Delay-Throughput Performance the Deep-Space Ka-band Link

by

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Introduction (1/3)

- Future Deep-Space Missions will use 32-GHz Ka-band due to lack of bandwidth at 8.42 GHz X-band.
  - 500 MHz Ka-band allocation, 50 MHz X-band allocation.
- Ka-band is much more susceptible to adverse weather than X-band and Retransmissions have too be used to assure data completeness
  - For every dB of loss at X-band due to bad weather, Ka-band suffers approximately 4 dBs of loss on the deep-space link.
- Retransmissions imply
  - Additional Storage
  - Bandwidth Allocation for Retransmissions
  - Delay in Receiving the Data
  - Reduced Throughput
- Need to evaluate the delay-throughput performance of the Ka-band link.

Introduction (2/3)

- Mars Reconnaissance Orbiter (MRO) Ka-band Demonstration was to have evaluated Deep-Space Ka-band Link Performance and its retransmission requirements
  - Promising cruise phase results.
  - Experiment was postponed indefinitely due to spacecraft Ka-band hardware failure during aerobraking.
  - Need to meet the experiment objectives through other means.

Introduction (3/3)

- Idea: Use Water Vapor Radiometer (WVR) and Advanced Water Vapor Radiometer (AWVR) data to evaluate the performance of the Ka-band Link at the three Deep Space Network (DSN) Communication Complexes (DSCCs):
  - 31.4-GHz sky brightness temperatures could be converted to 32-GHz and 8.42-GHz zenith atmospheric noise temperature (ZANT) measurements.
  - Models for antenna performances at the DSN could be used to evaluate the link performance along with ZANT.
  - MRO Ka-band and X-band telecom parameters can be used to emulate the spacecraft performance.
  - MRO DSN schedule could be used to determine the time and geometry of the passes for emulation.
  - Compare Ka-band Delay-Throughput Performance with X-band Delay-Throughput Performance.

MRO Telecommunication Parameters

- Common 3-m aperture antenna for both X-band and Ka-band
- Ka-band System:
  - 80 W DC Input Power/35 W RF Output Power TWTA
  - 101.3 dBm EIRP
- X-band System:
  - 172 W DC Input Power/ 100 W RF Output Power TWTA
  - 96.2 dBm EIRP
- Ka-band and X-band use the same data rates.

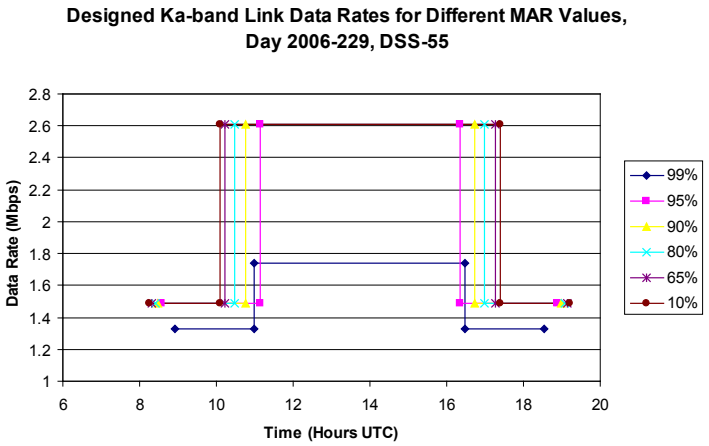
Information Rate (bps)	Channel Code
27846.76	Concatenated Coding
331397.95	(8920,1/6) Turbo Code
497096.92	(8920,1/6) Turbo Code
662795.89	(8920,1/6) Turbo Code
745645.38	(8920,1/2) Turbo Code
994193.84	(8920,1/3) Turbo Code
1325591.78	(8920,1/3) Turbo Code
1491290.75	(8920,1/2) Turbo Code
1740.422.20	Concatenated Coding
2610633.31	Concatenated Coding
2871696.64	Reed-Solomon Only
3480844.41	Reed-Solomon Only
5221266.61	Reed-Solomon Only

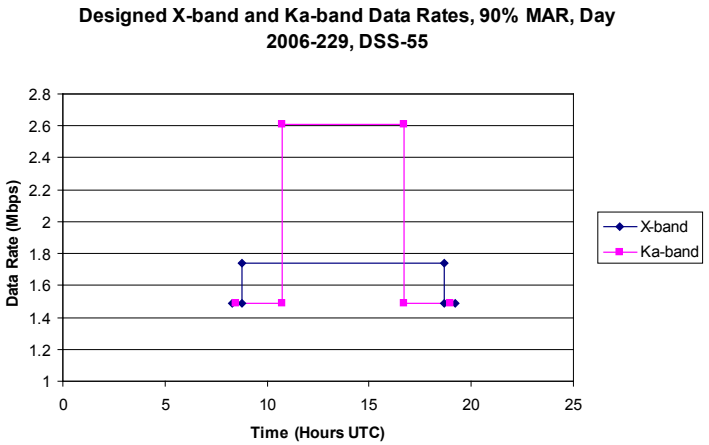
Selection of Passes

- One pass per week per complex was selected from the MRO DSN Schedule from April 1, 2006 through July 31, 2007.
  - DSN Complexes at Goldstone, California; near Madrid, Spain and near Canberra, Australia
  - 69 passes per complex.
  - Ka-band Deep-Space Stations (DSS):
    - Goldstone: DSS-25 and DSS-26
    - Madrid: DSS-55
    - Canberra: DSS-34
  - Passes selected such that WVR/AWVR data are available for them.
    - If a week does not have any WVR/AWVR data for the complex, an additional pass for that complex are selected from weeks before or after that week.

Link Design

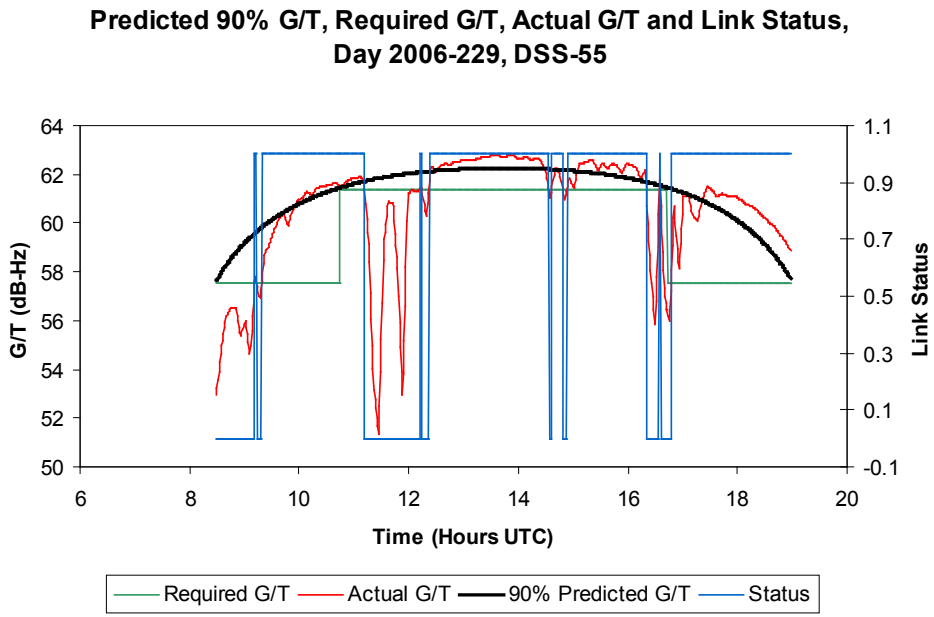
- For each pass at most two data rates are used such that the expected pass capacity is maximized subject to a minimum availability requirement (MAR).
  - Expected capacity is calculated by using long-term monthly ZANT statistics for each complex along with standard link equations.
  - Method maximizes data return while limiting the operational complexity (at most two data rates)
  - The method is applied to both X-band and Ka-band.
  - Depending on the MAR value, the data rates selected for the pass and the time periods over which these data rates are used vary.
  - Because X-band and Ka-band links have different characteristics, the same MAR value leads to a different link designs.





Channel Emulation

- WVR/AWVR data along with models for DSN antennas performances are used to emulate the actual G/T during the pass and compared with required G/T for the data rates used during pass.
  - Antenna pointing losses are assumed to be zero.
  - WVR/AWVR data are sampled at 5-minute intervals. Linear interpolation was used to calculate G/T at 1-minute intervals.
- When the actual G/T is greater than required G/T, the data is received correctly (good periods).
- When the actual G/T is less than required G/T, the data is assumed lost (bad periods).
- Data return is calculated from good periods and bad periods.
- Frame errors caused by additive white Gaussian noise are ignored.
- Solar scintillation and spacecraft occultations were ignored for better analysis of the performance.

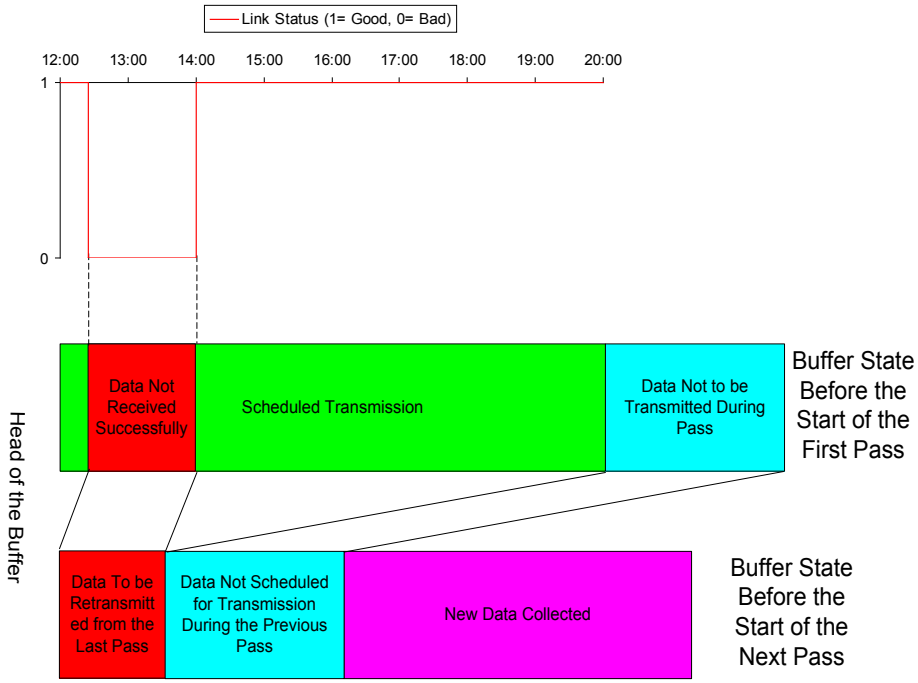


Data Management

- How much data to collect:
  - Since the link design provides the expected link capacity, we assume that the amount of data collected before a pass is fraction of that expected capacity. This fractions, $p_{d,}$ is referred as the data collection factor.
  - p_d is kept less than or equal one in order not to overload the system (queueing theory).
  - Example: If the expected capacity is 1 Gbits and p_d=0.95, then only 950 Mbits of data is collected before the pass.
  - This is similar to current MRO operations where the amount of data collected before each pass is only 97% of the total pass capacity.
  - For simplification, we assume no data is collected during the pass.

Data Management (cont.)

- What Data to Transmit:
  - Modified First-In-First-Out Buffer.
  - Before each pass, the spacecraft is programmed to transmit the oldest data first.
  - At the end of the pass, the spacecraft is commanded to purge all the data that were received successfully from its buffer.
  - The data that were not successfully received are moved to the head of the buffer and will be transmitted first during the next pass.
  - Infinite storage on the spacecraft is assumed to obtain the maximum storage requirement.



Performance Metrics

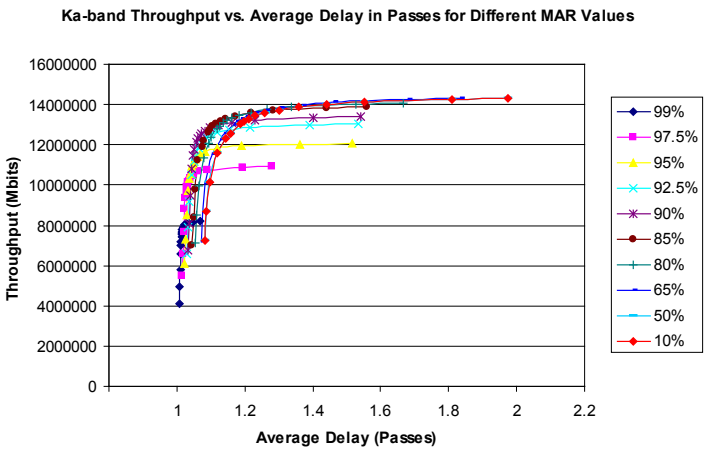
- Delay: Measured in number of passes.
  - Since passes are not scheduled on regular intervals, delay cannot be measured in actual units of time.
  - A delay of one indicates that the data were received correctly on the pass immediately before which they were collected.
  - Delay distributions and average delay are evaluated in our analysis.
- Throughput: Measured in terms of the number of bits received correctly.
  - Delay-Throughput curves are obtained by plotting the throughput vs. average delay.
- Maximum of the ratio of the amount of data on the spacecraft (buffer size) at the beginning of the pass to the amount of new data collected immediately before that pass
  - This measure provides some degree of normalization for variations in the geometry of the link and duration of the pass which affect the capacity of the pass.
  - It is a conservative estimate.

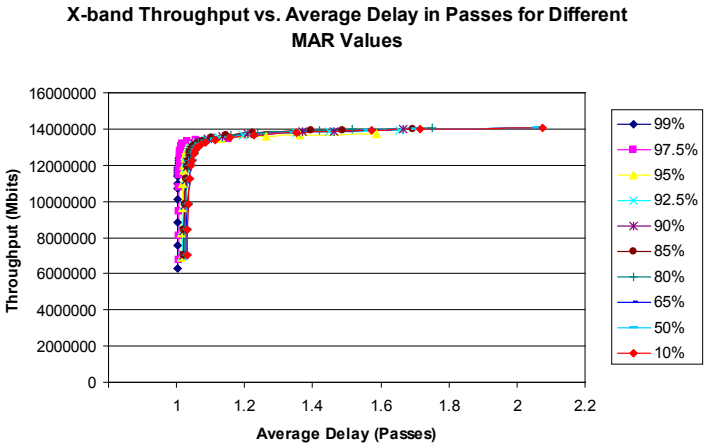
Emulation Setup

- Minimum Availability Requirement (MAR) was varied
  - MAR values of 10%, 50%, 65%, 80%, 85%, 90%, 92.5%, 95%, 97.5% and 99% were used to design the links.
- For each MAR value, data collection fact, p_d, was varied to change the loading on the system.
  - p_d values of 0.5, 0.6, 0.7, 0.8, 0.85, 0.87, 0.9, 0.91, 0.92, 0.93, 0.94, 0.95, 0.96, 0.97, 0.98, 0.99, 0.994 and 1.0 were used.

Results: Delay-Throughput Performance (1/2)

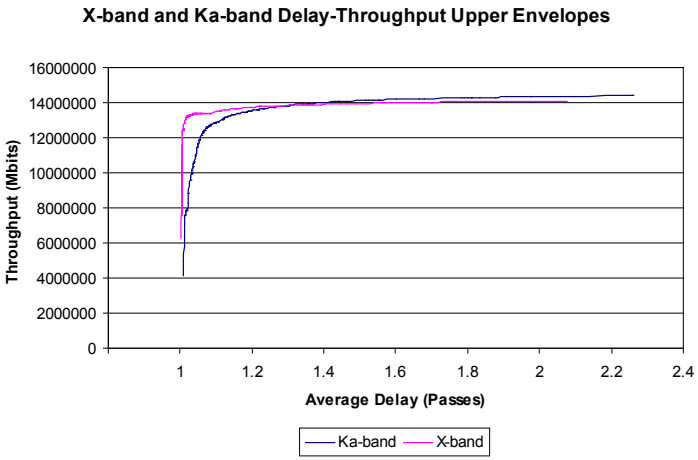
- Higher throughput for lower MAR values, smaller delay for higher MAR values.
- Asymptotic behavior, typical in queues.
  - When heavily loaded (high p_d value), a slight increase in the throughput is associated with a large increase in the delay.
- Ka-band more sensitive to variations to MAR values.
  - Ka-band expected capacity shows a much greater variation as a function of MAR than X-band's.

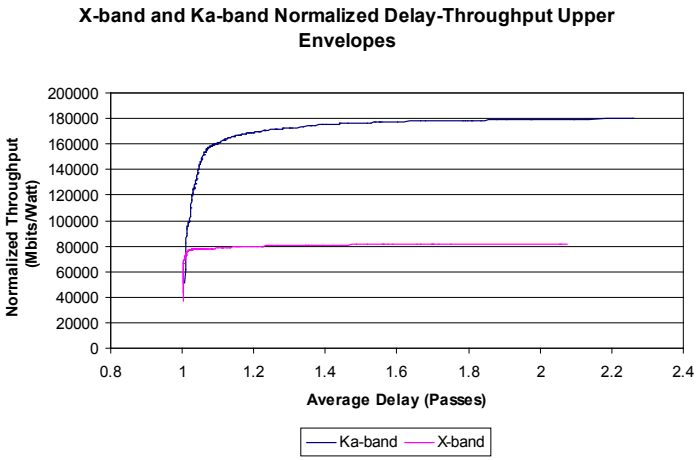




Results: Delay-Through Performance

- The MAR that provides the maximum throughput changes as a function of average delay
  - The upper envelope of the delay-throughput curves form the overall delay-throughput curve for each frequency.
- Comparing X-band and Ka-band delay-throughput envelopes shows higher throughput for X-band at lower average delay values and slightly better throughput for Ka-band at higher average delay values.
  - X-band system consumes 172 W DC power while Ka-band only consumes 80 W.
- Delay-throughput envelopes, normalized for DC power indicate that Ka-band delivers almost twice the throughput per watt of X-band for all but the smallest average delay values.
  - Normalization is done for actual amplifier values.
  - Higher transmitted RF power amplifiers are more efficient than lower RF power amplifiers.
  - X-band Amplifier. more efficient than Ka-band amplifiers for the same transmitted RF power.
  - The Ka-band results could be better for increased Ka-band RF power and worse for lowered Ka-band RF power.



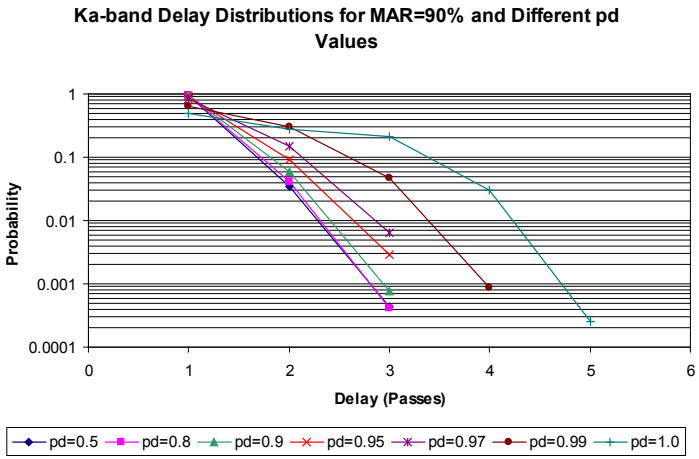


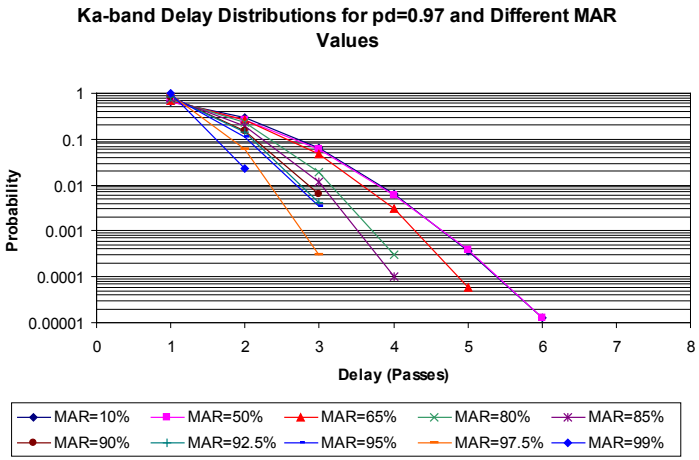
Results: Delay Distributions (1/3)

- Average delay may not be sufficient to characterize the delay process.
  - If the delay distribution has a heavy tail (i.e., a significant amount of data experiences large delays), even though the average delay maybe acceptable, the overall delay process may not be acceptable.
  - Need to consider the shape of the delay distribution and its sensitivity to changes in MAR and p_d.
- In all the emulations, no data experienced a delay of larger than seven passes.
  - Occurred only in four cases: MARs of 10% and 50% with p_d values of 0.994 and 1.0.
  - In all four case, the amount of data that experienced a delay of seven passes constituted less than 0.02% of the total data received.

Results: Delay Distributions (2/3)

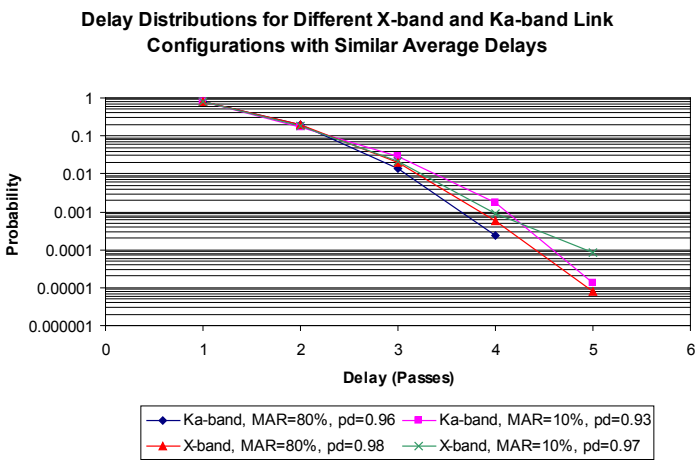
- For a fixed MAR, an increase in p_d shifts the delay distributions to the right.
  - Expected. Increased loading in a work-conserving queue increases the delay.
- For a fixed p_d, an increase in MAR shifts the delay distributions to the left.
  - Expected, with increased MAR, the link reliability increases, reducing the number of retransmission and thus the delay.





Results: Delay Distributions (3/3)

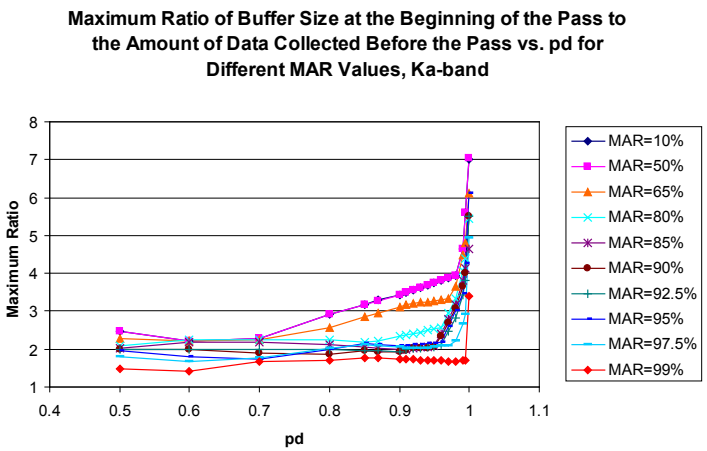
- Average delay seems to be a good measure of the delay distributions.
  - Cases with the same average delay values, seem to have similar delay distributions and delay standard deviations, regardless of frequency, MAR or p_d.
  - Validates delay-throughput comparison between X-band and Ka-band.
  - Further analysis is required.

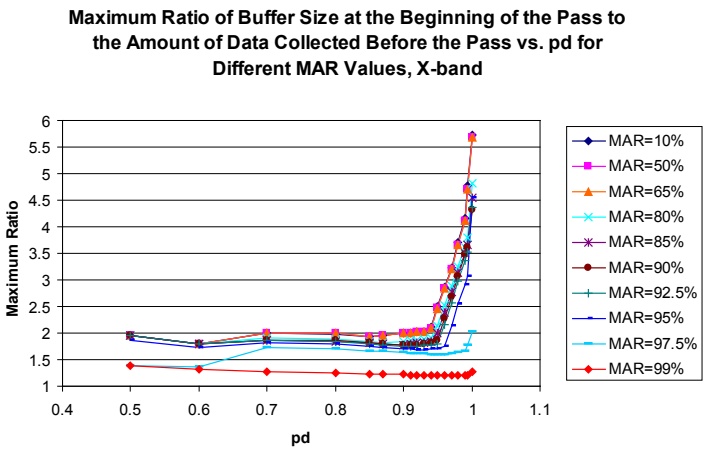


Freq.	MAR	p_d	Avg. Delay	Delay Sd.
Ka	80%	0.96	1.216	1.297
Ka	10%	0.93	1.228	1.326
X	80%	0.98	1.239	1.327
X	10%	0.97	1.227	1.316

Results: Buffer Size (1/3)

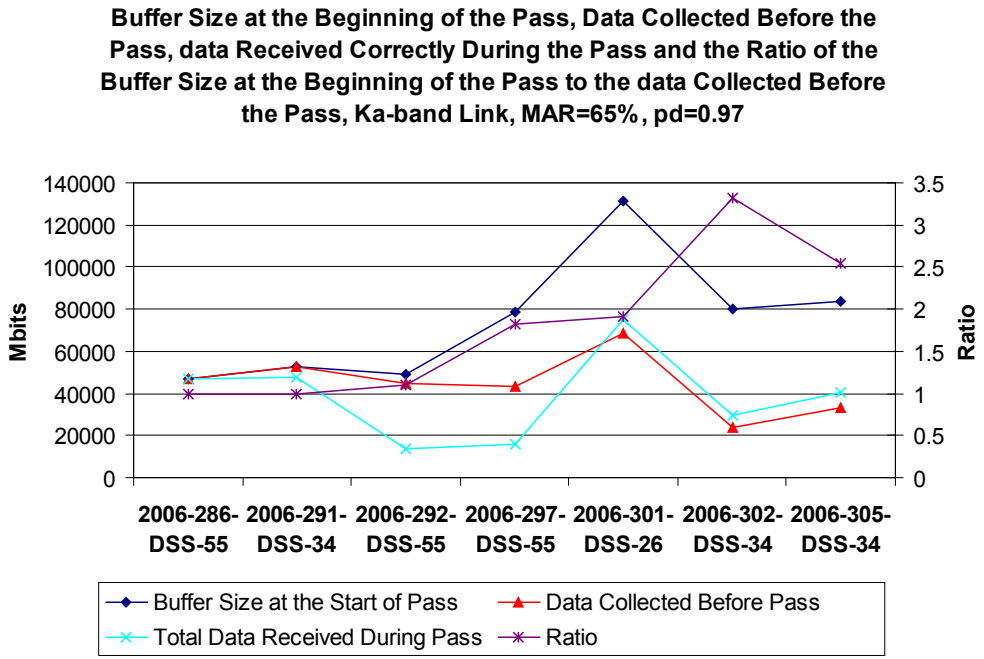
- Maximum of the ratio of buffer size at the beginning of the pass to data collected before the pass is selected as metric
  - Pass duration and pass capacity vary as a function of Earth-Spacecraft geometry.
  - This metric normalizes to some degree for the pass to pass variations and the spacecraft capabilities.
- In general, for both X-band and Ka-band, for a given MAR, this metric increases rapidly for p_d values greater than 0.9





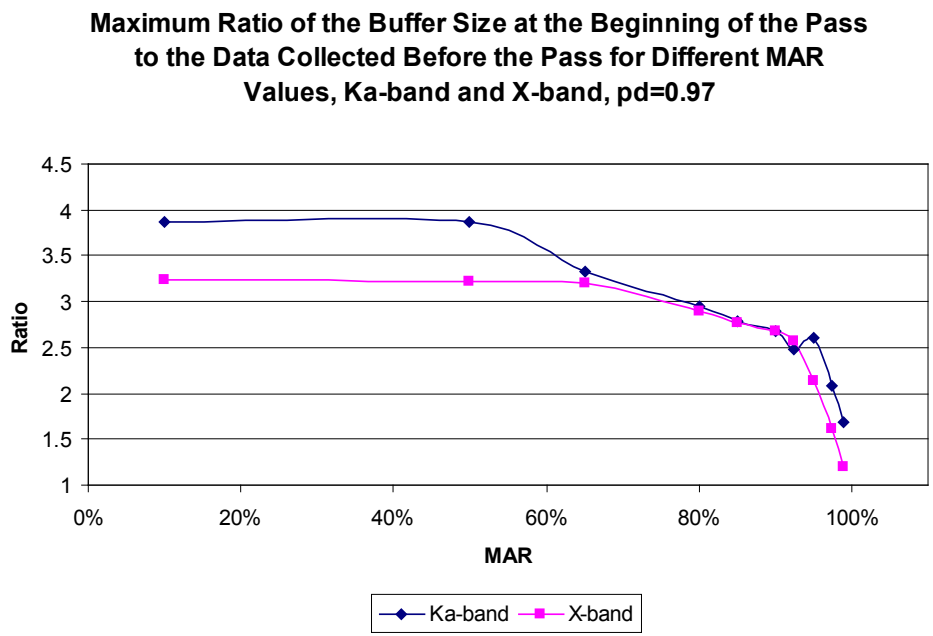
Results: Buffer Size (2/3)

- The selected metric is imperfect
  - Variations in the pass length and capacity for a few passes could affect the metric greatly.
  - More passes are needed.
- Example:
  - For the case presented in the figure, passes on days 2006-291, 2006-292 and 2006-297 suffer losses due to the weather, causing a build up of data in the buffer.
  - The ratio of buffer size to data collected before the pass is maximum for pass on 2006-302 not because of the amount of the data in the buffer but because so little data is collected before that pass.
  - Maximum buffer size occurs for the pass on 2006-301.



Results: Buffer Size (3/3)

- Storage requirements for X-band and Ka-band under the proposed regime is roughly the same for high MAR values.
  - Current X-band missions at a equivalent MAR value of better 99%. The results indicate that under such a regime, storage requirements is slightly greater than the maximum amount of data the spacecraft collects between the two passes.
  - For p_d value of 0.97 Ka-band storage requirements seem to be reasonable, equaling 2 to 3 times the maximum amount of data collected between two passes.



Conclusions

- Delay-Throughput characteristics of the deep-space Ka-band and deep-space X-band links have been obtained through emulation.
- For the same amount of DC power, Ka-band provides better than twice the throughput as X-band except under the conditions where very low delay in data delivery is required.
- The storage requirements of the Ka-band system is less than three times the maximum amount of data that the spacecraft collects between two passes and are not prohibitive.

Caveats

- WVR/AWVR are sampled at roughly once every five minutes.
  - Not sufficient to resolve short time scale variations on the link.
  - Short time scale variations on the link could change the results.
- The results are provided only for one pass per complex per week.
  - Weather systems that linger for a few consecutive days over a complex could change the results if more passes per week were scheduled over the same complex.
- Other environmental effects on the link such as wind loading were ignored.
  - While MRO Ka-band demonstration cruise phase results did not indicate any problems with wind loading either on the antenna gain or on the antenna active pointing, they may exist and reduce Ka-band performance advantage presented here.
- X-band and Ka-band amplifiers do not have the same RF output power.
  - For the same RF output power, Ka-band advantage could be higher for higher RF output power values and lower for lower RF power values.