On the Performance of Adaptive Data Rate over Deep Space Ka-Band Link: Case Study Using Kepler Data

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Abstract—**Future missions envisioned for both human and robotic exploration demand increasing communication capacity through the use of Ka-band communications. The Ka-band channel, being more sensitive to weather impairments, presents a unique trade-offs between data storage, latency, data volume and reliability. While there are many possible techniques for optimizing Ka-band operations such as adaptive modulation and coding and site-diversity, this study focus exclusively on the use of adaptive data rate (ADR) to achieve significant improvement in the data volume-availability trade-off over a wide range of link distances for near Earth and Mars exploration.**

Four years of Kepler Ka-band downlink symbol signal-to-noise (SNR) data reported by the Deep Space Network were utilized to characterize the Ka-band channel statistics at each site and conduct various *what-if* performance analysis for different link distances. We model a notional closed-loop adaptive data rate system in which an algorithm predicts the channel condition two-way light time (TWLT) into the future using symbol SNR reported in near-real time by the ground receiver and determines the best data rate to use. Fixed and adaptive margins were used to mitigate errors in channel prediction. The performance of this closed-loop adaptive data rate approach is quantified in terms of data volume and availability and compared to the actual mission configuration and a hypothetical, optimized single rate configuration assuming full a priori channel knowledge.

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1. INTRODUCTION

A key metric for a deep space link is *availability*, defined as the probability that the signal-to-noise ratio (SNR) of a link will stay above a certain threshold required for reliable communication. The degree to which the SNR of a received signal will remain above the required threshold depends on the statistical nature of the noise and the phenomena causing attenuation. There is an inherent trade-off between *availability* and *capacity* in that when more power is allocated to protect against attenuation and noise, the supportable data rate will be lower given the same power budget. Because Ka-band communications is known to have higher sensitivity to atmospheric attenuation than X-band, more power margin will be required to achieve the same availability and this will reduce the achievable capacity gain.

Previous studies had examined a variety of Ka-band related performance trades. For example, in [3] a coarse-grain on/off model was used to analyze the delay performance of reliable file transfer over weather-dependent correlated Ka-band channel. In [1], Water Vapor Radiometer (WVR) measurements collected by the Deep Space Network (DSN) were used to generate empirical distribution of atmospheric noise temperature for a Ka-band channel, and based on this distribution an adaptive data rate algorithm was proposed and evaluated. In [2] various pre-scheduled rate optimization criteria were examined and compared between Ka-band and X-band links for deep space missions.

In this study we will evaluate the performance of ADR, for the first time, using symbol SNR measurements taken from operational Ka-band downlink passes of the Kepler mission. The advantage of operating on the symbol SNR instead of the WVR or other weather metrics is that it provides a direct measure of the link quality that included the combined effects all factors affecting link performance, not just atmospheric loss. Also symbol SNR measurements are typically available in real-time from the ground receiver and can easily be incorporated into an operational control loop.

2. FADING DISTRIBUTIONS OF KEPLER'S KA-BAND DOWNLINK

The Kepler spacecraft is in an Earth-trailing, heliocentric orbit. The bulk of its science data is downlinked through Ka-band passes over the three DSN sites, scheduled once or twice each month. Kepler's Ka-band system can support up to 20 symbol rates, from 550ksps up to 8.6Msps with 0.6 dB steps. Kepler has a conservative link budget designed to compensate for the loss of signal strength as its distance to Earth increases over its primary science phase.

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Our study utilized the symbol SNR measurements recorded by DSN stations for 70 Ka-band downlink passes over a 4-year period starting January 2010 (DOY19) and ending November 2013 (DOY324). The dataset covered passes supported by the 34-m Beam Waveguide (BWG) antennas: DSS 25, DSS 26, DSS 54, DSS 55, and DSS 34. The symbol SNR were reported on an best effort basis, and averaged one sample every 1 to 2 minutes.

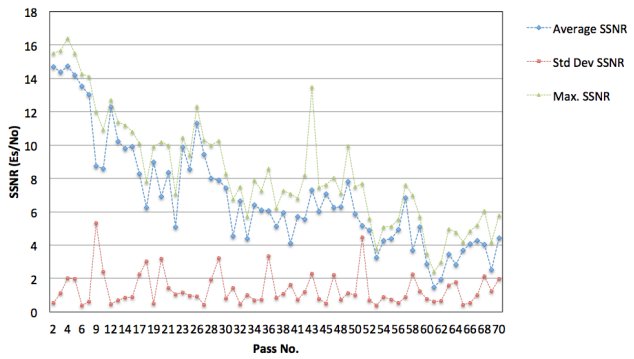

Figure 1: Symbol SNR Statistics

Figure 1 shows the symbol SNR statistics, the average, maximum, and standard deviation for each of the 70 passes. During this 4-year period, Kepler's distance to Earth increases gradually from 0.08AU to 0.57AU, a factor of 7 increase. By end of the 2013, an additional 17dB of free space loss (factor of 49 reduction) had absorbed all design margin, and Kepler was compensating by using lower symbol rate. (See Figure 2). Pass durations ranged from 40 minutes to 550 minutes. The maximum elevation angle was 80 degrees, and the minimum elevation angle was 9 degrees.

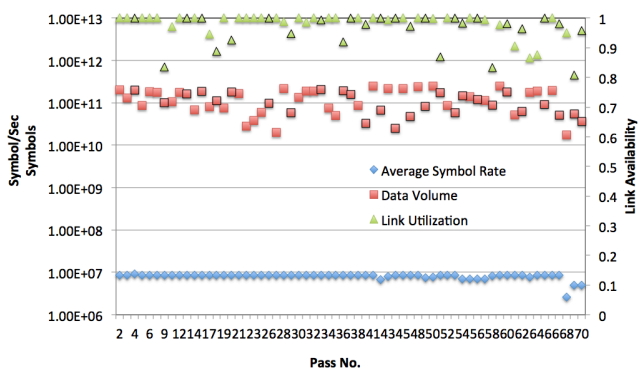

Figure 2: Data Volume and Link Availability

Figure 2 shows the data volume, link availability (or utilization) and average symbol rate. Even with high link margin in the early part of the primary mission phase, there were still many passes experiencing availability below 90%.

Before using the channel data to evaluate ADR performance, we first examine the fading characteristic of the reported data set. Even though the Kepler mission made no specific attempt to avoid rain or cloudy conditions when scheduling downlink passes, it is important to compare the data with existing models and check for discrepancies.

Determining the Actual Received SSNR Threshold

In order to set the proper constraint when selecting data rate adaptively, we must first determine the true SSNR threshold. Using equations provided by [7], we can plot the frame error rate as a function of symbol SNR (Figure 3) for the Concatenated RS(255,223) Convolutional (7,1/2) code. Given that each RS code word has 233*8 bits, each Kepler frame contains 5 RS code words, and a nominal bit error rate target of 10^{-6}, the theoretical SSNR threshold should be set to approximately 0.2% or -1.4 dB.

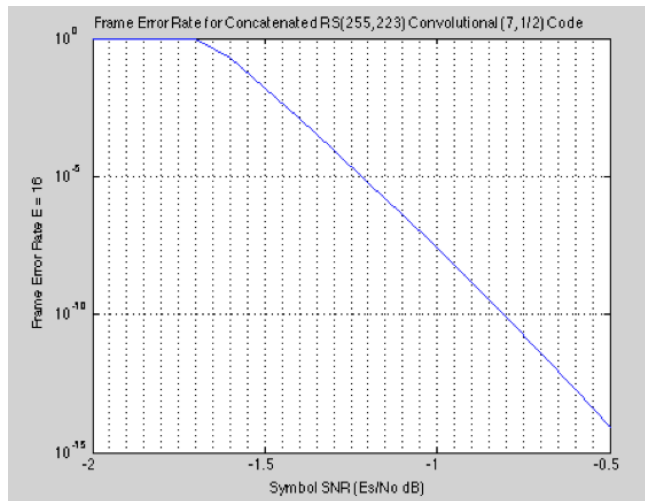

Figure 3: Frame Error Rate for RS(255,223) CC(7,1/2) Code

However to account for ground system losses, we use the SSNR data set for calibration. In the DSN telemetry system, the frame synchronization flag is often, but not always, provided. We find that a fixed threshold of 0.1dB is 96% accurate in matching the frame synchronization flag reports. This also suggests that there is approximately 1.5dB of ground system loss.

Isolation of Fading from Clear Sky Predicts

The reported symbol SNR is a function of both link geometry such as elevation angle and slant range, and weather conditions. In order to examine fading due to weather impairment only, the symbol SNR data must be isolated from the clear-sky predict.

For each of the 70 passes, we used the Telecom Forecaster Predictor (TFP) tool [6] configured for Kepler to generate the symbol SNR for Clear Sky condition. Figure 4 shows both the reported SSNR of pass no. 69 and the clear sky predict for the same pass. The reported SSNR is subtracted from the clear sky predict to isolate the fading due to weather.

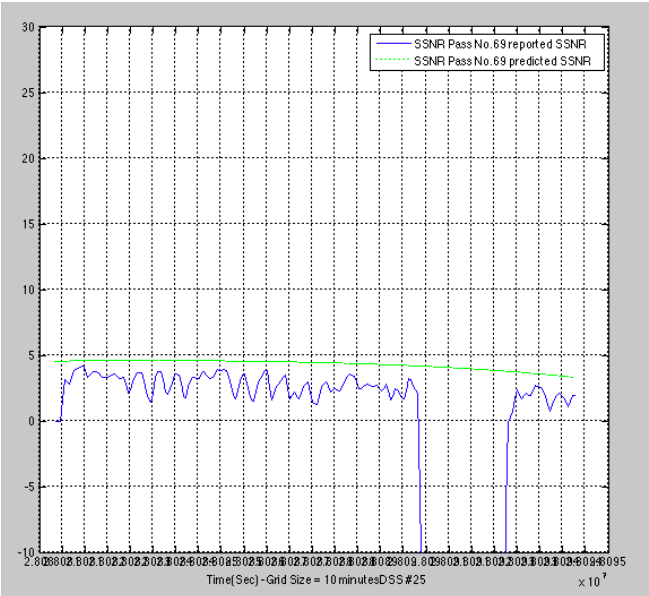

Figure 4: Pass 69, reported vs. Clear Sky SSNR

Comparison with ACTS experiment data

The model to which we compare the fading distribution is provided by the ACTS experiment [4]. It should be noted that the ACTS data were taken from elevation angles ranging from 8 to 52 degrees, while for Kepler passes the elevation angles were ranging from 9 to 80 degrees.

To compare Kepler's Ka-band signal at 32GHz against the ACTS data, which is measured at 27.5 GHz, a frequency scaling method is applied as described in section 2.2.1.2 of the ITU recommendation [5]. ITU-R rain zones [6] were used to select the appropriate ACTS dataset for matching with each of the three DSN sites. For Goldstone, ACTS experiment results collected at Norman, OK were most appropriate as both locations are in ITU rain zone E. For Canberra, which is in rain zone K, ACTS data from Reston, VA were selected for comparison. Unfortunately the published ACTS data did not contain suitable data for comparison to Madrid, which is in ITU rain zone H.

Figure 5 and Figure 6 show the fading distributions for Goldstone and Canberra, and how they compared against the ACTS empirical distributions. The data shows that Goldstone exhibits more fading than ACTS statistics would predict. The Goldstone data had 6 dB more fading at 95% weather and 10dB more at 99% weather. The Canberra dataset showed good fit with ACTS data, within 1 dB up to 99.7% weather. Although there is a sharp drop off above 99.7% weather, it is most likely due to insufficient sampling of tail events; the Canberra data set contained only 2800 sample points overall, the smallest of all three sites. The fading distribution for Madrid (not shown) exhibited similar roll-off to the tail of the distribution as Canberra. Overall, Goldstone has the worst fading, which is counter-intuitive to our general expectation of a dry, desert climate.

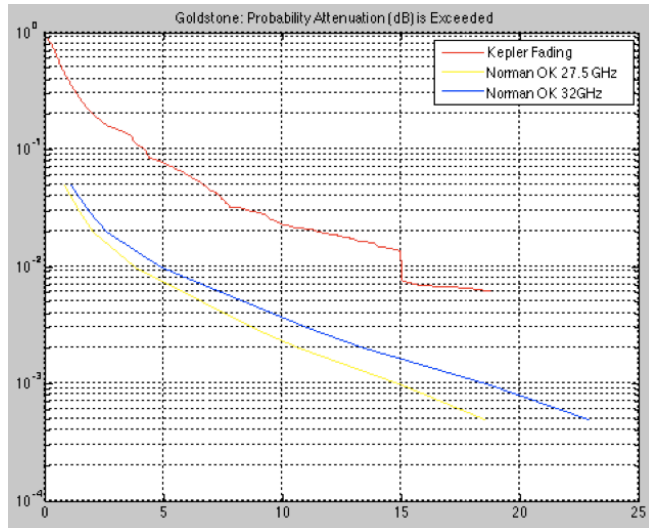

Figure 5: Fading Distribution at Goldstone

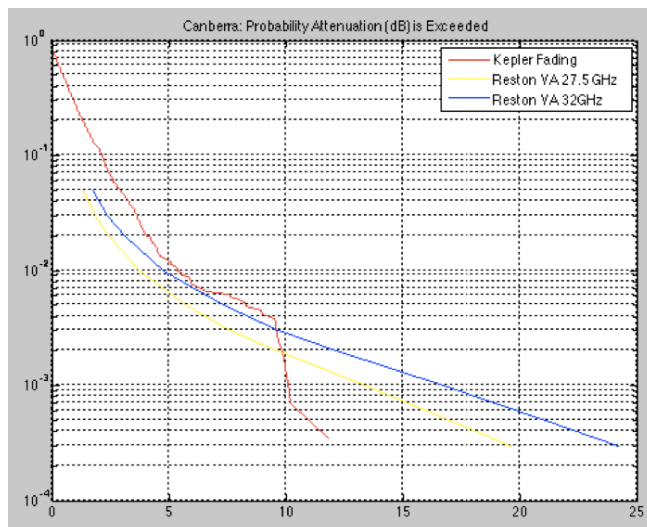

Figure 6: Fading Distribution at Canberra

Using AWVR Data To Understand Goldstone Downlinks

In order to explain the stronger fade observed at Goldstone for Kepler, several possible causes were investigated. Goldstone is the most windy of the three DSN sites and the deformation of reflector and pointing losses due to high wind loading could contribute additional losses.

The average pointing error for Ka-band with CONSCAN is approximately 0.004 degree at 45mph wind loading [8], which corresponds to a 0.8dB gain reduction. If the pointing error can be modeled as a normal distribution, then the 3-sigma (99.7%) error will be 0.012 degree which translates to a 6 dB loss. The deformation of the reflector can contribution another 0.5 dB of loss. But this still does not fully explain the 10dB+ additional fading observed.

Another factor considered was that since Kepler mission did not intentionally prevent scheduling during poor weather, there is a chance that a significant number of passes at Goldstone were impacted by poor weather, despite it being

the best of the three DSN sites in terms of average weather condition. Although the DSN reports from Kepler telemetry contain some weather indications, they were often incomplete. So we turn to the Advanced WVR (AWVR) data set collected at Goldstone between January 2010 and December 2013 to correlate weather and the Kepler downlink passes. Figure 7 shows sample AWVR data for June of 2013 at Goldstone.

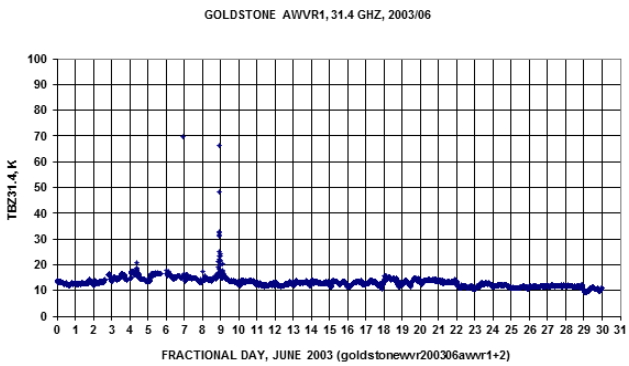

Figure 7: Zenith Sky Noise Temperature at Goldstone, June 2013

The vertical axis is the Zenith sky noise temperature and for a clear sky it is typically in the range of 11-13K. When there are clouds, the noise temperature will go up to 15 to 20K. Above 20K, there is rain. By examining the AWVR data such as this we have confirmed that out of 26 Goldstone passes, 5 passes had rain and 3 passes were under cloudy conditions. That means about 1/3 of the Goldstone passes were impacted by weather. In addition, there are 5 Goldstone passes with 3dB or higher fading lasting from 25 minutes up to 6 hours and for which unfortunately we could not confirm the weather conditions due to gaps in the AWVR data set. Nonetheless, the AWVR data revealed that the Kepler downlink passes at Goldstone were indeed more strongly impacted by weather than one would expect based on average weather statistics.

3. ADR ALGORITHM & SIMULATION

Having investigated the fading distribution, we now turn our attention to characterizing the temporal dynamic of the channel. In order to design an adaptive data rate algorithm, we must first understand the correlation of the channel state to make an effective prediction.

The core of the ADR algorithm is the channel predictor, that predicts the state of the channel after a minimum of two-way light-time (TWLT) delay based on current channel state measurements. For space communications, data rate change cannot be executed until a minimal delay of TWLT so that transmitter and receiver can properly synchronize on the decision to change data rate. In general the stronger the correlation in channel state, the better the predictor can perform.

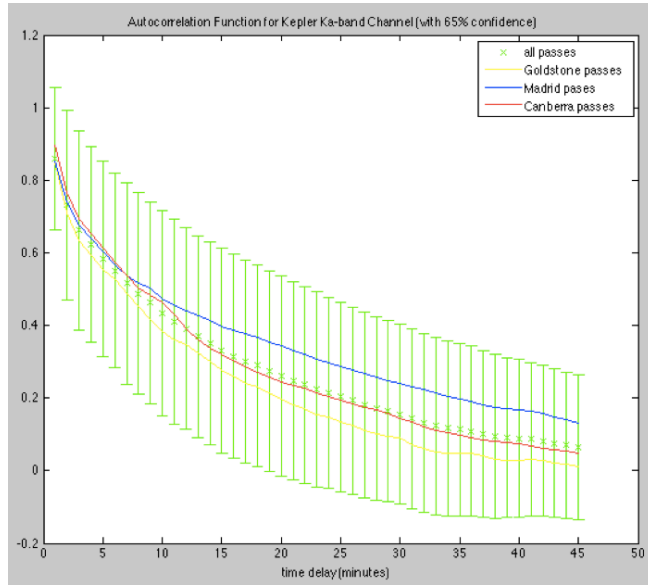

Figure 8: Autocorrelation Function of Ka-band SSNR

Modeling the Channel as an AR Process

Similar to [1] we make the observation that the maximum entropy model for a stochastic process is an auto-regressive (AR) process whose coefficient is the auto-correlation function. To simplify the channel predictor, we do not distinguish between the three ground sites; as shown in Figure 8, the autocorrelation functions of the channels at the three DSN sites are actually quite similar. The green bars shows the 65% confidence interval. We further simplified the predictor by reducing the AR model to order 1, and using curve fitting method to produce the equation for estimating SSNR at time k based on the current SSNR, time =0,

$$SSNR_{est}(k) = SSNR(0) * a^k \qquad (1)$$

where $a = e^{-0.0733} = 0.9293$, k is the time in units of minutes. Basically the parameter a is a discount factor to reflect the rate of channel state de-correlation over time. In our study we will use $a = 0.92$ as a lower bound and test out the effects of using more aggressive predictor setting.

Link Configuration and Metrics

To simulate and compare ADR and non-ADR links performance, we define the following configurations:

(1) Fixed-Rate Operation (FRO) – this is the nominal Kepler configuration. As a reference point, for the 70 passes used for this analysis, the average link availability was 97.9%, with the worst case being 60% and the best case 100%. The average data volume per pass is 800 Gigabits or 100Gigabytes. All data volume comparisons in the following sections are normalized to this data volume.

(2) Fixed Rate Genie Model (FRGM) – this is a configuration in which the data rate is set to a single rate that maximizes the data volume—*assuming the actual SSNR process of a pass is fully known a priori without error*. Because it is impossible to know the entire SSNR process *a priori*, it is a genie model, a hypothetical configuration for setting performance benchmarks. To maximize data volume, substantial link disruption/lower availability is tolerated. As a reference point, the average availability of this configuration over the 70 passes considered was 85.6% - consistent with the estimates in [2] – with worst case availability of 62.1% and best case 100%. This configuration produces data volume approximately 4 times (6 dB) higher than FRO.

(3) Adaptive Data Rate (ADR) mode – this is where the link rate is controlled by an ADR algorithm that determines the rate based on reported SSNR and channel predictor. With the proper configuration setting, ADR is able to outperform FRGM in both data volume and availability.

The trade space of this study will encompass the following parameters:

(1) Aggressiveness of channel predictor: AR1 coefficient *a* will vary from 0.92 to 1.

(2) Margin (0 to 3 dB in 0.1dB steps): this is an additional margin applied on the channel predictor

(3) Round-trip delay (from 0 to 40 minutes): this is the minimum delay in executing the ADR control loop

In the ADR simulation, data volume and availability metrics will be derived for various link configurations and parameters setting as scoped out in our trade space.

4. ADR Performance & Scenarios

Data Volume

Figures 9 and 10 show the contour plot of data volume gain (not in dB) of ADR over FRO configuration for $a = 1$ and $a = 0.92$.

In general, we observe that the data volume gain reduces with increased delay and margin, and it is predominantly determined by the aggressiveness of the channel estimator. As a point of reference, the FRGM configuration has performance gain factor of 4 over FRO.

In the most aggressive setting ($a = 1$), ADR is able to outperform FRGM over the entire range of round-trip delay. A gain factor of 5.5 (or 7.4dB) is achievable for TWLT < 30 sec, while keeping fixed margin < 0.25 dB; a gain factor of 4.5 (6.5dB) for TWLT < 2000 sec (33.3 minutes) is possible when keeping approximately 0.5 dB of margin. With a more conservative setting, a = 0.92, the data volume is traded for high availability, which we will discuss next.

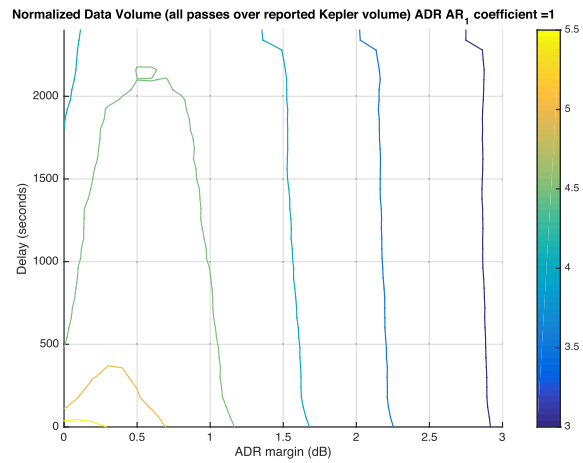

Figure 9: ADR Data Volume Gain, *a* = 1

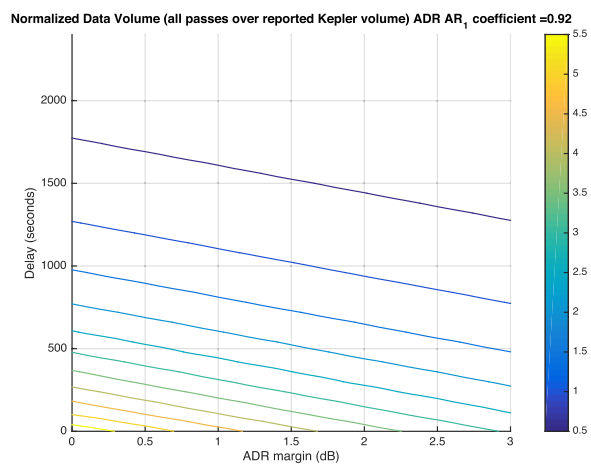

Figure 10: ADR Data Volume Gain, *a* = 0.92

Availability

When using the most aggressive ADR setting, link availability is strongly impacted by round-trip delay, as shown in Figure 11, which must be mitigated by fixed margin. When some delay-dependent margin is introduced (i.e., setting the coefficient $a = 0.99$), link availability improves significantly for the entire range of TWLT values. In Figure 12, one observes a local minimum centered around 3-minute round-trip delay and 0 dB fixed margin. This is due to the presence of random attenuation of the signal not related to weather, and can only be countered by using fixed margin.

Operation Regions

Figure 13 shows the region in the trade space where ADR will outperform FRGM. For each AR coefficient *a*, the area to the *left of the curve* achieves data volume gain factor

from 4 up to 5.8. One should keep in mind that there is still substantial gain to the right. Although we are using FRGM performance as a benchmark, it is a hypothetical configuration that requires full a priori knowledge of random events. The most aggressive setting (a = 1) is required to achieve better than FRGM performance at maximum Mars distance.

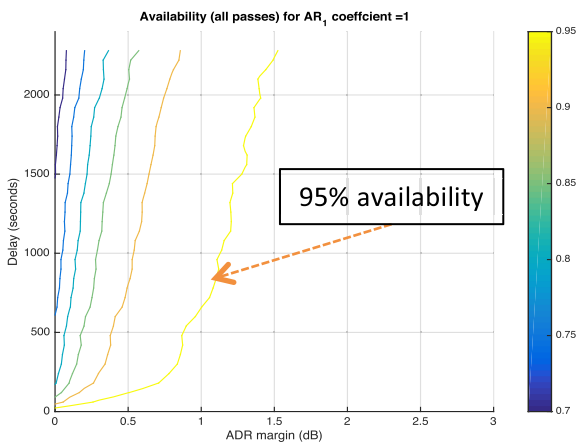

Figure 11: Link Availability at a = 1

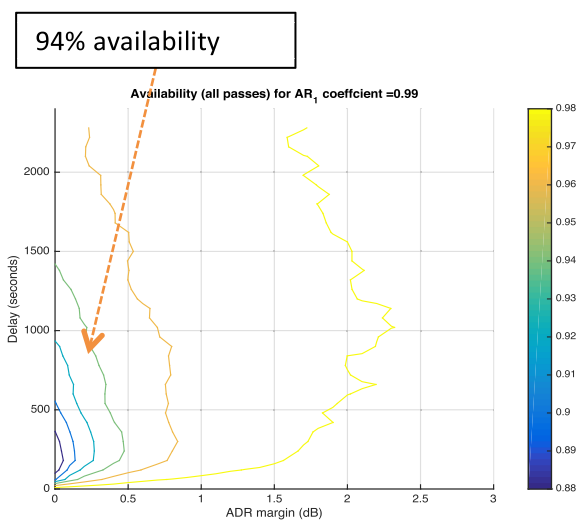

Figure 12: Availability for a = 0.99

For Figure 14, the region to the right of the curve achieves better than 97% availability. At short range, for example less than 180 sec round-trip, one must rely on fixed margin to improve availability due to fast fading. If a mission has high availability requirement over a wide range of round-trip delay, then it must rely more on delay-dependent margin (lower AR coefficient a) in addition to a fixed margin.

Recommendations For Four Different Mission Scenarios

In this section we provide general recommendations on four different scenarios distinguished by round-trip delay:

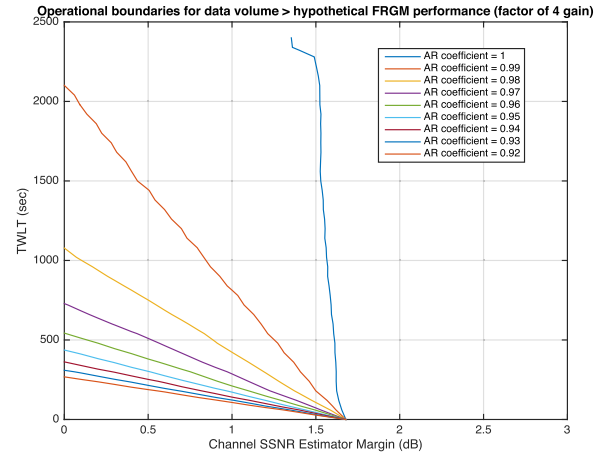

Figure 13: Data Volume Gain > 4 (6dB)

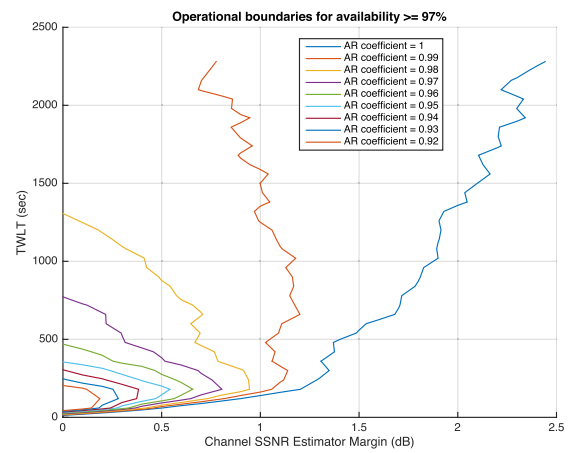

Figure 14: Operation Region for Availability > 97%

(1) Short range – for missions operating from distance less than 0.06AU or TWLT < 60 sec, which include near Earth, lunar, and SEL2, etc, we recommend using ADR with the most aggressive setting (a = 1) and carrying fairly low margin. At this distance, data volume performance can achieve its maximum gain factor of 5.8 (7.5 dB), minus the fixed margin. Availability up to 99% can be achieved.

(2) Minimum Mars distance – for missions operating up to 0.6AU or TWLT < 600 seconds, which includes early cruise phase, minimum Mars distance, earth-trailing orbits, ADR provides 4x or higher data volume gain while maintaining 97% availability. Set ADR to most aggressive setting (a = 1) and carry 1 to 1.5 dB of fixed margin on the channel predictor.

(3) Medium Mars distance – for missions operating from 0.6 to 1.5AU, or TWLT up to 1500 seconds, medium Mars-Earth distance. AR coefficient a should be set to 0.99. Data volume of 4x; availability of 95% possible depending on margin setting.

(4) Maximum Mars distance – for missions operating from 1.5 to 2.4 AU or TWLT up to 2400 seconds. For data driven mission, the most aggressive ADR setting should be used (a = 1) to achieve gain factor of 4 or higher; best availability is 90% (see Figure 15). If high availability is the driver, one must increase margin as well as lowering a; data volume gain will be less than factor of 4.

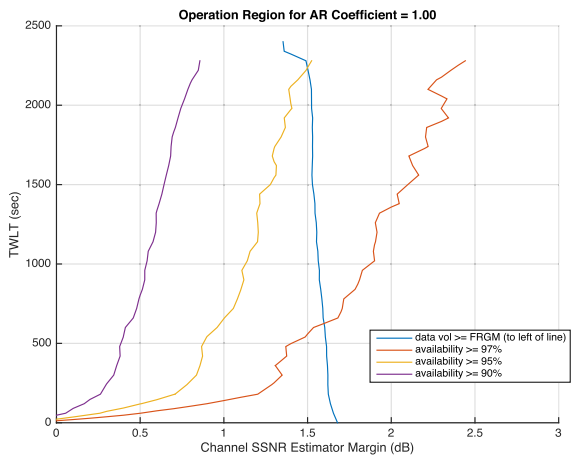

Figure 15: Maximum Mars Distance performance region

5. SUMMARY

Using channel data collected from Kepler downlink to the three DSN ground sites, our study has shown that adaptive data rate (ADR) technique can increase data volume by 7.5 dB, or 1.5 dB better than the best fixed rate configuration given full knowledge of the channel. For lunar distance, better than 99% link availability is achievable due to the short delay of closing the data rate control loop. For maximum Mars distance, 90% availability is possible with appropriate margin setting while still achieving a 6dB data volume gain over Kepler performance.

ACKNOWLEDGEMENTS

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REFERENCES

[1] Sun, J., Gao J., Shambayatti, S., and Modiano, E., "Ka-Band Link Optimization with Rate Adaptation for Mars and Lunar Communications," International Journal of Satellite communications and Networking, Vol 25., No. 2, March/April 2007, p147-165

[2] Shambayati, S., "A Comparison of the Ka-band Deep-Space Link with the X-band Link through Emulation", IPN Progress Report 42-178, August 15, 2009.

[3] Gao, J.L., and Woo, S., "CCSDS File Delivery Protocol Performance over Weather-Dependent Ka-Band Channel", Space Operations: Mission Management, Technologies, and Current Applications (Progress in Astronautics and Aeronautics), Chapter 8, p 129, AIAA, ISBN: 9781563479199

[4] R. Crane, A. Dissanayake, "ACTS Propagation Experiment: Attenuation Distribution Observations and Prediction Model Comparisons," Proceedings of the IEEE, Vol. 85, No. 6, June 1997.

[5] ITU-R P.618-11, Propagation data and prediction methods required for the design of Earth-space telecommunication systems.

[6] K. Tong, R. Tung, "A Multimission Deep-Space Telecommunications Analysis Tool: The Telecom Forecaster Predictor", TMO Progress Report 42-140, Jet Propulsion Laboratory, February 2000.

[7] "34-,m and 70-m Telemetry Reception", Module 207, Rev A, DSMS Telecommunications Link Design Handbook, 810-005, Rev. E, June 13, 2003.

[8] "Antenna Positioning" DSN No. 810-005, 302, Rev C, Jet Propulsion Laboratory, February 09, 2015.

BIOGRAPHY

Jay L. Gao *joined the Jet Propulsion Laboratory in 2001 and is currently a senior research staff in the Telecommunication Research and Architecture section. His research is primarily focused on space-based wireless communications and networking, with emphasis on adaptive data rate, demand access, and Ka-band and optical link optimization technologies for the envisioned Interplanetary Network (IPN), the Mars Relay Network, and deep space communications. He has also supported requirements definition and interface design activities for the Department of Defense's Transformational Communications MilSatcom project. Other research interests include sensorweb, distributed communication/sensor systems, energy efficient routing and self-organization algorithm for cooperative signal processing and sensor networks. He received his Ph.D. degree in Electrical Engineering from UCLA in 2000.*