Link Analysis for Space Communication Links Using ARQ Protocol

Kar-Ming Cheung
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive,
Pasadena, CA 91109
818-393-0662
Kar-Ming.Cheung@jpl.nasa.gov

Chi-Wung Lau
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive,
Pasadena, CA 91109
818-354-0887
Chi-Wung.Lau@jpl.nasa.gov

Charles Lee
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive,
Pasadena, CA 91109
818-354-0887
Charles.H.Lee@jpl.nasa.gov

Abstract[1]— **In space communications, standard link analysis assumes that messages are sent once. For a communication link that uses an error-correction coding scheme, bit-error-rate (BER) or frame-error-rate (FER), and link margins are common metrics that characterize the quality of a link, and they are used to determine the supportable data rate. With the advent of Automatic Repeat-reQuest (ARQ) protocols, when messages are corrupted during transmission, they can be re-sent multiple times automatically until they are correctly received and acknowledged. The concept of BER, FER, and link margin cannot be directly applied, and the link analysis approach for ARQ links needs to be re-examined.**

In [1] we described the problem formulation and defined the evaluation metrics to analyze the performance of ARQ links, and derived analytical models that describe the statistical behavior of the space links that use ARQ. In this paper, we show that by integrating these analytical ARQ protocol models into the standard link analysis, we bypass the need to simulate or emulate the ARQ protocol operations, and generate analytical models on effective data rate, effective throughput, latency, and FER. We demonstrate this approach using the Lunar L2 Flyby Mission communication scenarios, and discuss the insights and trades between link efficiency, latency, and error rate.

TABLE OF CONTENTS

1. INTRODUCTION

In space communications, standard link analysis assumes that messages are only sent once[2]. Also when an error-correction coding (ECC) scheme is used, to ensure that the decoder at the receiving side does not misinterpret an erroneous code-block to be a correct one, the ECC scheme is typically designed with powerful error-detection capability such that the undetected error probability is negligible [2]. Under these assumptions, the *bit error rate* (BER) or *frame error rate* (FER), and link margin (M) are common metrics that characterize the performance of a link, and they are used to determine the supportable data rate. Common BER's of choice in many NASA links (which we can find in many requirement documents) range from 10^{-5} to 10^{-8}. For a given BER, there is a corresponding *energy per bit to noise power spectral density ratio threshold*, denoted by $(Eb/No)_{Th}$, whose characteristics depend on the underlying coding schemes used. In the standard link analysis and planning process, the link margin policy specifies the link margin M to ensure that the random received power fluctuations would have a small likelihood to cause the received Eb/No to dip below the coding threshold $(Eb/No)_{Th}$. Link analysis and the corresponding link margin policy are typically expressed in logarithmic scale (in decibel, or dB). The supportable data rate R_b is determined such that the received Eb/No exceeds the sum of $(Eb/No)_{Th}$ and M (in dB) to ensure reliable communication. Typical link margins of choice are 3 dB, 2-σ[3] and 3-σ. In the above standard link analysis process, the underlying assumption is that data that are corrupted in the channel are non-recoverable. Therefore the link analysis approach is to apply adequate link margin to maintain a maximum tolerable error rate (BER or FER) to ensure data integrity and to minimize data gaps in the received data. On the receiving end, non-decodable code frames are discarded.

With the advent of Automatic Repeat-reQuest (ARQ) protocol when data are corrupted during transmission, messages can be re-sent multiple times until they are received and acknowledged. Much work has been done in the performance analysis of ARQ protocols in the wireless communication areas. Throughput and latency analyses can be found in early papers [3][4] under the assumption that code-block errors occur independently. To analyze wireless communication channels that are characterized by fast fading and bursty errors, recent literature introduces

[2] We denote this kind of link as "send-once" link.

978-1-4799-1622-1/14/$31.00 ©2014 IEEE

[3] σ is the standard deviation of the Gaussian distribution used in statistical link analysis [12][13].

channel models that assume an error process that is not random, and is modeled as a Markov process [5][6][7][8].

As in [1] and [2], we limit the scope to 1-hop space communication scenarios (no routing) that assume independent code-block errors. The ARQ link can be considered as "error-free" in the sense that a data frame will eventually be successfully delivered, assuming (for now) there is no limit on the number of re-transmission. However the penalties for ARQ link are i) increased latency for re-transmission, and ii) reduced link efficiency (measured in higher power or lower data rate) to accommodate the re-transmitted data frames.

Thus to analyze the "error-free" ARQ link, we need to consider:

1. Transmission latency in some statistical sense (e.g. maximum latency, mean latency, etc.)
2. Effective data rate R_{eff} in terms of the net data throughput discounting the portion of the bandwidth that accommodates re-transmissions.

The concept of effective data rate is also applicable to "send-once" links. By assuming the smallest data unit to be a frame, and denoting P_{bk} as the FER, the effective data rate R_{eff}, in terms of the amount of reliable data available on the receiving end, can be measured as

$$R_{eff} = R_b(1 - P_{bk}) \qquad (1)$$

Note that in this interpretation of effective data rate for the "sent-once" link, R_{eff} includes the portion of the data frames that are successfully received. The corrupted data frames are lost and non-recoverable.

Earlier work in analyzing ARQ methods for deeps space links can be found in [9], which investigates the ARQ links mainly from a coding performance perspective, and considers only the Selective Repeat protocol. The current paper addresses the ARQ problem from the viewpoint of extending the standard link analysis techniques to the ARQ links, and provides explicit analytical expressions to estimate the supportable effective data rate R_{eff}.

The rest of the paper is organized as follows: Section 2 summarizes the results on ARQ link analysis as described in [1], both for the case of unlimited number of re-transmission and for the case when the number of re-transmission is restricted to a finite number *K*. Section 3 describes the application of the ARQ analytical models to support high-fidelity simulation of different space communication operation strategies. By integrating the analytical ARQ protocol models into the standard link analysis, we bypass the need to simulate or emulate the ARQ protocol operations, and generate accurate and useful results on effective data rate, effective throughput, and latency to support communication and network architecture trade-off. Section 4 provides the concluding remarks.

2. Summary of Prior Results

In [1] we provide the problem formulation and extend the standard link analysis approach to the ARQ link, under the assumption that code-block errors occur independently as in the case of space communications. Given the fact that $E_b / N_o \propto 1/R_b$ one can construct the function $f(\cdot)$[5] that represents the FER performance curve of the error-correction code, and express P_{bk} as

$$P_{bk} = f(E_b / N_0) = f(C / R_b) \qquad (2)$$

where *C* is the data signal-to-noise ratio P_D / N_o, which can be computed from standard link analysis. The results on effective data rate R_{eff} and latency are summarized in the following sub-sections.

2.1 ARQ Links with No Limit on Number of Re-Transmissions

The ARQ protocols examined in [1] are Selective Repeat and Go-Back-N. Using the same notations, we denote by P_{ack} the error rate of the acknowledgement link, and by N the number of code block are sent for each re-transmission. Let T_c be the one-way light time (OWLT) delay between the transmitter and the receiver. It is shown in [1] that with some simplified assumptions, the latency of an ARQ link follows the discrete geometric distribution. Notice that the latency for each additional re-transmission is T_{out}, which includes two OWLT delays and the receiver's acknowledgement and processing time. The probability that the code block is successfully sent and acknowledged after the i^{th} transmission, with latency = $T_c + iT_{out}$, is

$$\text{Prob}[\text{i}^{\text{th}} \text{ re-transmission}] = \theta(1-\theta)^i. \qquad (3)$$

where $\theta = (1 - P_{bk})(1 - P_{ack})$. The mean latency as observed by the receiver can be computed to be $T_c + T_{out}(1-\theta)/\theta$, and the corresponding variance is $T_{out}^2(1-\theta)/\theta^2$. Thus on an average sense, the additional latency cost of an ARQ link compared to a "send-once" link is $T_{out}(1-\theta)/\theta$. The effective data rate R_{eff} is given by the following expression:

$$R_{eff} = R_b\left(1 + \frac{N(1-(1-f(\frac{C}{R_b}))(1-P_{ack}))}{(1-f(\frac{C}{R_b}))(1-P_{ack})}\right)^{-1} \qquad (4)$$

2.2 Truncated ARQ Links with Up to *K* Re-Transmissions

To impose a maximum delay on the code-block reception, some ARQ links limit the number of re-transmissions to *K*. In this case the ARQ links cannot be considered as error-

[5] *Eb/No* of *f(Eb/No)* is expressed as a ratio, not in dB.

free. K is determined by the maximum allowable delay and/or buffer sizes that the communication nodes can tolerate. The metric to measure the link quality is similar to the metric that measures the quality of the 'sent-once' link; that is, the supportable data rate $R_{b,K}$ that meets the FER requirement $P_{b,K}$. The term $R_{b,K}$ is interpreted as the effective supportable data rate with a maximum of K re-transmissions, and $P_{b,K}$ is defined as the frame-error-rate with a maximum of K re-transmissions.

$R_{eff,K}$ can be computed as

$$R_{eff,K} = R_b(1+\frac{\delta N(1-\delta^K)}{1-\delta})^{-1} = R_b(1+\frac{\delta N}{1-\delta}-\frac{\delta^{K+1}N}{1-\delta})^{-1} \quad (5)$$

and $P_{b,K}$ is derived to be

$$P_{b,K} = \delta^{K+1}\text{, where} \quad (6)$$

$$\delta = 1-(1-P_{bk})(1-P_{ack}) = 1-(1-f(\frac{C}{R_b}))(1-P_{ack}) \quad (7)$$

Note that for a well-design link δ is a small number, and $P_{b,K}$ decrease geometrically with K. $R_{eff,K}$, on the other hand, only decreases by a small fraction proportional to δ.

For latency analysis, most engineering applications are only interested in the latency of the code-blocks that are successfully transmitted and received. The discrete probability that the latency equals to T_c, T_c+T_{out}, $T_c+2T_{out},\cdots,T_c+KT_{out}$ given that the code-block is successfully transmitted can be expressed as the following conditional probability:

$$\text{Prob[latency} = T_c+iT_{out}\text{]} = \frac{1-\delta}{1-\delta^{K+1}}\delta^i \quad (8)$$

For $i = 0,1,\cdots,K$.

The average latency can be computed to be $T_c+(K+\frac{1}{1-\delta}-\frac{1+K}{1-\delta^{K+1}})T_{out}$, and the variance is $T_{out}^2\frac{\delta+\delta^{2K+3}-\delta^{K+1}((K+1)^2-2K(K+2)\delta+(K+1)^2\delta^2)}{(1-\delta)^2(1-\delta^{K+1})^2}$.

3. Lunar L2 Flyby Communication Scenarios

In this section, we demonstrate the use of ARQ analytical models derived from previous sections to support high-fidelity simulation of different communication operation scenarios of the Lunar L2 Flyby mission.

3.1 Mission Background and Communication Operation Strategies

The mission concept describes a 28-day mission that involves a manned spacecraft known as Multi-Purpose Crew Vehicle (MPCV) that goes into a halo orbit[6] around the Earth-Moon Lagrange Point 2 (EML2). The timeline of the trajectories for the spacecraft and the moon with its EML2 are displayed in Figure 1. The MPCV communicates with the Deep Space Network (DSN)[7] ground stations in S- and Ka-bands, with range approximately 460,000 km. The MPCV is equipped with a 0.7m high-gain antenna. Its transmitter powers for the S-band and Ka-band are 7 watts and 0.7 watts, respectively. The coding scheme is the (7, 1/2) convolutional code, and the data frame size is 8192 bits.

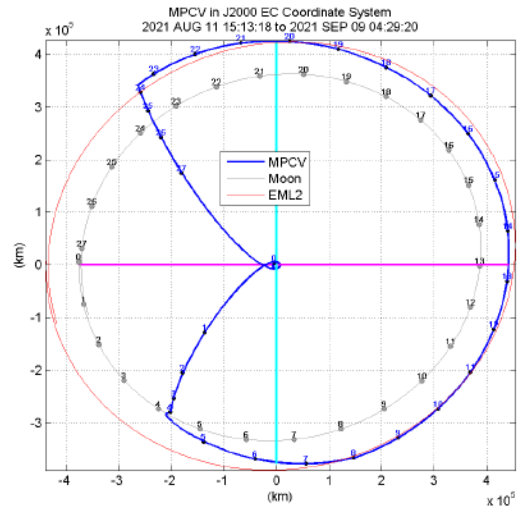


Figure 1 Trajectories of MPCV (blue), the Moon (gray), and the Earth-Moon Lagrange Point 2 (red) and the timeline (days)

We only consider the 20 days of the orbiting phase (day 4-24), where the spacecraft is in the moon's vicinity. The simulation takes into account the environmental and mechanical effects that are specific to Lunar missions such as

(i) DSN coverage gap between Goldstone and Madrid. This is more noticeable at Ka-band as the required horizontal elevation angle is higher.

(ii) Lunar hot body noise temperature when the moon is within the primary beam-width of the DSN antenna. Noise contribution is modeled using measurements of the temperature brightness for the moon with large DSN antennas [10].

(iii) Structural deformations that are unique to the DSN antenna.

(iv) Weather effects.

This high-fidelity modeling and simulation platform provides a virtual mission setup to assess different space

[6] Radius is 22000 km.

[7] The DSN sites are at Goldstone in United States, Canberra in Australia, and Madrid in Spain.

communication techniques.

In this study, we simulate the total data return using the ARQ link with Selective Repeat protocol[8] operating at the optimal Eb/No= 3.7 dB (FER = 0.08), and compare with the data return of correctly received data that uses two 'sent-once' links, one operating at $(Eb/No)_{Th}$ = 4.3 dB that corresponds to BER = 10^{-5} (FER = 0.013), and the other operating at the same $(Eb/No)_{Th}$ = 4.3 dB, plus 3 dB margin (FER ≈ 0.0). We subject the three link configurations to four High Efficiency Tracking (HET)[9] communication operation strategies, in the following order of decreasing complexity:

HET-1: Continuous data rate change per pass.
HET-2: Discrete set of 10 data rates; no limit on number of data rate change per pass.
HET-3: Discrete set of 10 data rates; data rate duration ≥ 50 minutes.
HET-4: Discrete set of 10 data rates; one data rate per pass.

Note that HET-1 is hypothetical, as there is no transmitter and receiver that can track through the continuously changing data rate of a pass. But this case can provide us with an upper bound of the data return performance. HET-4 corresponds to the simplest way of communication operation of one data rate per pass, which is still commonly used by many space missions. HET-2 and HET-3 are efficient yet realizable approaches, depending on to what extend that a mission is willing to deal with the development and operation complexity.

We compute the optimal set of 10 data rates for S- and Ka-bands based on the statistics of the supportable data rate during the 20-day orbiting phase. They are:

S-Band Discrete Supportable Data Rates (Mbps)									
0.3	0.93	0.98	1.04	1.09	1.15	1.22	1.28	1.35	1.43
Ka-Band Discrete Supportable Data Rates (Mbps)									
1.66	4.87	5.66	6.57	7.64	8.88	10.3	12	13.9	16.2

Table 1 – Discrete Supportable Data Rates

The sets of S-band and Ka-band data rates are used in HET-2, HET-3, and HET-4. We assume that whenever there is a data rate change, 10 seconds are required to re-sync and to re-establish the link. For HET-2, a straightforward greedy algorithm is used to compute the time of data rate change. For HET-3 and HET-4, constrained-optimization method is employed to compute the number of data rate changes and the start and end times of each data rate so as to maximize the total data return of the pass and to satisfied the given operation constraints.

Supportable data rate profiles of a typical S-band pass and a Ka-band pass are shown in Figures 2 and 3, respectively. Note that the S-band pass has a more gradual change in supportable data rate due to the S-band's insensitivity to weather effects (Figure 2). The difference between the lowest and the highest supportable data rate is less than a factor of 2. On the other hand, the Ka-band pass (Figure 3) exhibits a relatively higher dynamic behavior. The "double-hump" phenomenon of the Ka-band curve is the artifact of the DSN 34m Beam Wave Guide (BWG) antenna design that the structural deformation is the lowest at 45° elevation angle. Also the difference between the lowest and highest supportable data rate is more than a factor of 4 for the Ka-band pass. The percentages displayed in legends of Figures 2 and 3 signify the data throughput efficiencies for the different communication operation strategies.

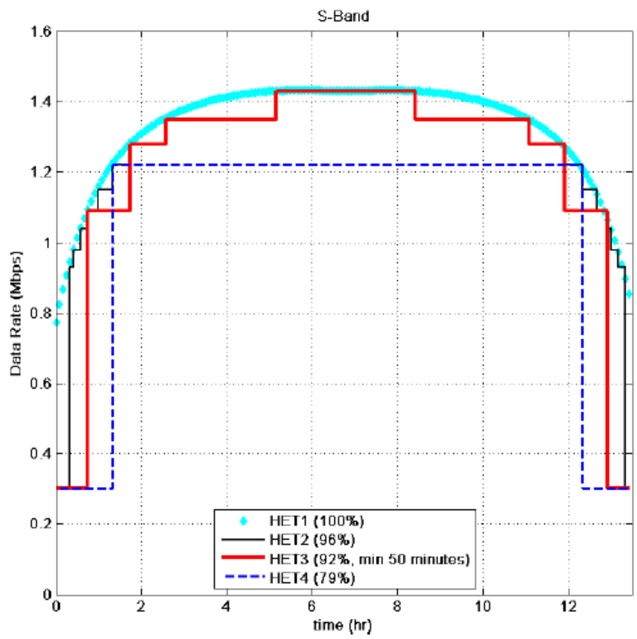
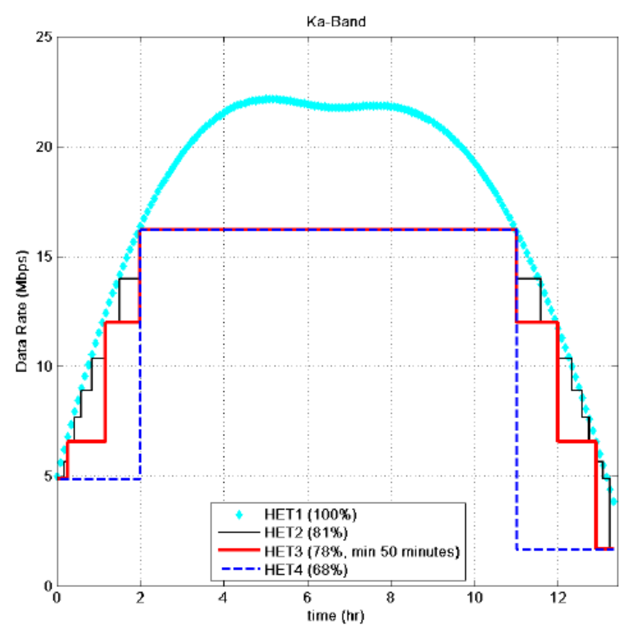


Figure 2 - Data Rate Profile of an S-Band Pass



[8] With no limit on the number of re-transmissions.

[9] High Efficiency Tracking (HET) is the communication operation process of changing data rate, code rate, and modulation scheme during a tracking pass in order to maximize the data return.

Figure 3 - Data Rate Profile of a Ka-band Pass

3.2 Comparison of Simulation Results

The 20-day of orbiting phase of the Lunar L2 Flyby Mission is simulated for the three different links and the four different HET operation strategies (a total of 12 scenarios), and the statistics of data volume[10] are collected. The data return statistics are summarized in Figures 4-5.

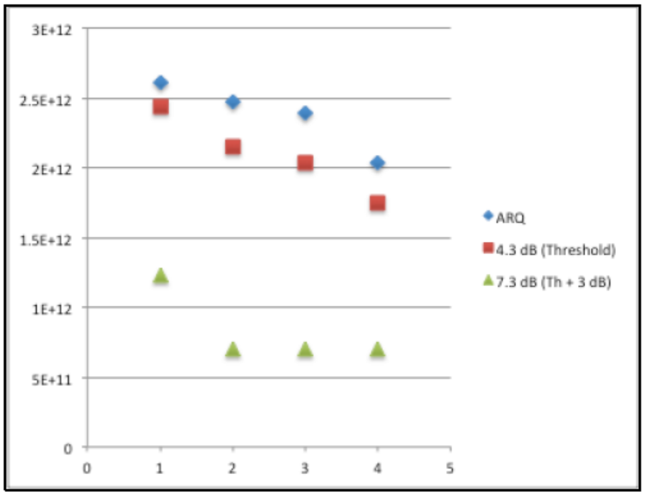


Figure 4 - Data Return Statistics for S-Band

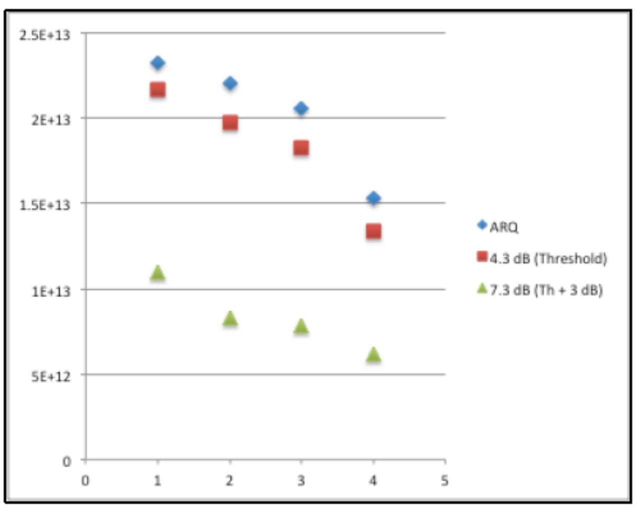


Figure 5 - Return Statistics for Ka-Band

The simulation results is summarized as follows:

1. The ARQ link provides higher data return and higher reliability in the expense of higher latency. From Figure 2, we observe 2X or higher improvement compared to the 'sent-once' link that meets the error rate requirement of BER=10^{-5} plus 3 dB margin.
2. Data rate increase using HET for the Lunar L2 Flyby mission is modest – less than 30% for S-band and less than 50% for Ka-band. From Figures 2 and 3, for both the S-band and Ka-band passes that are between 8 and 12 hours in duration, we observe that the supportable data rate curves have an approximate shape this is 'concave downward'. The link inefficiency at both ends of the curve is due to the impairments of weather effects on the link at low elevation angle, with Ka-band being more profound than S-band. This is typical for spacecraft beyond the Geosynchronous Orbit (GEO), where variation in link capability is primary due to Earth's rotation. In a prior study on assessing HET for spacecraft below GEO or at Low Earth Orbit (LEO), we show that the supportable data rate curves exhibit a high dynamic "inverse Cosine" shape of the form $\frac{c}{a-\cos(\omega t+\delta)}$, and the large variation is due to the large change of distance within a short pass between the spacecraft and the ground station on Earth's surface. A typical data rate profile is shown in Figure 6. In this case the data return improvement of HET compared to one data rate per pass (HET-1) can be as high as a factor of 15.
3. The higher data return improvement on using HET in Ka-band is due to the larger variation in link capability within a Ka-band pass.

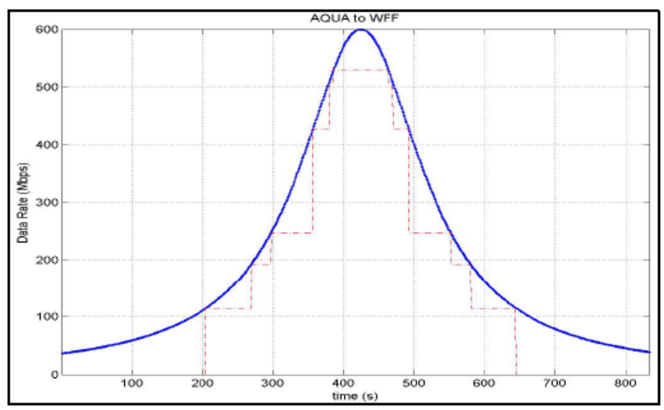


Figure 6 – Data Rate Profile of a LEO Pass

4. Conclusion

In [1] we described the problem formulation and defined the evaluation metrics to analyze the performance of ARQ links, and derived analytical models that describe the statistical behavior of the space links that use ARQ. In this paper, we show that by integrating these analytical ARQ protocol models into the standard link analysis, we bypass the need to simulate or emulate the ARQ protocol operations, and generate analytical models on effective data rate, effective throughput, latency, and FER. We demonstrate this approach to evaluate different HET

[10] The data volume consists only of data that are correctly received.

operation strategies, and discuss the insights and trades between link efficiency, latency, and error rate.

In this study, we demonstrate that the ARQ approach provides higher data return and higher reliability, compared to the traditional 'sent-once' links. ARQ links would be ideal for applications like science data return that can tolerate higher latency. For applications like real-time audio and video communications, the less efficient 'sent-once' link with reasonable link margin is still needed to guarantee reliable and time-critical communications.

We also show that the improvement of data return using HET is modest for spacecraft that operate beyond GEO, where variation in link capability is primary attributed to weather impairments during the rise and set of a tracking pass. This contrasts with the large increase in data return for spacecraft that uses some forms of HET and operates below GEO or at LEO, where the link capability varies greatly due to the rapid change of distance between the spacecraft and the ground station on Earth's surface.

Acknowledgements

The authors would like to thank John Segui and Jay Gao for their engineering and simulation support.

The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. The research was supported by the NASA's Space Communication and Navigation (SCaN) Program.

References

[1] K. Cheung, "Problem Formulation and Analysis of the 1-Hop ARQ Links," *Interplanetary Network Progress Report*, Vol. 42-194, pp. 1-15, August 15, 2013.

[2] K. Cheung, "On the Decoder Error Probability of Linear Codes," *IEEE Transactions on Communications*, Vol 40, Issue 5, May 1992.

[3] G. Fayolle, E. Gelenbe, and G. Pujolle, "An Analytic Evaluation of the "Send and Wait"", IEEE Trans. Commun., Vol. COM-26, Mar 1978,

[4] D. Towsley and J. Wolf, "On the Statistical Analysis Queue Lengths and Waiting Times for Statistical Multiplexer with ARQ Retransmission Scheme," IEEE Trans. Commun., Vol. COM-27, Apr 1979.

[5] D. Towsley, "A Statistical Analysis of ARQ Protocols Operating in a Nonindependent Error Environment," IEEE Trans. Commun., Vol. COM-29, Jul 1981.

[6] M. Zorzi and R. Rao, "Throughput Analysis of Go-Back-N ARQ in Markov Channels with Unreliable Feedback," Proc. IEEE ICC'95, Nov 1995.

[7] M. Zorzi and R. Rao, "On the Use of Renewal Theory in the Analysis of ARQ Protocols," IEEE Trans. Commun., Vol. COM-44, Sep 1996.

[8] M. Zorzi and R. Rao,"Performance of ARQ Go-Back-N Protocol in Markov Channels with Unreliable Feedback," Mobile Networks and Applications 2 (1997) 183-193.

[9] F. Pollara and L. Ekroot, "Analysis of Automatic Repeat Request Methods for Deep-Space Downlinks," TDA Progress Report 42-122, April-June 1995, pp. 66-83, August 15, 1995.

[10] Morabito, D.D.; Imbriale, W.; Keihm, S., "Observing the Moon at Microwave Frequencies Using a Large-Diameter Deep Space Network Antenna," Antennas and Propagation, IEEE Transactions on , vol.56, no.3, pp.650,660, March 2008

BIOGRAPHY

Kar-Ming Cheung is a Principal Engineer and Technical Group Supervisor in the Communication Architectures and Research Section (332) at JPL. His group supports design and specification of future deep-space and near-Earth communication systems and architectures. Kar-Ming Cheung received NASA's Exceptional Service Medal for his work on Galileo's onboard image compression scheme. He has authored or co-authored 30+ journal papers and conference papers in the areas of error-correction coding, data compression, image processing, and telecom system operations. Since 1987 he has been with JPL where he is involved in research, development, production, operation, and management of advanced channel coding, source coding, synchronization, image restoration, and communication analysis schemes. He got his B.S.E.E. degree from the University of Michigan, Ann Arbor in 1984, his M.S. degree and Ph.D. degree from California Institute of Technology in 1985 and 1987 respectively.

Charles H. Lee is a Professor of Applied Mathematics at the California State University Fullerton and a faculty part time staff member in the Communications Architectures and Research Section (332) at the Jet Propulsion Laboratory. He received his Doctor of Philosophy degree in Applied Mathematics in 1996 from the University of California at Irvine. Before becoming a faculty member in 1999, he spent three years as a Post-Doctorate fellow at the Center for Research in Scientific Computation, Raleigh, North Carolina, where he was the recipient of the 1997-1999 National Science Foundation Industrial Post-Doctorate Fellowship. He was an Assistant Professor in 1999, an Associated Professor in 2005, and became Full Professor in 2011. His research has been Computational Applied Mathematics with emphases in Control, Fluid Dynamics, Smart Material Structures and Telecommunications and Biomedical Engineering. He has published over 45 professionally refereed papers, including 17 mathematical and engineering journal articles. In 2002, Dr. Lee received the Outstanding Paper Award from the International Congress on Biological and Medical Engineering.

Chi-Wung Lau is a member of the Signal Processing Research group at Jet Propulsion Laboratories. He has been working at JPL for 15 years and has been involved with projects such as Galileo, Deep Impact, MER, Phoenix and MSL. Research areas of interest are 34 meter array tracking quantum communications, and link analysis. He received his bachelor's from U.C. Berkeley in 1996 and master's from the University of Southern California in 2001.