The Role of Margin in Link Design and Optimization

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Abstract— **Link analysis is a system engineering process in the design, development, and operation of communication systems and networks. Link models that are mathematical abstractions representing the useful signal power and the undesirable noise and attenuation effects (including weather effects if the signal path transverses through the atmosphere) that are integrated into the link budget calculation that provides the estimates of signal power and noise power at the receiver. Then the link margin is applied which attempts to counteract the fluctuations of the signal and noise power to ensure reliable data delivery from transmitter to receiver. (Link margin is dictated by the link margin policy or requirements.)**

A simple link budgeting approach assumes link parameters to be deterministic values typically adopted a rule-of-thumb policy of 3 dB link margin. This policy works for most S- and X-band links due to their insensitivity to weather effects. But for higher frequency links like Ka-band, Ku-band, and optical communication links, it is unclear if a 3 dB link margin would guarantee link closure.

Statistical link analysis that adopted the 2-σ or 3-σ link margin incorporates link uncertainties in the σ calculation. (The Deep Space Network (DSN) link margin policies are 2-σ for downlink and 3-σ for uplink.) The link reliability can therefore be quantified statistically even for higher frequency links. However in the current statistical link analysis approach, link reliability is only expressed as the likelihood of exceeding the signal-to-noise ratio (SNR) threshold that corresponds to a given bit-error-rate (BER) or frame-error-rate (FER) requirement. The method does not provide the true BER or FER estimate of the link with margin, or the required signal-to-noise ratio (SNR) that would meet the BER or FER requirement in the statistical sense.

In this paper, we perform in-depth analysis on the relationship between BER/FER requirement, operating SNR, and coding performance curve, in the case when the channel coherence time of link fluctuation is comparable or larger than the time duration of a codeword. We compute the "true" SNR design point that would meet the BER/FER requirement by taking into account the fluctuation of signal power and noise power at the receiver, and the shape of the coding performance curve. This analysis yields a number of valuable insights on the design choices of coding scheme and link margin for the reliable data delivery of a communication system – space and ground. We illustrate the aforementioned analysis using a number of standard NASA error-correcting codes.

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1. INTRODUCTION

In this paper, we discuss the role of margin in link design and optimization for links between a spacecraft and an existing communication network infrastructure.[1]

Link analysis is an indispensable system-engineering process used for sizing up the spacecraft communication system design and in planning for mission data return. The process is iterative in nature, and it is used in all phases of a mission lifecycle – from proposal phase through design, development, and operation phases. For space missions in the early mission phases, link analysis emphasizes finding the right spacecraft communication system components (e.g., antenna and power amplifier) that would meet the mission data return requirements. In later phases after the flight system design and mission operation concept are mature, link analysis is used to estimate the detailed data return profile of the mission.

Link analysis consists of the calculation and tabulation of the useful signal power and the interfering noise power available at the receiver. The signal and noise terms in the link equation are mathematical abstractions of the performance behavior expressed in decibels (dB), and by summing up these terms, one can generate an overall signal-to-noise ratio (SNR) estimate that can be used to characterize communication system performance, to support system design trade-off, and to manage the operational risks associate with the usage of a link. The goal of link analysis

[1] This refers to NASA's communication networks – Space Network, Near-Earth Network, and Deep Space Network.

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is to maximize the data throughput over a noisy channel, yet to maintain the integrity of the data.

One important consideration in link analysis is the allocation of link margin, which is a balancing act between data return and communication reliability. There are inherent uncertainties associated with the signal power (e.g., atmospheric attenuations) and the noise power (e.g., equipment noise and hot body noise) at the receivers. Link margin is defined as the additional SNR (in dB) that imposes on top of a given SNR design point to guarantee the link design would meet a given data integrity requirement, which is typically expressed in bit-error-rate (BER) or frame-error-rate (FER). The current link analysis approaches used by telecommunication engineers either adopt some rule-of-thumb link margin policy irrespective of the signal and noise statistics, or they compute a link margin quantity that addresses a different metrics, namely the probability of 'not closing the link', instead of computing the SNR that meets the given data integrity requirement.

In this paper, we quantify statistically the relationship between the BER/FER requirement, the operating SNR, and the coding performance curve. We compute the "true" SNR design point that would meet the BER/FER requirement by taking into account the fluctuation of signal power and noise power at the receiver, and the shape of the coding performance curve. We assume that no time diversity technique (e.g. interleaving) is used, and the channel coherence time of link fluctuation is comparable or larger than the time duration of a codeword length such that the time-fluctuation of the link does not get randomized or averaged out within a codeword. This analysis yields a number of valuable insights on the design choice of coding scheme and link margin for the reliable data delivery of a communication system – space and ground.

The rest of the paper is organized as follows: Section 2 provides an overview of current link analysis techniques. Section 3 describes the role of link margin and the subtleties in communication link design and optimization. We also outline the procedures to evaluate the link margin required to meet the BER/FER requirement by taking into account the fluctuation of signal power and noise power at the receiver, and the shape of the coding performance curve. Section 4 illustrates the methodology discussed in Section 3 using a number of NASA error-correction codes. Section 5 provides some observations and insights of the analysis, and the concept of "minimum margin". Section 6 discusses the concluding remarks and future work.

2. REVIEW OF LINK ANALYSIS TECHNIQUES

As the subject of link analysis, particularly the statistical link analysis, is not widely popular in the literature, we provide a brief overview on this topic to make the paper more "self-contained." Link analysis starts with the following link equation:

$$\frac{P_T}{N_0} = \frac{EIRP \cdot G/T}{k \cdot L_s \cdot L_o} \qquad (1)$$

where $\frac{P_T}{N_0}$ is the total power to noise power spectral density ratio, *EIRP* is the effective isotropic radiator power of the transmitter, *G*/*T* is the "Gain over System Noise Temperature" which is a measure of the receiver sensitivity, k is the Boltzmann's constant (1.38×10^{-23} J/K), $L_s = \left(\frac{4\pi d}{\lambda}\right)^2$ is the space-loss where d is the distance between transmitter and receiver, λ is the wavelength, and L_0 denotes all other losses and degradation factors not specifically addressed in equation (1).

The *EIRP* term includes all of the gain and loss terms on the transmission side including pointing loss, the *G/T* term includes all of the gain and loss terms on the receiver side, and the L_0 term includes contributions of the intervening transmission media. Note that the link equation (1) is multiplicative in nature. By taking the base-10 logarithm and multiplying by 10 on both sides of (1), we convert the multiplicative relationship of the gain and loss terms to become an additive relationship. The additive terms are expressed in units of decibels (dB). Equation (1) can therefore be re-written as

$$\frac{P_T}{N_0}(in\ dB) = EIRP(in\ dB) + G/T(in\ dB) - k(in\ dB) - L_s(in\ dB) - L_o(in\ dB) \qquad (2)$$

Depending on the link environment, the system noise temperature T in the *G/T* term sometimes includes a number of components that are additive, namely, the equipment noise temperature, the atmospheric noise, and the cosmic background noise, etc.

There are two major schools of thought on link analysis – the link budgeting approach and the statistical link analysis approach.

2.1 Link Budgeting Approach

The link budgeting approach assumes that the link parameters – the gain and loss terms of a link, are all single (deterministic values. The SNR at the receiver is computed by summing up the link parameters (in dB) along the signal processing chain as shown in equation (2). A rule-of-thumb margin policy, typically 3 dB, is then imposed to compute the supportable data rate for the given link design.

This approach is simple, and has been popular in the analysis of communication links that are not power constrained. The problems with this approach are as follows:

1. Some link parameters are inherently statistical, for example, polarization loss, antenna pointing loss, and different weather effects. By restricting the link parameters to be single-value, the worst-case values are typically chosen for use. This introduces a systematic bias in link analysis towards the pessimistic direction.
2. There is no mathematical and statistical justification for the choice of 3-dB margin policy (a factor of 2). Why is a 3-dB margin enough, or is 3-dB too much?

2.2 Statistical Link Analysis

The concept of statistical link analysis relies on the additive nature of the link equation as given in equation (2). Instead of treating the gain and loss terms (with units of dB) as deterministic values, the link parameters are treated as random variables.[2]

Yuen formulated the analysis framework of statistical link analysis in the 1970's [1]. Since then the Jet Propulsion Laboratory (JPL) has adopted this approach as a flight principle to conduct link analysis for its deep space missions. The JPL Projects and the Deep Space Network (DSN) measure the performance statistics of hardware components, and they conduct experiments to characterize the statistics of weather effects on the link. These statistical data are folded into the statistical link analysis process.

JPL's statistical link analysis methodology is summarized as follows: without loss of generality, we express the link parameters as x_i's. Each statistical link parameter x_i can be described in terms of a design value $x_{\text{design},i}$, a minimum value $x_{min,i}$ a maximum value $x_{max,i}$, and a probability distribution function (*pdf*) $f_i(x_i)$ such that that $f_i(x_i) \neq 0$ for $x_i < x_{,min,i} < \text{x} < x_{max,i}$ and $f_i(x_i) = 0$ for $x_i < x_{i,min,i}$ and $x_i > x_{i,\ max}$. Some common forms of $f(x)$ are the rectangular (or uniform), triangular, and Gaussian distributions.[3] From this setup, one can deduce the mean of x (denoted by m) and the variance of x (denoted by σ^2). Let's denote the design value $D_x = x_{design}$, and define the favorable tolerance $Fx = x_{max} - x_{\text{design}}$ and the adverse tolerance $A_x = x_{min} - x_{\text{design}}$. The computations of the mean and variance of the uniform, triangular, and Gaussian distribution are given in Figure 1.

Assume that there are n link parameters x_i's that are independent. The ensemble of these link parameters $z = \sum_i x_i$ has a mean $m_z = \sum_i m_{x_i}$ and a variance $\sigma_z^2 = \sum_i \sigma_{x_i}^2$. The *pdf* of z, which we denote as $f(z)$, can be computed by convolving $f_{x_1}(x_1), f_{x_2}(x_2), \cdots, f_{x_n}(x_n)$. This is in general a computationally intensive process as this involves $n-1$ levels of integration.

To simplify the computation, when a large number of independent link parameters are added together (in dB), Yuen proposed to approximate the resulting received signal-to-noise ratio term with a Gaussian distribution $N(m_z, \sigma_z^2)$, where m_z is the mean and σ_z^2 is the variance as defined above. From this, one can design a link and establish link margin policy based on statistical confidence level measured in terms of the σ of a Gaussian distribution function (e.g., 2-σ event, 3-σ event etc.).

Note that in general link parameters have different means, variances, and *pdf*'s; thus the above Gaussian approximation approach does not conform to the sufficient conditions of the classical Central Limit Theorem, which requires that all the link parameters be independent and identically distributed. The procedure outlined by Yuen [1] did not justify this Gaussian approximation in a mathematically rigorous manner, and it did not explicitly state the conditions under which this Gaussian approximation is valid. However decades of experience shows that for links where there are many link parameters, this approach works well in most cases and closely approximates the Gaussian distribution.

In [2], the author fills this gap by invoking a variant of the Central Limit Theorem known as the "Lyapunov's condition" that provides the sufficient condition for the aforementioned Gaussian approximation to be valid under the condition that the link parameters do not include one or more "dominant terms". A dominant term is one that has a variance that greatly exceeds the variances of the other terms.

[2] Some of the link parameters, like transmission power and antenna gains, can still be treated as deterministic values. Their pdf's are just Delta Dirac functions.

[3] Strictly speaking the Gaussian distribution is unbounded. In link analysis it is typically used to model certain weather effects or to model the combined effect of a number of link parameters (derived parameter).

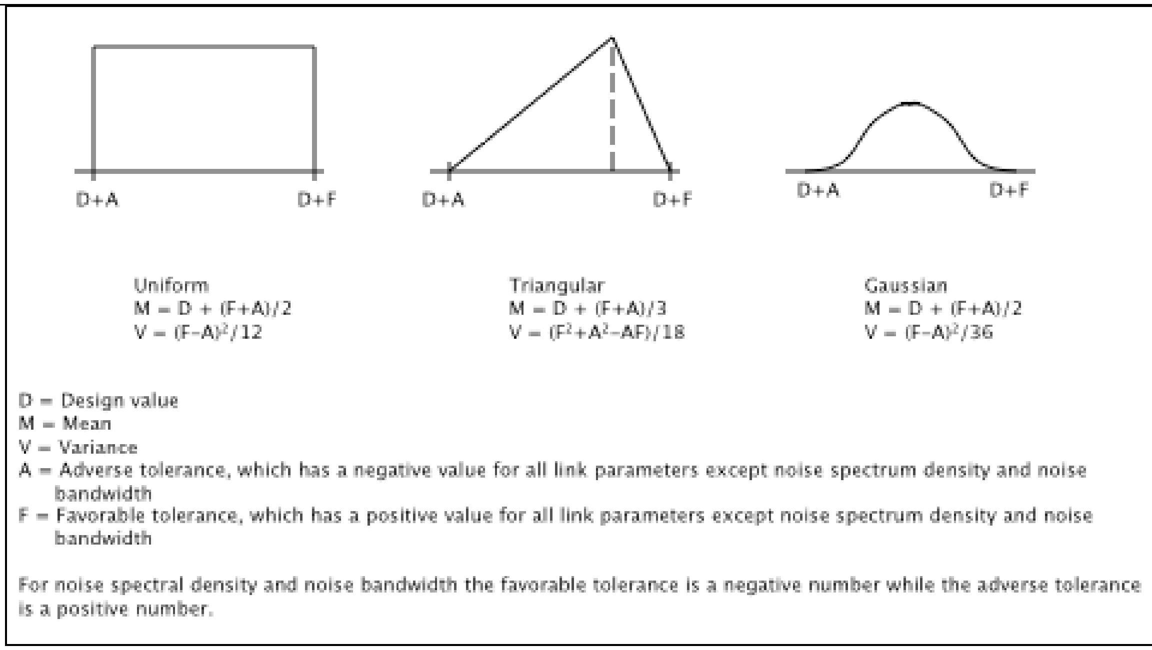

Figure 1. Conversions between Design, Favorable Tolerance, and Adverse Tolerance and Mean and Variance of Some Popular Probability Density Functions (from [1])

In [3], using sound statistical principles on Ka-band link analysis, the author describes a new technique that incorporates the dominant link terms in statistical link analysis by using a weighted sum of Gaussian distributions with the same variance and shifted means.

Thus, the current statistical link analysis approach expresses link reliability as the likelihood of exceeding the SNR threshold that corresponds to a given BER/FER requirement. The method, however, does not provide the true BER or FER estimate of the link with margin, or the required SNR that would meet the BER or FER requirement in the statistical sense.

3. Link Margin for Link Design and Optimization

In standard telecommunication system engineering, requirements on link design and link reliability are typically expressed in two parts: 1) tolerable error rate of received data, and 2) link margin policy of the link.

The tolerable error rate is typically expressed as BER or FER, and the choice is dependent upon the required quality of the received data. For example, uncompressed spacecraft telemetry data typically can tolerate a higher error rate, whereas compressed instrument data would require a lower error rate that minimizes error propagation [4]. Once the BER/FER requirement is established, a telecommunication system engineer would look up the SNR threshold value on the coding performance curve that delivers the required BER/FER. Now knowing that many link parameters are inherently statistical,[4] the received SNR can take on random values within a certain range about the SNR design point. To ensure link reliability, a link margin is imposed onto the link design such that the SNR operates at a value higher than the SNR threshold such that the likelihood that the SNR would dip below the SNR threshold is sufficiently small.

The standard approach to generate a coding performance data point is by simulating and/or emulating the processes of encoding a known information bit stream, sending the encoded symbols through a noisy channel representative of a given SNR, and decoding the received symbols back into the information bit stream. The original bit stream is then compared to the decoded bit stream to collect un-decodable errors that are used to estimate the code's error rate for the given operating SNR. As the confidence level in estimating the code's error rate depends on the number of error events, it takes more computation effort to generate data points at high SNR than at low SNR. Once a sufficient number of data points are generated, the data points are interpolated

[4] In link budgeting approach, the assumption that link parameters take on deterministic values (most likely worst-case values), and the need to adopt a link margin policy seem schizophrenic.

and/or sometimes extrapolated to form the coding performance curve. We denote this coding performance curve as $y = h(x)$, where x is the SNR (in dB).

However, during a communication session, signals can be attenuated by various unpredictable non-ideal operation effects and natural phenomena, and different random noises can be added to the receiver, the received SNR at the receiver is in fact a random variable.

Without loss of generality, we denote the distribution of the received SNR to be $f(x \mid .)$. In Section 2 and in References 1–2, we show that this SNR fluctuation can be modeled as a Gaussian process when there is no dominant component in the link. In this case the SNR distribution can be expressed as

$$f(x \mid m; \sigma) = \frac{1}{\sqrt{2\pi}\sigma} e^{\frac{(x-m)^2}{2\sigma^2}} \qquad (3)$$

where m is the mean of the link parameters (in dB) and σ is the standard deviation. Also m is the maximum likelihood estimate of the SNR in the Gaussian case, so m is chosen to be the SNR design value that the link analysis is based on.

When there are one or more dominant components, and when empirical measurements for each of the dominant components exist, we show in [3] that the SNR fluctuation can be modeled as a sum of Gaussian with shifted means. Using the same notations as in [3], for a given weather availability cumulative distribution CD, where $10 \le CD \le 99$%, we define the discrete random variable L_D with a finite set of values $\{l_{10}, l_{11}, \cdots l_{CD}\}$ with probability $\{P_{10}, P_{11}, \cdots P_{CD}\}$, where l_i corresponds to the i-th percentile value of the total weather loss $L_{tot}^{dB}(\theta)$, where θ is the elevation angle of the ground antenna, and m and σ are the mean and standard deviation respectively of the link parameters excluding the weather effects. In this case $P_{10} = \frac{10}{CD}$, and $P_i = \frac{1}{CD}$ for $10 \le i \le CD$%.

The SNR distribution can be expressed as $f(x \mid m; \sigma; L_D) = \sum_{i=10}^{CD} P_i \frac{1}{\sqrt{2\pi}\sigma} e^{\frac{(x-m-l_i)^2}{2\sigma^2}}$. For this non-Gaussian case, there is no simple analytical way to find the value of x that maximize $f(x \mid m; \sigma; L_D)$, or to show that if $f(x \mid m; \sigma; L_D)$ is uni-modal at all. A reasonable SNR design point would be $\hat{m} = m + \bar{l}$, where $\bar{l} = \sum_{i=10}^{CD} P_i \, l_i$. Re-writing $f(x \mid m; \sigma; L_D)$ the SNR distribution can be expressed as

$$f(x \mid \hat{m}; \sigma; L_D) = \sum_{i=10}^{CD} P_i \frac{1}{\sqrt{2\pi}\sigma} e^{\frac{(x-\hat{m}+\bar{l}-l_i)^2}{2\sigma^2}} \qquad (4)$$

In the subsequent sections, we will evaluate the mean error rates for link variations typical for S- and X-bands (σ = 0.5 and σ = 1.0) and for Ka-band (σ = 1.5). To simplify the discussion for Ka-band, we will use the Gaussian approximation Equation (3) instead of the more complicated expression in Equation (4) that requires statistics of local weather loss measurements.

By averaging the error rate $h(x)$ over the distribution $f(x \mid m; \sigma)$, the mean error rate $\bar{e}(x, \sigma)$ for a given SNR design point x is given by

$$\bar{e}(x, \sigma) = \int_{-\infty}^{+\infty} h(y) f(y \mid x;\ \sigma) dy \qquad (5)$$

We will demonstrate by examples in the next section that $\bar{e}(x, \sigma) \ge h(x)$ for all x. Or equivalently we can say that for a given error rate ε and SNR's s_1 and s_2 such that ε = $h(s_1) = \bar{e}(s_2, \sigma)$, $M = s_2 - s_1$ is the additional SNR, or the minimum margin, required on top of the ideal SNR design point to guarantee that the link design would meet the given error rate requirement ε. We will discuss this concept in more detail in Section 5, using the link-adjusted coding performance curves generated in the next section (Section 4) for some NASA codes.

4. Examples

We use equation (5) in Section 3 to evaluate the link-adjusted error rate curve $y = \bar{e}(x, \sigma)$ for a number of popular error-correcting codes[5] that are used for NASA missions, and investigate the minimum margin required to meet an error rate requirement typical of each code:

[5] The analytical expressions of the ideal link performance curves $h(x)$'s are derived from an informal JPL student report by Adrienne Lam, a former intern student.

a) (7, ½) convolutional code, BER = 10^{-5}.

b) Concatenated code ((255, 223) Reed-Solomon Code and (7, ½) convolutional code, ideal interleaving), BER = 10^{-5} and BER = 10^{-7}.

c) Low-Density Parity Check (LDPC) (1024, ½) code, BER = 10^{-5}.

For each of the code, we compute the $\bar{e}(x,\sigma)$ for the following cases:

a) σ = 0.0 – the ideal case of traditional error rate curve assuming no SNR variation.

b) σ = 0.5 – the typical SNR variation for DSN S- and X-band links.

c) σ = 1.0 – the typical SNR variation for non-DSN S- and X-band links.

d) σ = 1.5 – the typical SNR variation for Ka-band links.

The results are shown in Figures 2, 3, and 4.

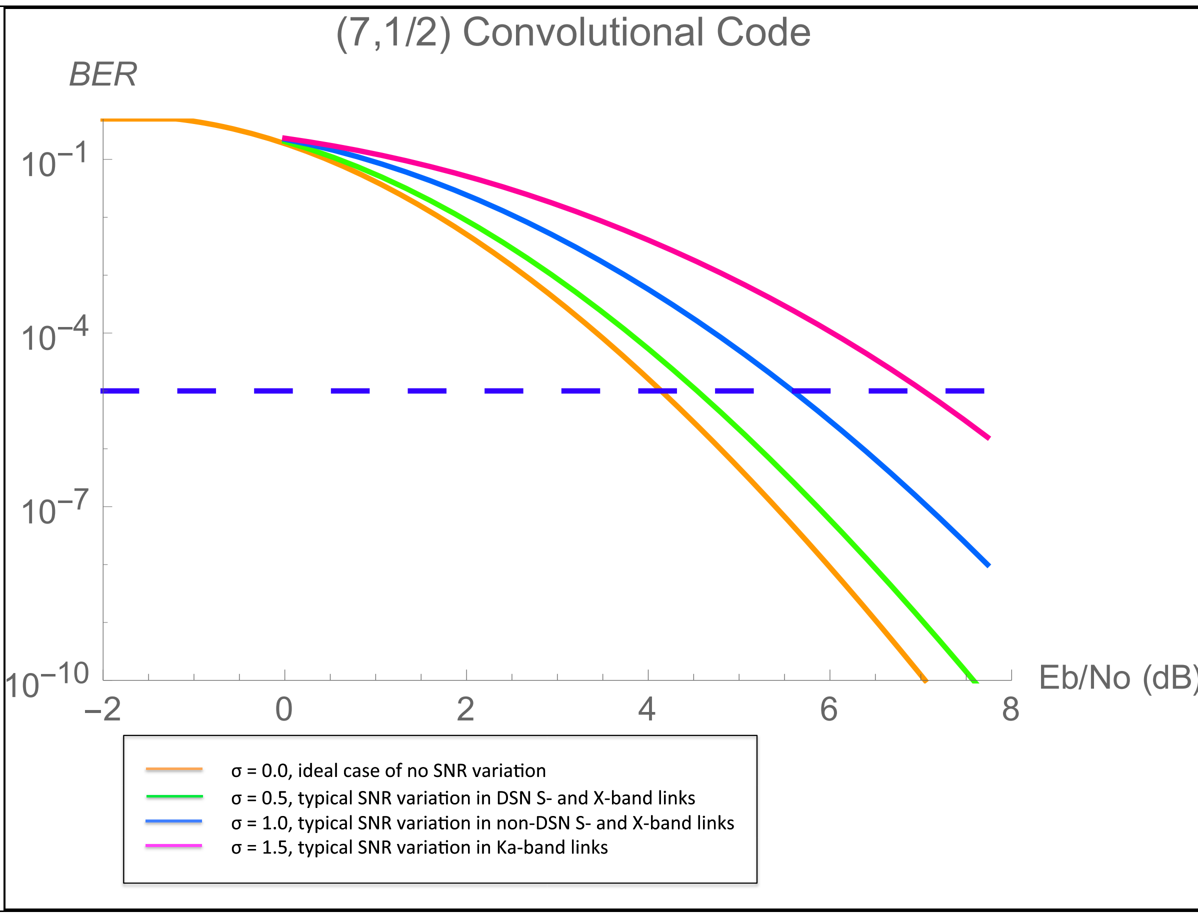

Figure 2. Comparison of Error Rate Performances for the (7, ½) Convolutional Code Under Different SNR Variations

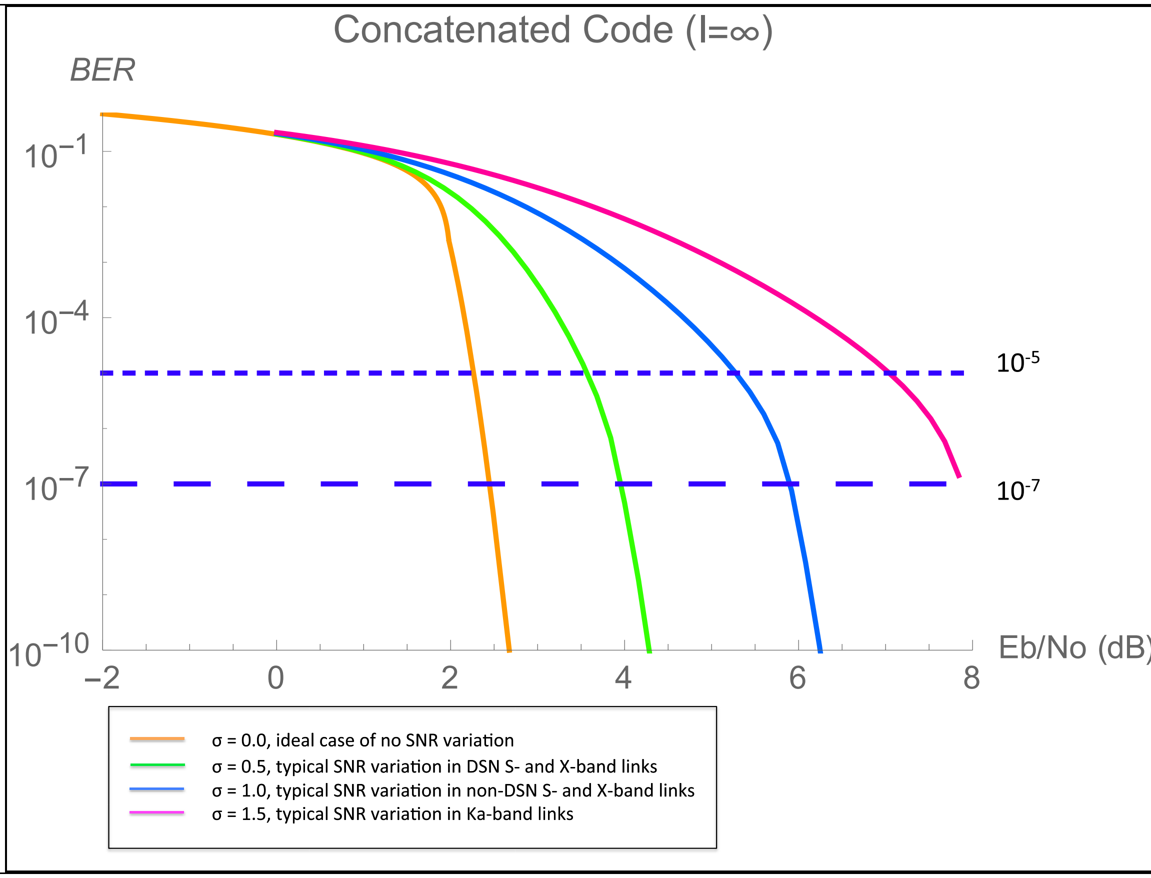

Figure 3. Comparison of Error Rate Performances for the Concatenated Code Under Different SNR Variations

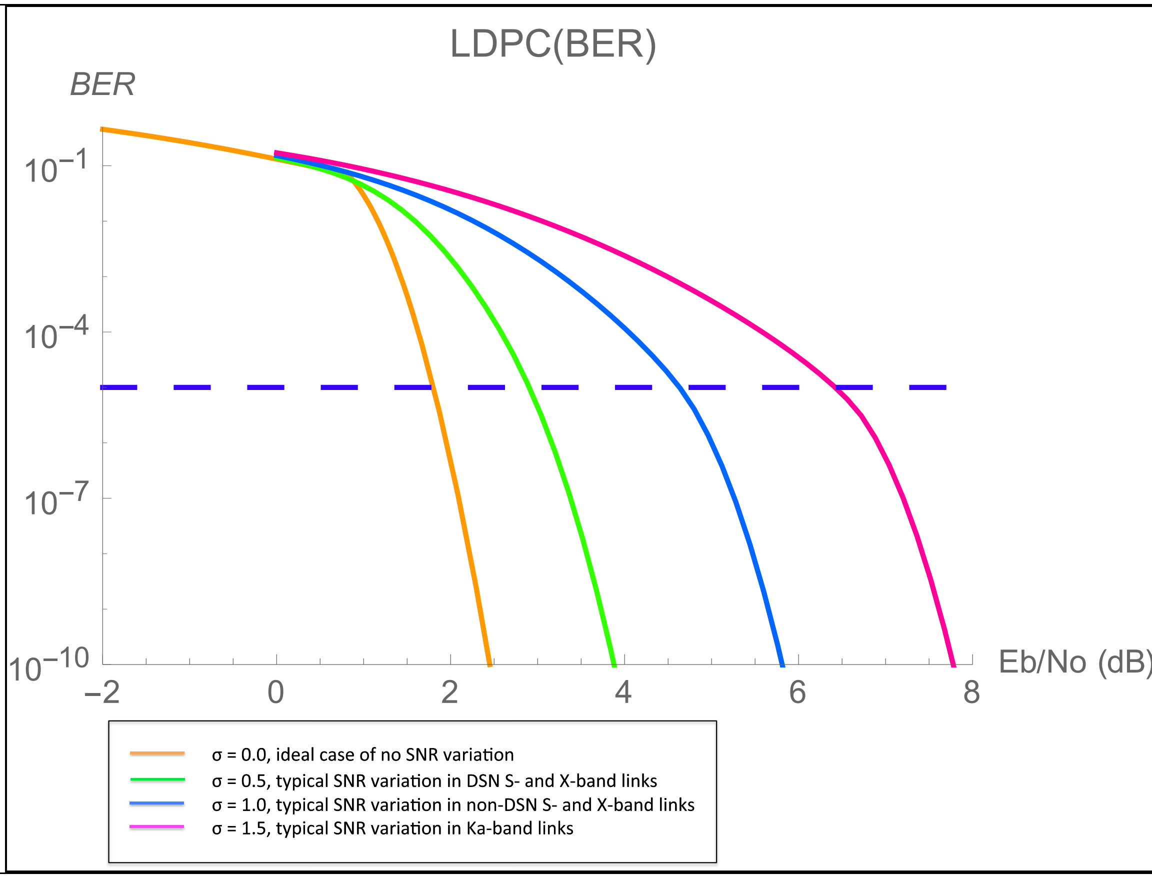

Figure 4. Comparison of Error Rate Performances for the LDPC (1024, ½) Code Under Different SNR Variations

5. ANALYSIS INSIGHTS AND CONCEPT OF "MINIMUM MARGIN"

The link-adjusted coding performance curves in Figures 2, 3, and 4 reveal a number of interesting and important behaviors when compared to the ideal error rate curves that assumes no SNR variation:

a) *The link-adjusted coding performance curves are always inferior compared to the ideal error rate curve for the same code.* This can be explained as follows. An ideal "waterfall" error rate curve of a reasonable code has a shape that concaves downward in an error rate (in log scale) versus SNR (in dB) plot. As the error rate is expressed in log scale and the SNR variation is symmetric about the SNR design point for the Gaussian distribution, the link-adjusted mean error rate $\bar{e}(x,\sigma)$ is more biased by the higher error rate on the left side of the SNR design point. This results in a higher mean error rate for the same SNR design point as shown in Figures 2, 3, and 4.

b) *A powerful code typified by a steep slope in the code performance plot is more sensitive to SNR variation, thus losing more coding gain compared to an average code.* This follows the same reasoning in a) that the link-adjusted mean error rate $\bar{e}(x,\sigma)$ can be a lot more biased by the higher error rate on the left side of the SNR design point for a coding performance curve with a steep slope. For example, to compensate for the SNR variation of σ = 1.5 for a BER requirement of 10^{-5}, Figure 4 shows that the powerful LDPC (1024, ½) code relinquishes a coding gain of 4.6 dB compared to the constant SNR case. Conversely, Figure 2 shows that the modest (7, ½) convolutional code only requires 2.8 dB. Thus, for high SNR variation scenario likes Ka-band, the LDPC (1024, ½) code is only better than the (7, ½) convolutional code by 0.6 dB in coding gain, and the coding gain of the concatenated code is the same as that of the convolutional code.

c) It takes more coding gain to compensate for the SNR variation in the link at lower error rate. As shown in Figures 2, 3, and 4, the link-adjusted coding performance curves all fan outward in the direction of lower error rate. In the case of the concatenated code in Figure 3, it takes 4.8 dB of coding gain to compensate for the link SNR variation σ = 1.5 at BER = 10^{-5}. Whereas in the case of BER = 10^{-7}, the loss in coding gain is 5.4 dB.

d) *The link budget's rule-of-thumb margin policy of 3 dB or the statistical link analysis' margin of 2 σ may not be enough for links with large SNR variation in the link.* In the case of concatenated code operating at BER = 10^{-7} as shown in Figure 3, the additional SNR required to compensate for σ = 1.5 is 5.5 dB. For the LDPC (1024, ½) code operating at BER = 10^{-5}, the additional SNR required is 3.6 dB.

The above examples illustrate the concept of using additional SNR (in dB) to compensate for the SNR variation in the link, so as to maintain the same link reliability as promised by the ideal coding performance curve. We can view this additional SNR to be the "true" margin or the "minimum" margin required to offset the "known unknowns" of the link. This "minimum" margin is particularly profound in links with large SNR variation like the Ka-band links. An in-depth understanding on the relationship between coding gain, required "minimum" margin, and SNR variation of a link is particularly important in the optimal design and efficient operation of a reliable Ka-band link.

The above results also provide some guidance on the operation of a dynamic link:

a) During the Mars Reconnaissance Orbiter (MRO) Ka-band operation experiment between August 2005 and March 2006, it was observed that the measured symbol SNR (Es/No) variation is a lot higher during the rise and set of a pass [4].[6] This is due to the longer signal path that traverses through the atmosphere at low elevation angle. Another observation in the Ka-band operation experiment is that the ratio between X-band link variation and Ka-band variation is about 1:4,[7] and this compares well with the analytical results of typical σ value of 0.5 dB for DSN X-band links, and 1.8 dB for DSN Ka-band links. Thus for Ka-band a higher link margin might be needed at the beginning and the end of a pass than the margin in the middle of a pass.

b) For communication system with Variable Coding and Modulation (VCM) capability that adapts to the dynamic link environment, one needs to take into account the SNR variation in addition to the mean SNR to determine the

[6] See Figures 11 and 13 of Ref. 4.

[7] Private communication with Shervin Shambayati.

choice of the data rate, coding scheme, and modulation scheme.

6. Concluding Remarks and Future Work

In this paper, by taking into account the fluctuation of signal power and noise power at the receiver, and the shape of the coding performance curve, we generate the link-adjusted error rate curve $y = \overline{e}(x, \sigma)$ for a number of popular error-correcting codes that are used for NASA missions. The link-adjusted coding performance curves reveal a number of interesting and important behaviors when compared to the ideal error rate curves that assumes no SNR variation. The results suggest some deviations from the "traditional wisdom" in the design and operation of a link, particularly for the links with large SNR variation like the Ka-band links.

Next we plan to investigate different communication system design techniques to mitigate the effects of SNR fluctuation in a link:

a) For communication applications that have stringent time-delay requirements (e.g. real-time audio and video links), we plan to consider code design that is robust against SNR variation. Tradition good code typical has a "waterfall" curve that is relatively flat at high error rate at low SNR, but the error rate drops off rapidly at some reasonable SNR. As shown in Sections 4 and 5, that the additional SNR requires to compensate the SNR variation outweighs the coding gain. For dynamic links, a better code design is one that has a more graceful degradation in the low SNR regime.

b) For links that can tolerate high latency, we plan to investigate using time-diversity techniques like interleaver and randomizer to "average out" the SNR fluctuation in a link. The depth of time-diversity schemes is dependent upon the channel coherence time of link fluctuation, and the statistics can be obtained from existing Ka-band propagation experiments.

c) We plan to investigate using Automatic Repeat request (ARQ) protocol to deal with the fast fading effects of Ka-band links. It was shown in [5] that ARQ protocol can "buy back" SNR by operating in a higher error rate regime. We will compare the link performance and latency performance of the ARQ approach versus the time-diversity approach as discussed in b).

Acknowledgement

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BIOGRAPHY

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