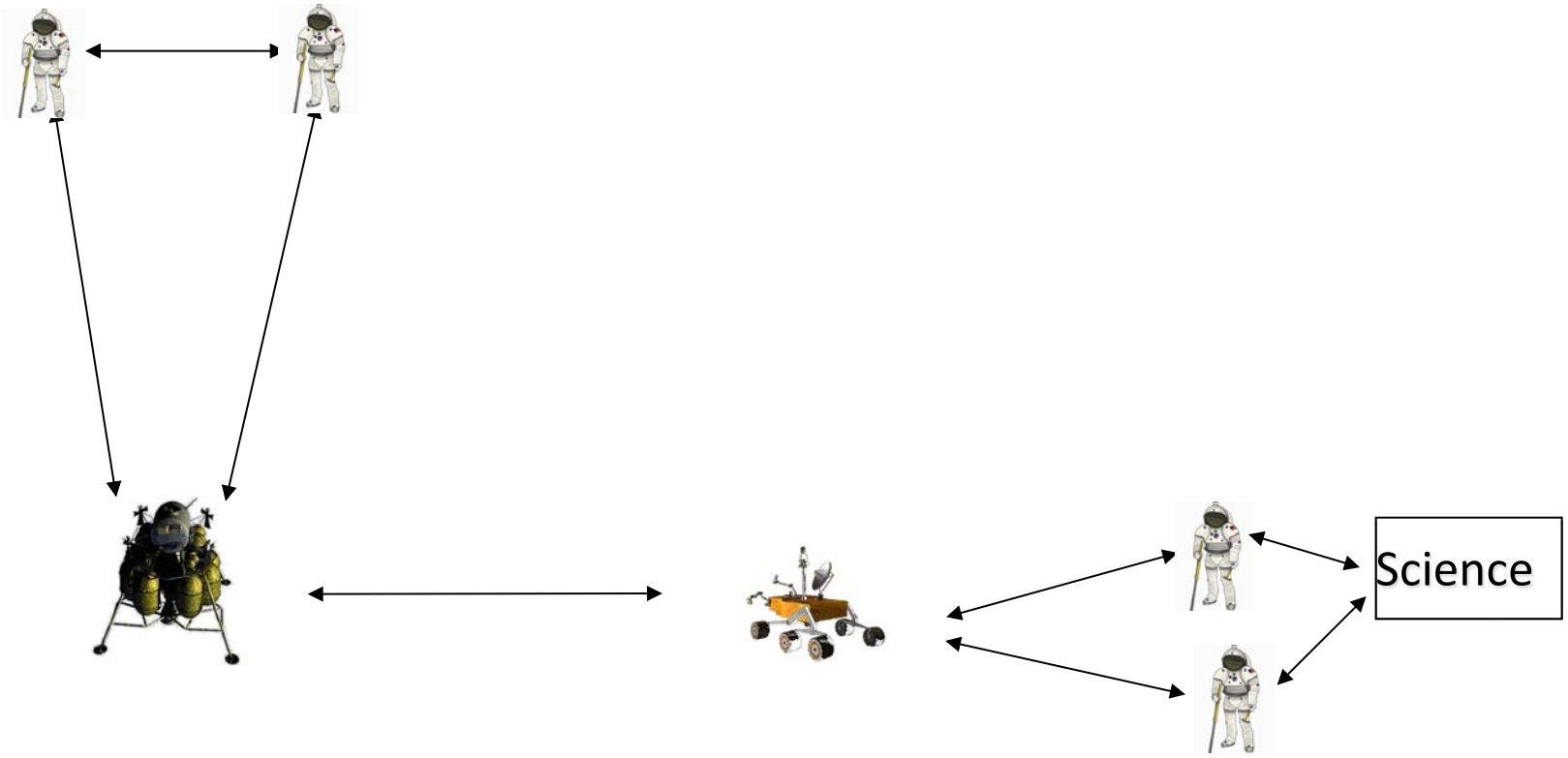
Lunar Surface Scenario



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Lunar Surface Elements

Surface Element: Lander

Functions:

(1) Transport astronauts and cargo from orbiting CEV to lunar surface.
(2) Serve as temporary habitat for initial lunar sorties and for post-outpost sorties to other lunar locations.
(3) Use lander's surface ascent module to transport astronauts from lunar surface to orbiting CEV.

Surface Element: EVA Suit

Functions:

(1) Serve as a mobile, tactile, pressurized ("shirtsleeve") element that allows the crew members to explore the lunar surface.
(2) Provide thermal control, ventilation, CO_2 scrubbing, crew hydration, power, communications, and informatics.

Surface Element: Rover

Functions:

(1) Transport astronauts to lunar locations beyond EVA distance.
(2) Serve as a tele-operated platform for remote exploration.
(3) Serve as a platform for scientific observations, either with astronauts onboard or via tele-operation.
(4) Using various tool attachments, serve as a platform for construction & maintenance, either with astronauts onboard or via tele-operation.

IEEE 802.11g/16e Protocols

- 802.11g
  - Ad hoc mode: any node can communicate with any other node within communication range
  - Does not take advantage of multi-hop (e.g. using rover as a relay between EVAs and Altair)
- 802.16e
  - Infrastructure based
  - Does not support multi-hop, base-station to base-station (e.g where rover and Altair are both base-stations)
    - rover is treated as a node; it does not extend communication range (multi-hop)
    - EVA to EVA (same team or different team) communication is routed through Altair.
    - Even if two EVAs are within communication range, their communication is routed through Altair.

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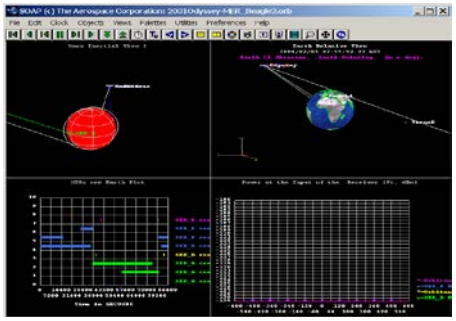
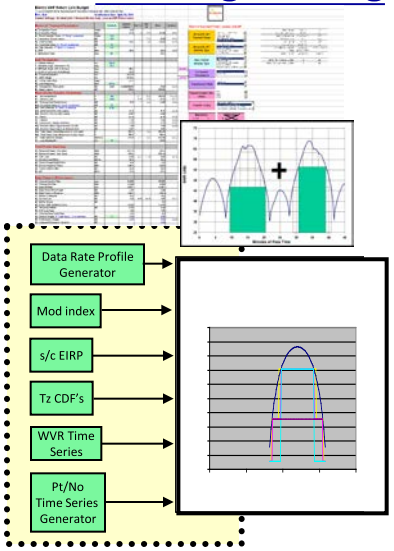
MACHETE Architecture

Deployment Geometry



- **Generates**:
  - View Period
  - Slant Range
  - Declination
  - Connectivity
- **Models**:
  - Orbit ephemeredes
  - Lander position
  - EDL
  - Antenna patterns

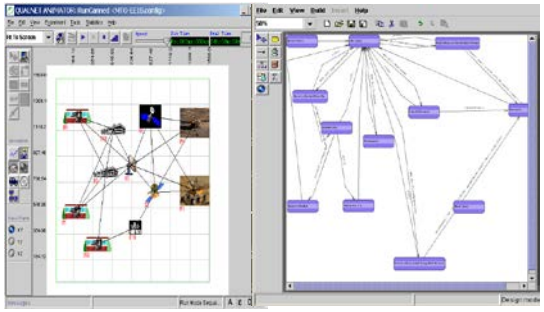
Link Engineering



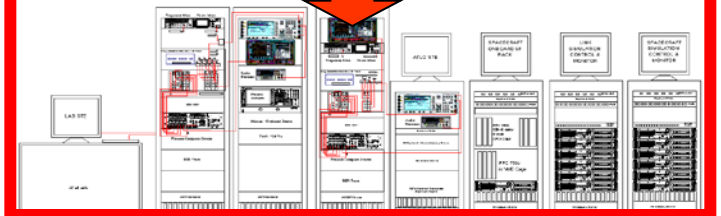
X,UHF, Ka Link Models

- **Models:**
  - Modulation/Data Rate
  - Antenna Pattern
  - Multi-path Effect
  - Coding
- **Computes:**
  - Bit/Frame Error-Rate
  - Eb/No profile

Network & Protocol Simulation



- **Simulates**:
  - Comm. Protocols
  - Relay/End-to-end Telemetry Flow
  - Data Loss/Error Process
- **Performance Metrics:**
  - Data Volume/Buffer Utilization
  - Throughput/Latency
- **Communications Effect Server (CES) Interface for Hybrid Simulation**



External HW/SW

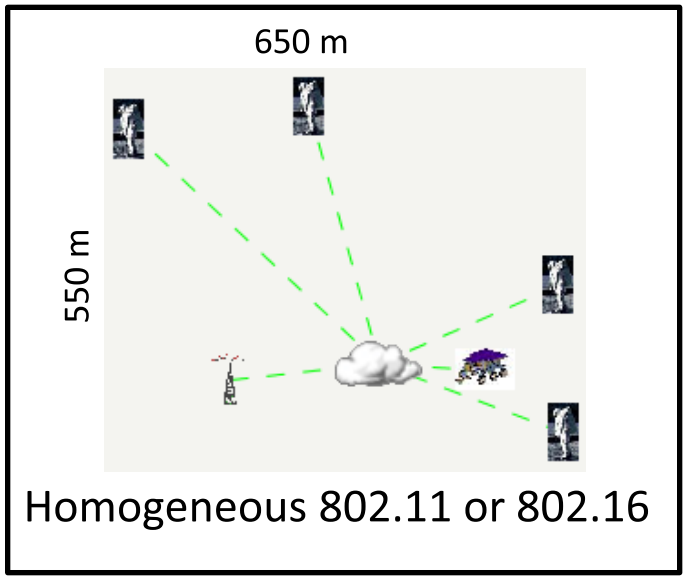
MACHETE Scenario

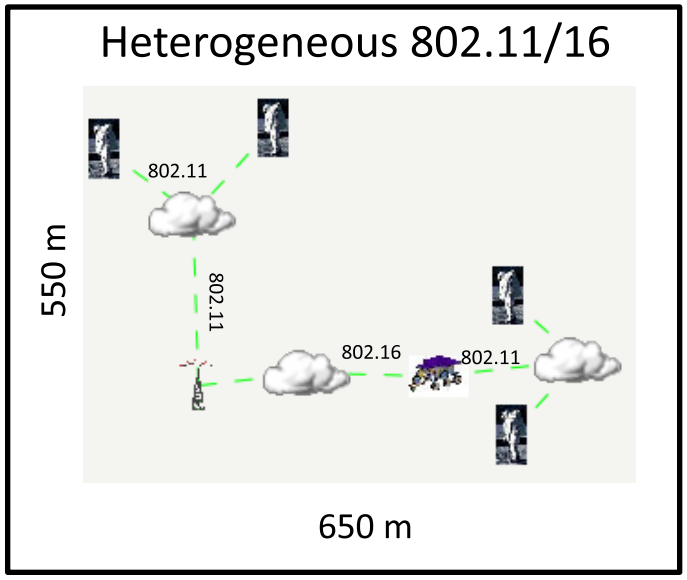
- 6 Nodes
  - Altair; 4 EVAs; Rover
- 650m x 550m Area
  - No mobility
- 4 Scenarios

  (1, 2) Homogeneous 802.11g
  - With/without link-layer retransmissions

  (3) Homogeneous 802.16e
  - Without link-layer retransmissions

  (4) Mixed 802.16 / 802.11
  - Without link-layer retransmissions

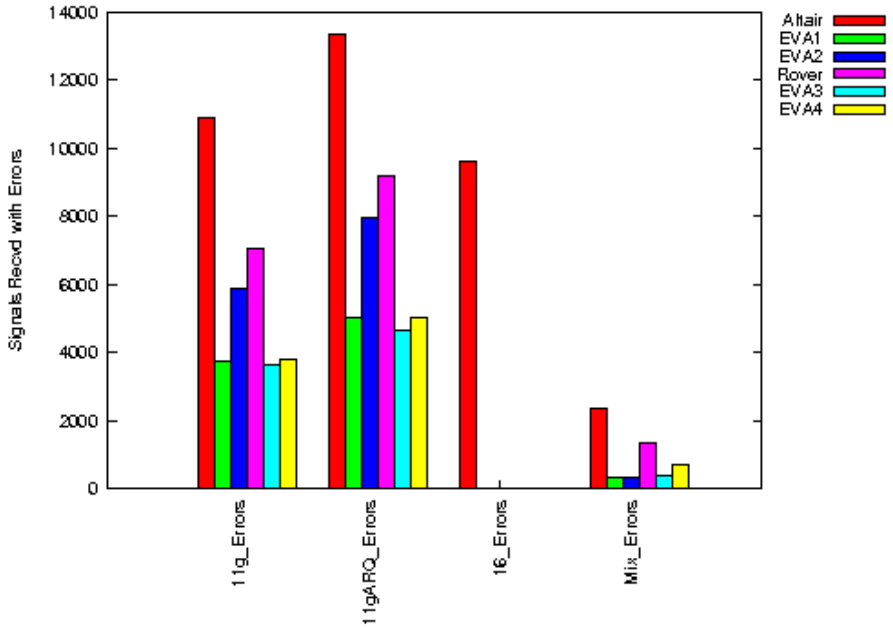




Data Traffic

- Modeled expected traffic patterns from NASA data traffic studies
- Five traffic types:
  - Caution and Warning
  - Voice
  - Command
  - Telemetry
  - File transfer
- Priority setting: Caution and Warning > Voice > Telemetry = Command > File Transfer

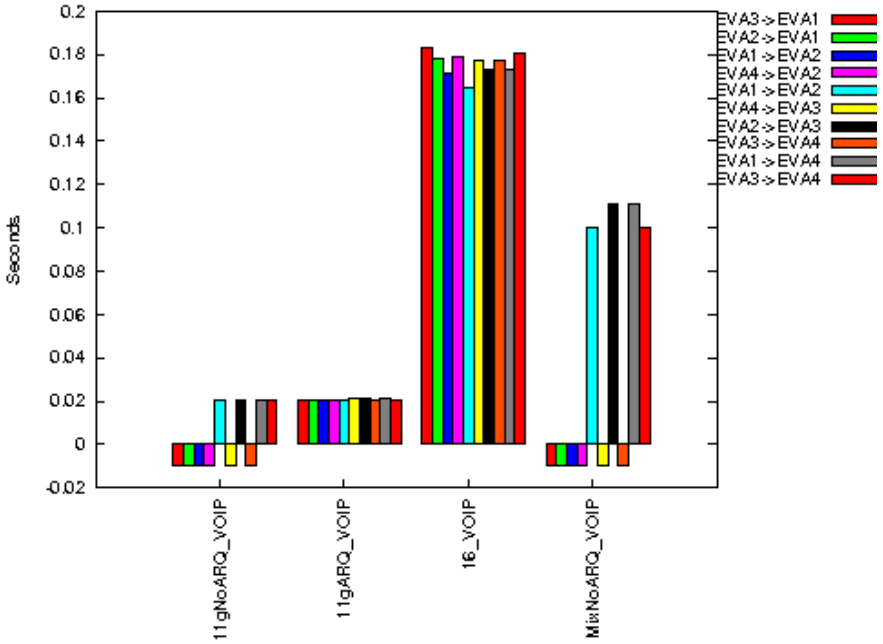
Signal Errors



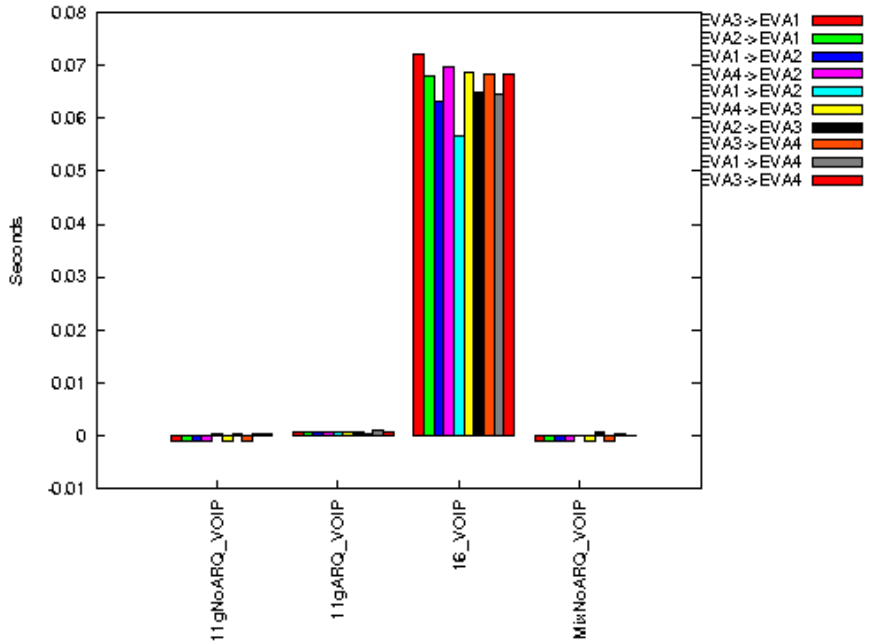
- 802.11g link-layer retransmissions increased channel load and likewise increased errors
- 802.16e best managed channel resource (centralized scheduler at Base Station)
- All 802.16e errors occurred at Altair's reception (base station)
- Mix network benefited from having separate channels

Voice

Delay



Jitter

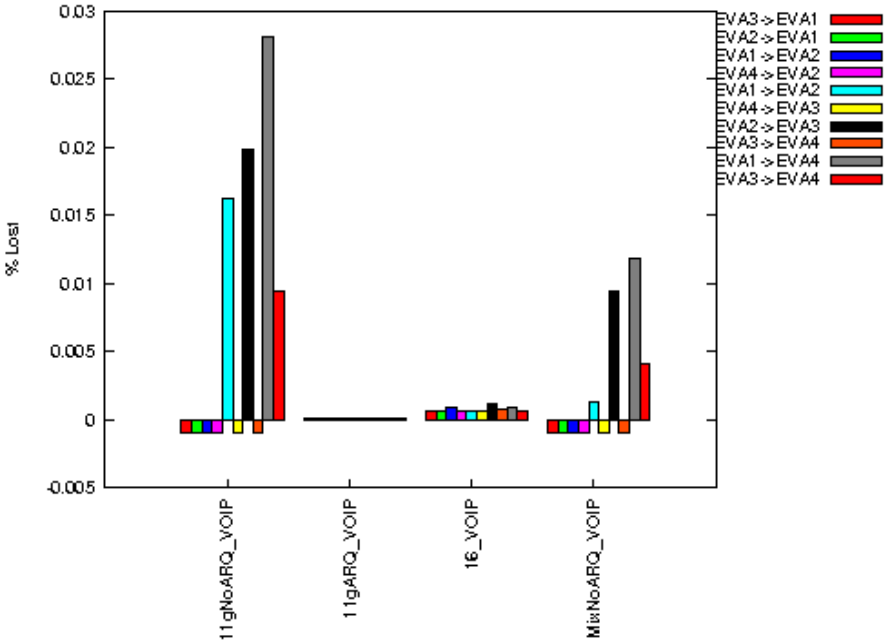


- Negative values represent calls which failed to be established
- Centralized architecture of 802.16e significantly increased delay and jitter
  - Required all data take extra hop through base station (Altair)
    - No voice traffic from Altair

Voice (cont.)

- Typical terrestrial VOIP systems desire <100ms latency, <20ms jitter and <1% loss which would be applicable to lunar surface
  - This needs to be evaluated for larger distances
- Preliminary simulations show 802.11g (w/ ARQ) as the only configuration satisfying typical terrestrial VOIP requirements with a lunar networked system
  - 802.11g and 802.16e/802.11g Mix configurations had calls unable to be established
  - Pure 802.16e network avg 180ms latency and 70ms jitter
- Further simulations required to investigate parameter tweaks to 802.16e and 802.16e/802.11g mix and to characterize distributions of loss, delay and jitter

Loss



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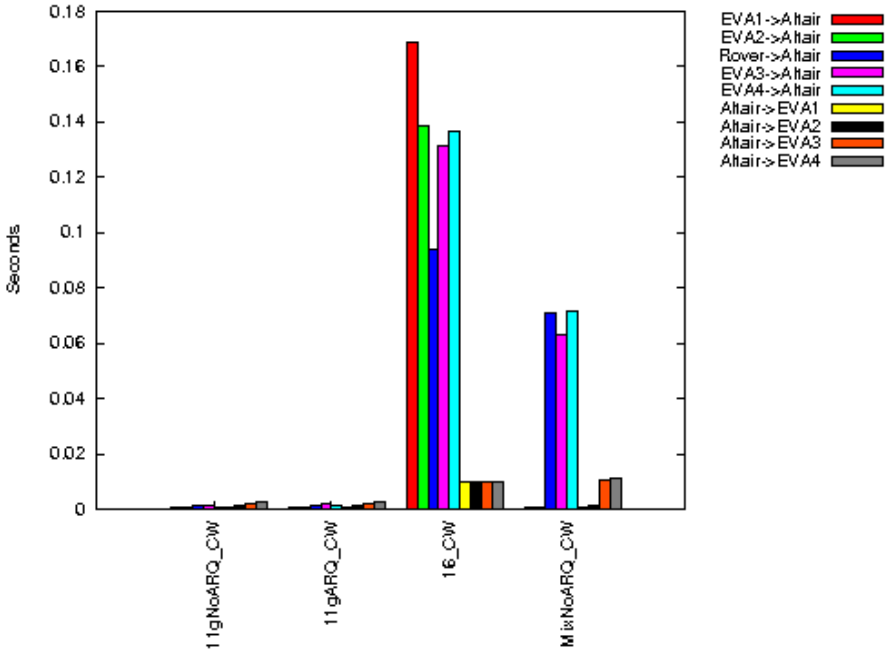
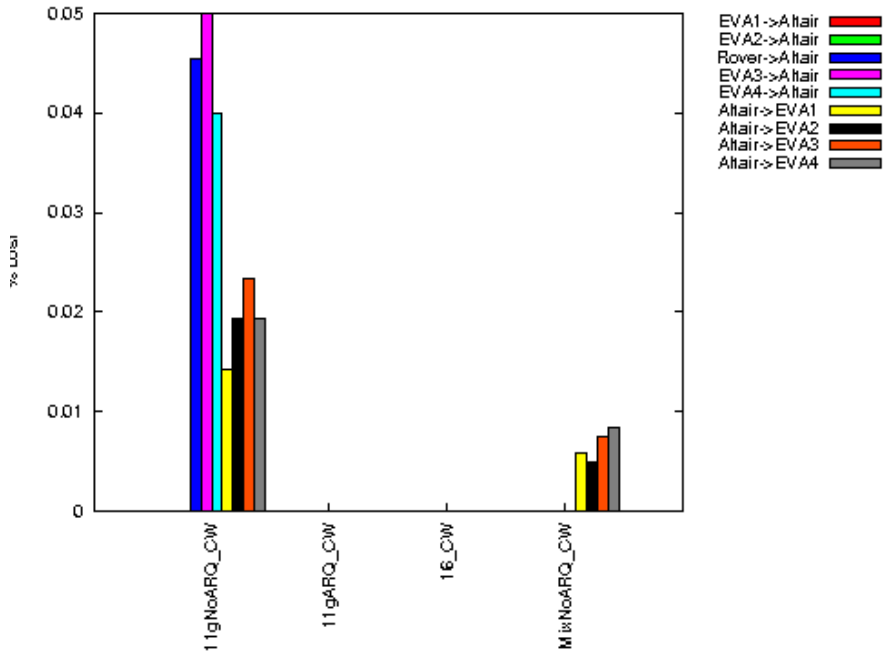
Caution & Warning

Delay



Loss



- 802.11g had less delay but more errors
- 802.16e had more delay due to infrastructure based network
- % Loss assuming connectionless transport layer (e.g. UDP)

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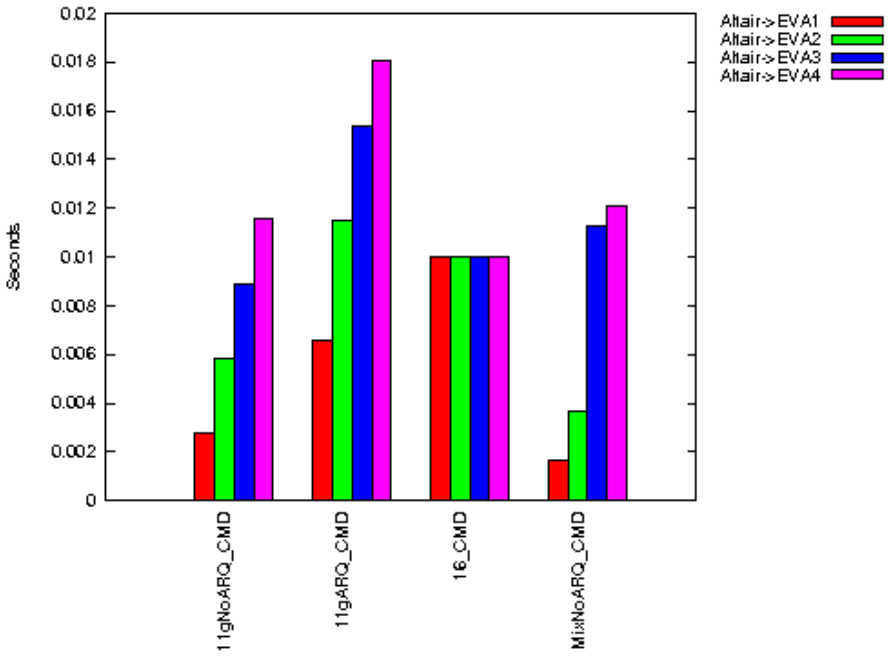
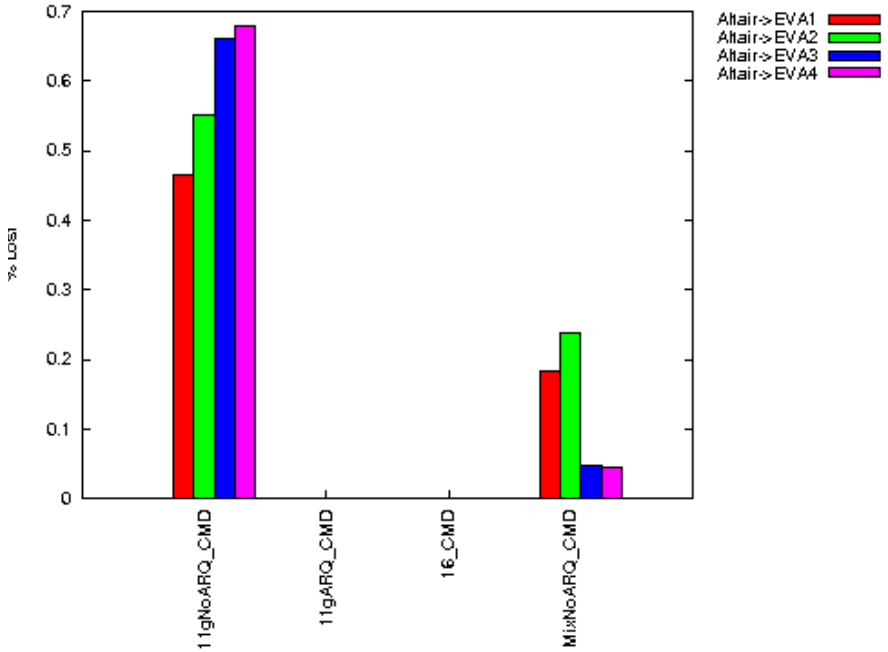
Command

Delay

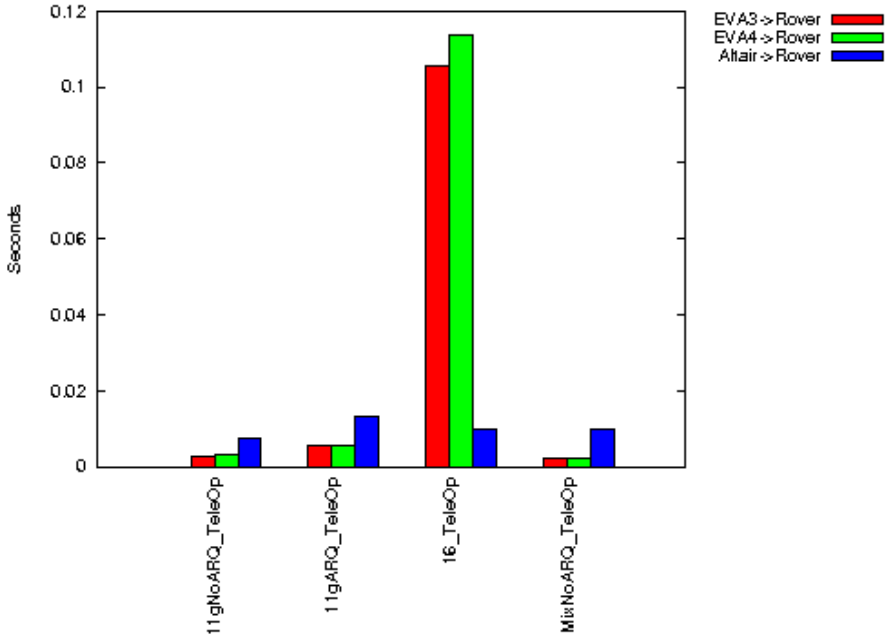


Loss

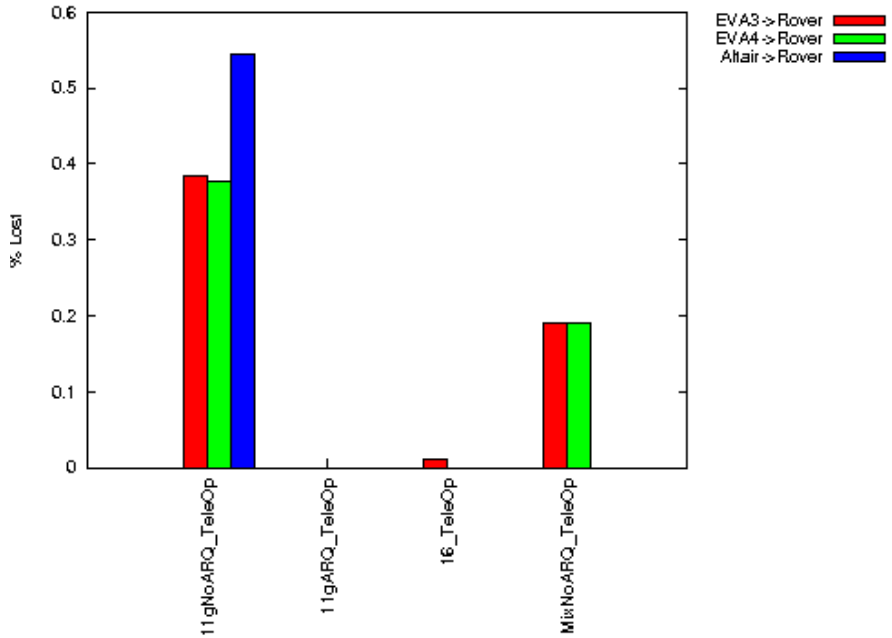


- 802.16e managed link resources best (wrt loss/delay)
  - Traffic streams from Altair (the Base Station) are single hop
  - Communicates with subscribers with separate sub-channels
- Mixed 11g/16e network benefited (less loss) from fewer subscribers on each channel
- Appearance of “steps” resulted from successive commands waiting for open 802.11 channel
  - All commands generated at exact time

Tele-Operate (Rover Commanding)



Delay

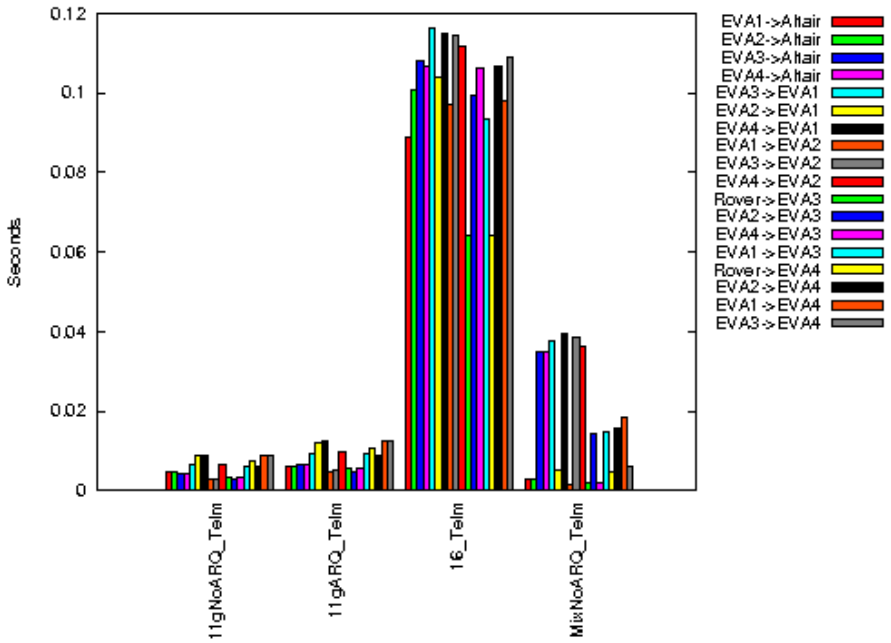


Loss

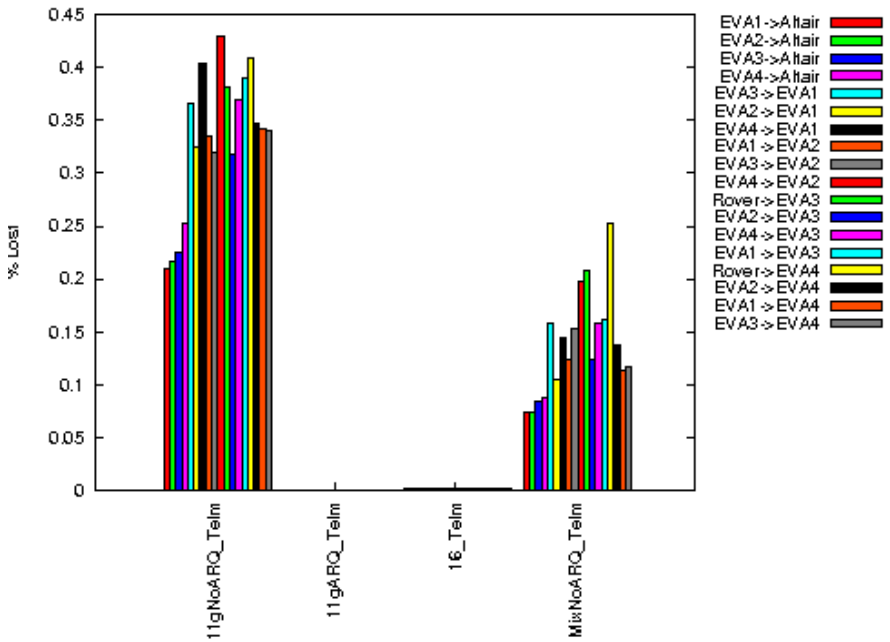
- 802.16e required traffic switched through base station and slotted communication channel
  - Altair to Rover was able to use single hop communication since Altair was base station
  - Other streams travelled through base station (Altair) which significantly increased delay
    - added extra hop and wait for next time slot
- 802.11g allowed any-to-any random communication resulting in shorter delay

Telemetry

Delay



Loss



- Centralized architecture of 802.16e increased delay
- 802.11g without link-layer retransmission suffered the most losses
- The heterogeneous network balanced delay and the loss
- Note: % application loss assumed connectionless transport layer (UDP)

Conclusions

- 802.16e's centralized architecture combined with time division duplex (TDD) significantly increased end-to-end delay in many cases
- 802.11g increased loss when run without link-layer retransmission due to ad-hoc unscheduled transmission model of 802.11
  - Most often run with link-layer retransmissions enabled
- 802.11g and Mix 11g/16e without link-layer retransmissions resulted in failed VOIP calls even sparsely populated channels
- 802.11g with link retransmissions performed "best" given current knowledge of traffic requirements
  - Potential limitation to network capacity (see signal errors) and range

- Note: Simulations were based on distance of 550m x 650m. Further evaluations planned at longer range.

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