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Bit Error Rate and Frame Error Rate Data Processing for Space Communications and Navigation-Related Communication System Analysis Tools

Victor Christopher A. Ong and Bryan W. Welch
Glenn Research Center, Cleveland, Ohio

June 2019

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Summary

One of the capabilities that the Space Communications and Navigation (SCaN) Strategic Center for Networking, Integration, and Communications (SCENIC) user interface (UI) web application intends to provide its users is the addition of network protocol and link encryption augmentations of communication system analyses. Before any of these analyses capabilities can be modeled, the simulations of bit error rate (BER) and frame error rate (FER) against signal-to-noise ratio (SNR) have been conducted, requiring parameters from several known coding types (low-density parity-check (LDPC), convolutional, etc.), signal modulations (binary phase shift keying (BPSK), quadrature phase shift keying (QPSK), etc.), coding rates (1/2, 1/3, etc.), and frame sizes (1,280, 3,580, etc.). However, in order to extract useful information from the results of these simulations, a curve fitting technique has been applied to each resulting dataset to extend and extrapolate the curve fit of BER and FER down to 10^{-30} using MATLAB® Curve Fitting Toolbox™ (The MathWorks, Inc.). This is a necessary step because simulations of BER and FER were only performed to around 10^{-9} due to the extensive simulation time that would be required to obtain significant simulation results at the error levels desired. Furthermore, the fitted curve results were applied to a finer resolution for the SNR at 0.01-dB interval instead of the 0.05-dB interval limitation used in the simulation. All the possible combinations of the coding types, signal modulations, coding rates, frame sizes, and the extension of BER and FER curves would enable users to capture a wide range of link performances that directly relates to the addition of higher level networking data encapsulated in a frame. The curve fitting results also led to the modeling of the optical link error rate performance by solving for coding gain, FER_BER SNR delta, coded optical BER-SNR, and coded optical FER–SNR.

Introduction

In the past, designing any new space communication architecture involved separately modeling the Space Communications and Navigation (SCaN) networks, which comprise the Near Earth Network (NEN), Space Network (SN), and Deep Space Network (DSN). Individual missions commonly perform analysis pertaining to the usage of these networks, but this is costly, duplicative, and subject to inconsistencies due to misunderstandings of the functionalities of these various networks. Therefore, the SCaN Strategic Center for Networking, Integration, and Communications (SCENIC) was chartered to develop a web-based system called SCENIC user interface (UI) to accomplish an integrated space communication architecture that would be easily available NASA-wide and to the desired customers (https://scenic.ndc.nasa.gov/).[2] One of the capabilities that will be included in the SCENIC UI web application is the addition of network protocol and link encryption augmentations of communication system analyses, intended for release version 3.3. The objectives of this project are to perform curve fitting for all the bit error rate (BER) and frame error rate (FER) simulation dataset results and be able to extract this information such that modeling the aforementioned capabilities could be done in the subsequent phases of the project.

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[1]Fall Intern in Lewis' Educational and Research Collaborative Internship Project (LeRCIP), undergraduate at California State University Long Beach.
[2]Website has restricted access, requiring NASA identity and approved NAMS request.

Background

In radio transmission, the signal containing the information modulates the carrier wave, which is converted to electromagnetic field for propagation to the desired destination (Ref. 1). The transmitted signal is not always received error free due to the noise associated with temperature, sky noise (e.g., atmosphere, etc.), system nonlinearities, and interference from other systems. In digital communications, the probability of error is normally expressed in terms of BER, the ratio of the bits received in error to the total count of bits received, or FER, the ratio of frames received in error to the total count of frames received. In addition, the ratio of signal power to noise power (a.k.a. signal-to-noise ratio (SNR)) can be used to measure the system performance based on the required level of BER and FER; for this project, both are functions of coding type, signal modulation scheme, coding rate, and frame size. Moreover, in the field of digital communications, most probability error curves illustrate a waterfall-like shape, as shown in Figure 1. This curve describes the error probability of the system's performance in terms of the available SNR (Ref. 1). If a model system requires a certain SNR, that model system's performance can be distinguished separately from another. This is because the smaller the required SNR for a given error rate, the more efficient is the system's modulation and detection process for a given probability error and vice versa (Ref. 1). Once a modulation scheme has been chosen, the requirement to meet a particular error probability dictates a particular operating point in the curve; that is, the required error performance dictates the value of SNR that must be made available at the receiver in order to meet that performance. The process of trade study between error probability and the required SNR and vice versa falls under link analysis. The primary purpose of a link analysis is to determine the actual system operating point and to establish that the error probability associated with that point (at certain SNR) is less than or equal to the system requirement (Ref. 1). The result that would come out of the link analysis is called the link budget. The link budget presents a concise set of information related to the system design and performance. For instance, one component found in link budget is the link margin, which shows whether a particular model system meets the requirement by a high margin, within the margin, or below the margin.
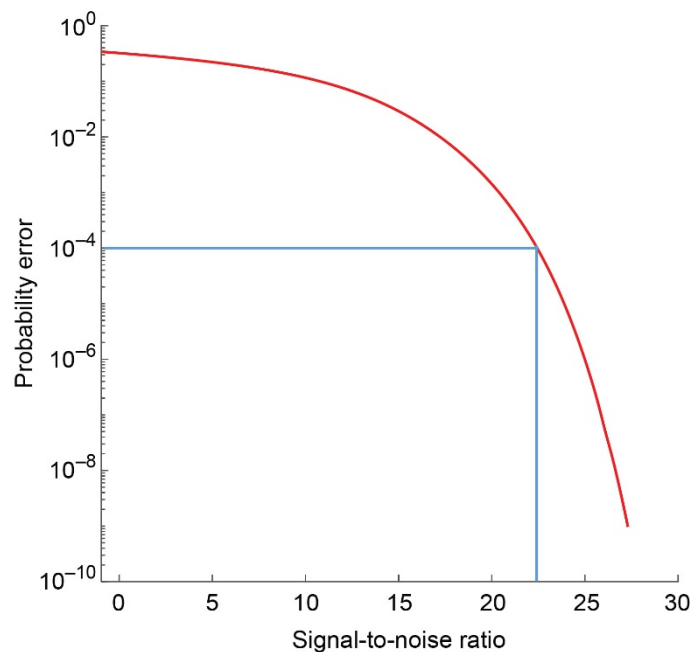

Figure 1.—Probability error versus signal-to-noise ratio.

As mentioned previously, signal modulation is one of the important parameters in the simulation of BER and FER for a given SNR. It is the process of varying the properties (a.k.a. modulating) of a periodic waveform, such as a sinusoid called a carrier wave (Ref. 1). The simulation that is referred to in this report utilizes binary phase shift keying (BPSK), quadrature phase shift keying (QPSK), eight phase shift keying (8PSK), 16 amplitude and phase shift keying (16APSK), 32 amplitude and phase shift keying (32APSK), and 64 amplitude and phase shift keying (64APSK) signal modulation schemes, which will not be covered in much detail except that as the number of modulation order increases (i.e., $B = 2$ and $Q = 4, 8, 16, 32,$ and 64), the data rate also increases but at the expense of the signal becoming more susceptible to noise or error. To illustrate, look at the vector view of BPSK, QPSK, and 8PSK signaling in Figure 2. In Figure 2(a), the binary antipodal signal vectors, S_1 and S_2, at 180° apart with a decision line (DL) that divides the signal space into two regions. Notice that the noise vector, N, is equal to that of the signal vectors. This indicates the minimum magnitude of noise energy that would cause the signal detector to make a symbol error (Ref. 1). In Figure 2(b), there are four signal vectors ($Q = 4$) at 90° apart divided into four regions by two DLs. Notice that the magnitude of the noise vector is smaller in comparison to the case in Figure 2(a). This means that the minimum magnitude of the noise vector, N, that would cause the detector to make a symbol error is even lower. Finally, in Figure 2(c) for 8PSK, there are eight signal vectors with four DLs dividing the signal space into eight regions. The minimum magnitude of noise vector N in this case is even lower, hence the most vulnerable to error among the three cases. Although higher modulation order suggests poor error performance, there is a tradeoff, which is a higher data rate, as represented by the number of signal vectors.

What if one could model the same cases as above but with higher threshold for error? One solution is increasing the signal power, which can be illustrated by lengthening of the signal vectors, and thus lengthens the noise vector. To clarify, this leads to an improved bandwidth performance and error performance at the expense of higher SNR.

Another important parameter in the simulation of BER and FER is the coding type or coding scheme. Coding scheme is an error-correcting code (ECC) where error performance (in terms of SNR) is improved in the presence of noise, but at the expense of additional bits needing to be transmitted with the data message, therefore increasing the bandwidth of the signal. The known ECC used on this project includes low-density parity-check (LDPC), convolutional, Reed-Solomon, concatenated Reed-Solomon, turbo, Digital Video Broadcasting-Satellite-Second Generation (DVB-S2), and Bose-Chaudhuri-Hocquenghem (BCH).
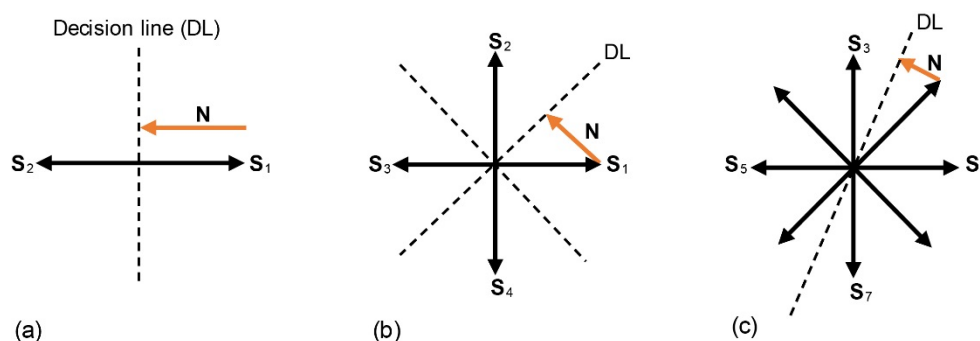

Figure 2.—Signaling vector view modulation schemes. (a) Binary phase shift keying. (b) Quadrature phase shift keying. (c) Eight phase shift keying.

In the real world, any two nodes in a network operate and exchange information encapsulated in a basic unit called a frame. A single frame is a collection of bits. The basic frame anatomy consists of a header (preamble and addresses), data field (payload), and trailer (frame checking and postamble), as shown in Table I. For instance, Figure 3 shows an Ethernet network frame segmented with size information in terms of bytes (1 byte = 8 bits).

The important point of Figure 3 is the data field of the frame. The data field may contain network-level information such as network protocols, routing protocols, link encryption, and other higher Open Systems Interconnection (OSI) layer level connection information and user data encapsulations. For instance, one of the capabilities intended for this effort is the network routing path update. It is the capability of the network to dynamically update network path information in the event of network connection losses due to line-of-sight blockages and/or connection degradation where alternate routes can be utilized to minimize network interruptions. This can be illustrated in Figure 4, where shortest path is chosen first among all the possible paths, and Figure 5, where an alternate path is activated because network connection loss occurred from an asteroid blockage. Another important capability is the routing protocols that can be employed and analyzed such that end-to-end network transmission is guaranteed.

Fundamentally, a frame is transmitted successfully if all the bits that composed it are successfully received during the transmission, otherwise it is dropped. That is, a single bit error in a frame would mean a frame loss. As a result, dropped frames cause network degradation whether a single bit is in error or a multiple of it. That is why BER data is not enough to capture and analyze a wide range of link performance when dealing with actual data transmission in the form of frames. Instead, data coming from FER would give a more stringent test as it requires that more correct bits per frame to be analyzed. This is especially important as more and more overheads are added and encapsulated on data frames when modeling network protocols and other higher level network information. The process to obtain FER data, however, is computationally expensive and requires a great deal of time during simulation compared to BER. Due to the time constraint, a technique to extend and extrapolate BER and FER data can be incorporated to account for all the possible performances as SNR is varied.

TABLE I.—BASIC FRAME ANATOMY

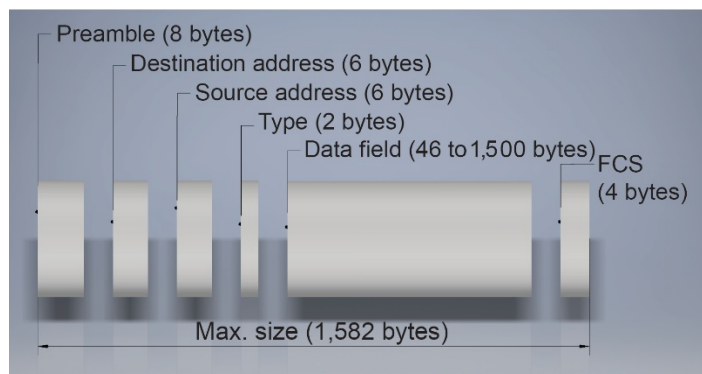| Header		Data field (payload)	Trailer	
Flag (01111110)	Address field		FCS[a]	Flag (01111001)

[a]Frame check sequence.

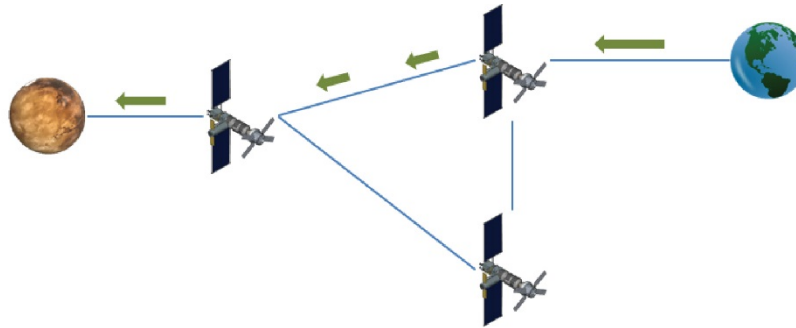Figure 3.—Ethernet frame, where FCS is frame check sequence.
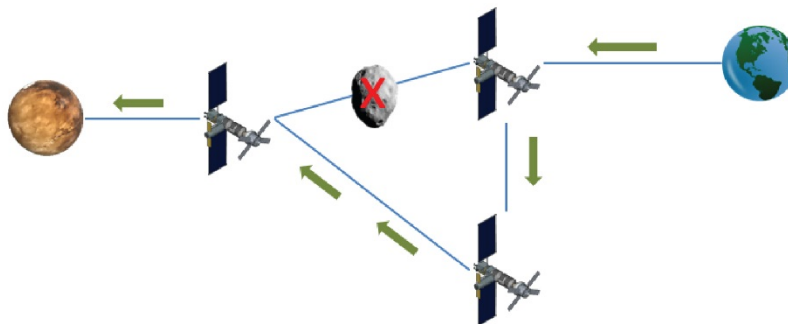
Figure 4.—Network path update: shortest path first.

Figure 5.—Network path update: alternate path.

Methodology

The following subsections will cover the concepts and steps taken to fulfill the objectives of this project.

Curve Fitting

Curve fitting examines the relationship between one or more predictors (independent variables) and a response variable (dependent variable), with the goal of defining a best-fit model of the relationship (Ref. 2). It is one of the most powerful and widely used tools in science and engineering when dealing with data. Therefore, it is also an integral part of processing the raw data that comes out of the BER and FER simulations. Note that curve fitting will be applied to both BER and FER raw data, but for the purposes of being concise and since the exact same processes apply to both, most figures only illustrate the FER. MATLAB® (The MathWorks, Inc.) and the MATLAB® Curve Fitting Toolbox™ will be used to accomplish tasks related to curve fitting, data archival, and data extraction and manipulation.

Figure 6 illustrates one of the raw datasets in which simulation parameters are also listed. The data are not smooth around the shoulder, as shown by scattered points. The data show an inflection point and outward flaring toward the lower FER values. The raw data may follow the general waterfall-like shape but lack smoothness and monotonic decrease in error rate as SNR increases. In addition, the data lack finer resolution and end somewhere between 10^{-5} and 10^{-6} FER values. These data are not very useful in the analysis unless processed and fitted as shown in Figure 7.

In Figure 7, the curve fit overlays the raw data to obtain the best possible fit and extended to 10^{-9} FER. This extension is computationally possible but at the expense of time. For this internship and for the time period necessary to implement the capabilities associated with the data obtained from the simulations, this extension and final extension must be done. The fits found in the MATLAB® Curve Fitting Toolbox™ that conform well to the general waterfall-like shape of the error curves are Smoothing Spline, Polynomial, and Gaussian. Since variation in data points exists per dataset, trial and error is necessary for the task.
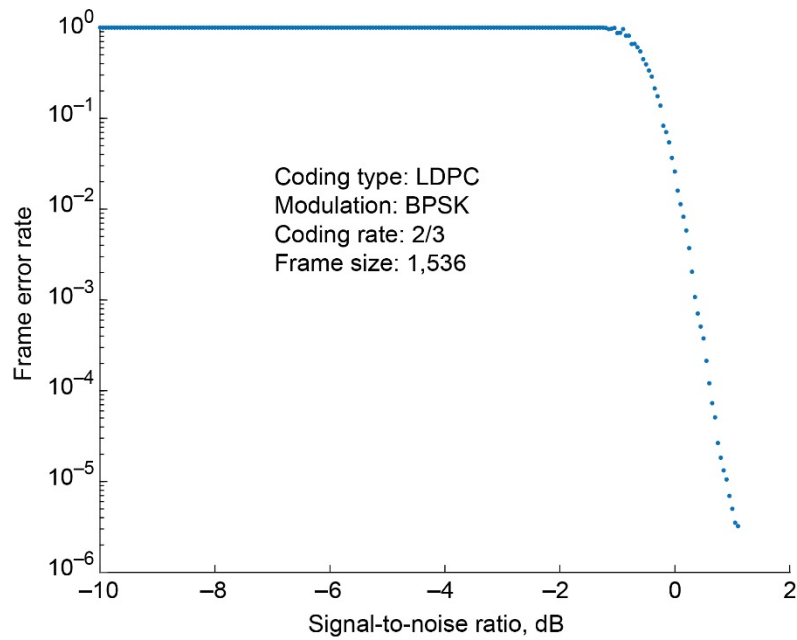
Figure 6.—Plotted raw data of frame error rate versus signal-to-noise ratio (raw data), where BPSK is binary phase shift keying and LDPC is low-density parity-check.
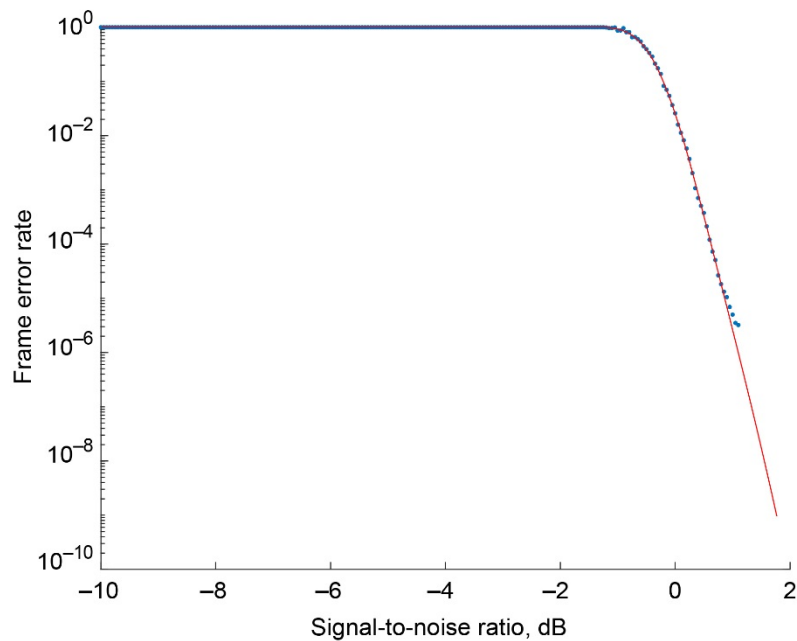

Figure 7.—Curve fit overlays raw data and extended to 10^{-9} for frame error rate versus signal-to-noise ratio.

The last and final step in the curve fitting is the extension of the curve from 10^{-9} to 10^{-30} FER as shown in Figure 8, which makes this dataset consistent with potential BER values from prior versions of this capability. This curve can be obtained using the MATLAB® Polynomial fit function of second degree.

The process to generate the curve fit utilized the following steps:

(1) Load the BER simulation result for the simulation to be processed (usually contained in the .mat file).
(2) Prepare the name of the data for archival usually following file naming convention codingType_modulation_codingRate_frameSize.
(3) Obtain the raw FER and SNR from the simulation result contained in the .mat file.
(4) Convert FER to common logarithmic scale (10log10() function).
(5) Open MATLAB® Curve Fitting Toolbox™ and select SNR for the x-axis and FER for the y-axis.
(6) Apply curve fit using either Smoothing Spline, Polynomial, or Gaussian and ensure that the curve monotonically extends downward past 10^{-9}.
(7) Once satisfied with the curve meeting the monotonically decreasing requirement (while maximizing the correlation) save the fitted model from the toolbox to the workspace and apply SNR as the input to the saved fitted model (usually fittedmodel(SNR)).
(8) The result of step (7) must be converted to base 10 (i.e., 10 .^ (fittedmodel(SNR)/10)).
(9) Truncate the fitted FER result to 10^{-9} and save the results to new .mat file for compilation.
(10) Plot the fitted FER versus SNR.
(11) To extend the curves beyond the initial extension, apply Polynomial fit of second degree to the existing curves and truncate to desired minimum error rate (10^{-30} for this project).
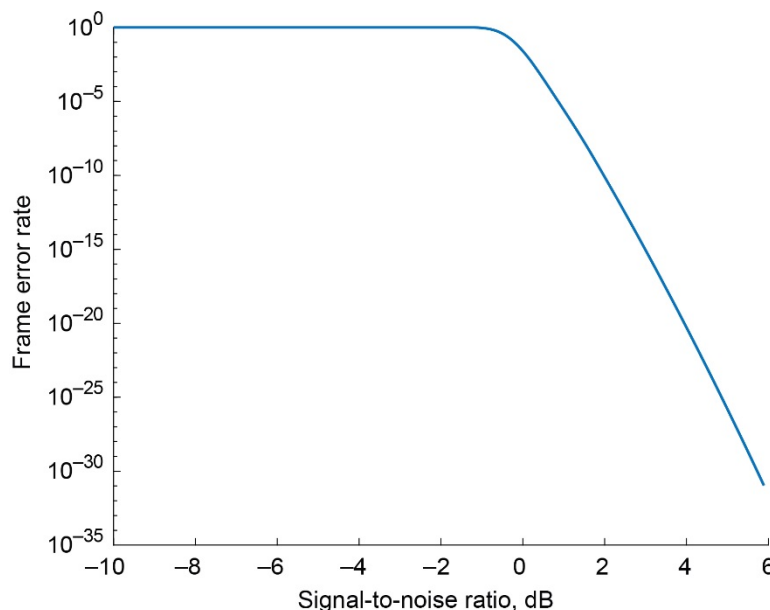

Figure 8.—Curve fit extended from 10^{-9} to 10^{-30} for frame error rate versus signal-to-noise ratio.

Data Archival, Search Routines, and Data Extraction

For archival purposes and as part of the curve fitting process, the processed dataset (curve fitted dataset) must follow a naming convention such that consistency is maintained across other processes employed in data extraction and search routines. The naming convention contains coding type, signal modulation, coding rate, and frame size. The actual name should appear as the previously enumerated components but separated by underscore, that is, codingType_signalModulation_codingRate_frameSize. For instance, a dataset with coding type of LDPC, signal modulation of BPSK, coding rate of 2/3, and frame size of 1,536 should be named LDPC_BPSK_2x3_1536. By having this information in the data name, the parameters used in the simulation of a particular dataset and the properties that relate to it can be easily identified.

Once a consistent naming convention is established, search routines or programs that access the data contained in the processed datasets (curve fits) can be employed, hence the data extraction. The routines involve loading the compiled datasets, searching for the desired named dataset, and extracting the SNR, BER, and FER data. However, the BER and FER data are not uniform in length and are tied to particular values of SNR. To use these contained data effectively, one dimension interpolation must be utilized. For a given BER or FER the specific search SNR routine must be able to output the correct SNR. Likewise, for a given SNR the specific search BER and/or FER routine must be able to output the correct BER and FER. Other information can also be output from search routines such as the coding type, signal modulation, coding rate, raw frame size, modulation index, and compression.

Radio Frequency (RF) Data Expansion to Optical Link

The simulations and the obtained data that are mentioned in the previous sections only pertain to RF transmission. However, SCENIC UI also covers analysis related to optical link transmission. So far, the available optical link data are based on theory and reasonable assumptions, which do not have definite set of standards compared to RF (Ref. 3). Rather, optical link data only contain theoretical BER of uncoded modulation schemes against the optical SNR and do not contain data pertaining to FER. To derive the coding counterpart of the RF in the optical link, the coding gain and FER_BER SNR delta can be calculated from the data obtained in the RF simulations. Afterward, other calculations can be made, which become the coded optical SNR BER and coded optical SNR FER.

Coding Gain (*CG*)

Coding gain is a performance metric where the difference in SNR (in decibels) is obtained between a nonerror-correcting code system and an ECC system required to meet the same BER. The implication of the coding gain result is that the higher the value, the more efficient the coding scheme. To calculate for the coding gain, a discretized BER will serve as an input such that for the same BER, and the corresponding SNRs can be obtained by interpolation on both uncoded and coded system. After the interpolation step to ensure the same BER inputs, direct subtraction of the results can be performed. In general, Equation (1) calculates for coding gain. Note that this project only accounts for BPSK signal modulation for every coding type, coding rate, and frame size.

$$CG_{BER} = \text{SNR}_{\text{uncoded, BPSK}} - \text{SNR}_{\text{coded, BPSK}} \tag{1}$$

FER_BER SNR Delta

As mentioned briefly in the beginning of this subsection, FER data do not exist for optical link in the current SCENIC capabilities. However, by taking the difference between the SNR for BER and SNR for FER of the same coding type, signal modulation, coding rate, and frame size, the resulting FER_BER

SNR delta can be used to produce a theoretical coded optical SNR FER, which will be covered in the following subsections. Note that the average deltas from datasets containing BPSK, QPSK, and 8PSK will be used to formulate the optical link's coded optical SNR FER data.

The following general equations calculates both the FER_BER SNR delta (Eq. (2)) and the average (Eq. (3)) in decibels:

$$[FER\_BER\ SNR\ \Delta]_{mod} = SNR_{FER,mod} - SNR_{BER,mod} \qquad (2)$$

where mod = BPSK, QPSK, and 8PSK

$$[FER\_BER\ SNR\ \Delta]_{ave} = \frac{\left(\sum_{i=mod}\left([FER\_BER\ SNR\ \Delta]_i\right)\right)}{3} \qquad (3)$$

Coded Optical SNR BER

As mentioned previously, the existing optical link data do not have the coding equivalent of RF, hence an uncoded optical link. To produce the coding equivalent in optical link, the coding gain (CG_{BER}) is deducted from uncoded optical SNR for BER. The deduction of CG_{BER} from optical SNR for BER simulates the improvement that coding schemes make against an uncoded system. The naming convention for uncoded optical link data follows optical modulation, link direction, and detector type (i.e., DPSK_G2S_NW); and the coded optical link data follows the uncoded optical link data name concatenated with RF's coding type, coding rate, and frame size (i.e., DPSK_G2S_NW_LDPC_2x3_1536).

Equation (4) calculates for coded optical SNR (in decibels) for BER:

$$[Coded\ Optical\ SNR]_{BER} = Uncoded\ Optical\ SNR - Coding\ Gain \qquad (4)$$

Coded Optical SNR FER

Another theoretical result in optical link that can be deduced from RF link data is the coded optical SNR for FER. Typically, SNR for FER is higher than SNR for BER in the RF system. When the SNR delta between FER and BER is obtained, it can be added to the optical SNR for BER in the optical system to produce coded optical SNR FER (in decibels). Equation (5) shows this relationship.

$$[Coded\ Optical\ SNR]_{FER} = [Coded\ Optical\ SNR]_{BER} + [FER\_BER\ SNR\ \Delta]_{ave} \qquad (5)$$

Code Optimization

As the number of datasets increases, the data extraction and search routines become tedious to manage and update. Now that the naming convention is consistent through all the datasets, algorithms involving string manipulation would greatly benefit the management of the routines. For instance, instead of statically coding all the names of the datasets in the search routine, dynamically generating the field names of the datasets contained in the .mat file and searching a unique string such as the type, frame size, or coding rate would parse the same dataset name.

Results

After curve fitting each of the datasets, the results are plotted and grouped in such a way that one graph consists of one coding type, one coding rate, one frame size, and the six modulation schemes. This is done in such a way that a group of six modulations only varies with the modulation order (B = 2 and Q = 4, 8, 16, 32, 64) as shown in Figure 9 to Figure 16. These figures pertain to RF system only.

Figure 9 shows the uncoded group with 100,000 frame size and six modulations schemes (BPSK, QPSK, 8PSK, 16APSK, 32APSK, and 64APSK). In general, an uncoded system (nonerror-correcting code) will require more SNR (horizontally shifted further right) in comparison to any coded system to achieve the same BER or FER. That is the case in Figure 9 where every modulation is generally higher than those in Figure 10 to Figure 15 for both BER and FER. Another point to keep in mind is the slope of the curve (or the rate of error performance). In the Figure 10, the BER slope is steeper than that of FER, which means that with an increase of SNR the BER performance increases significantly compared to FER.
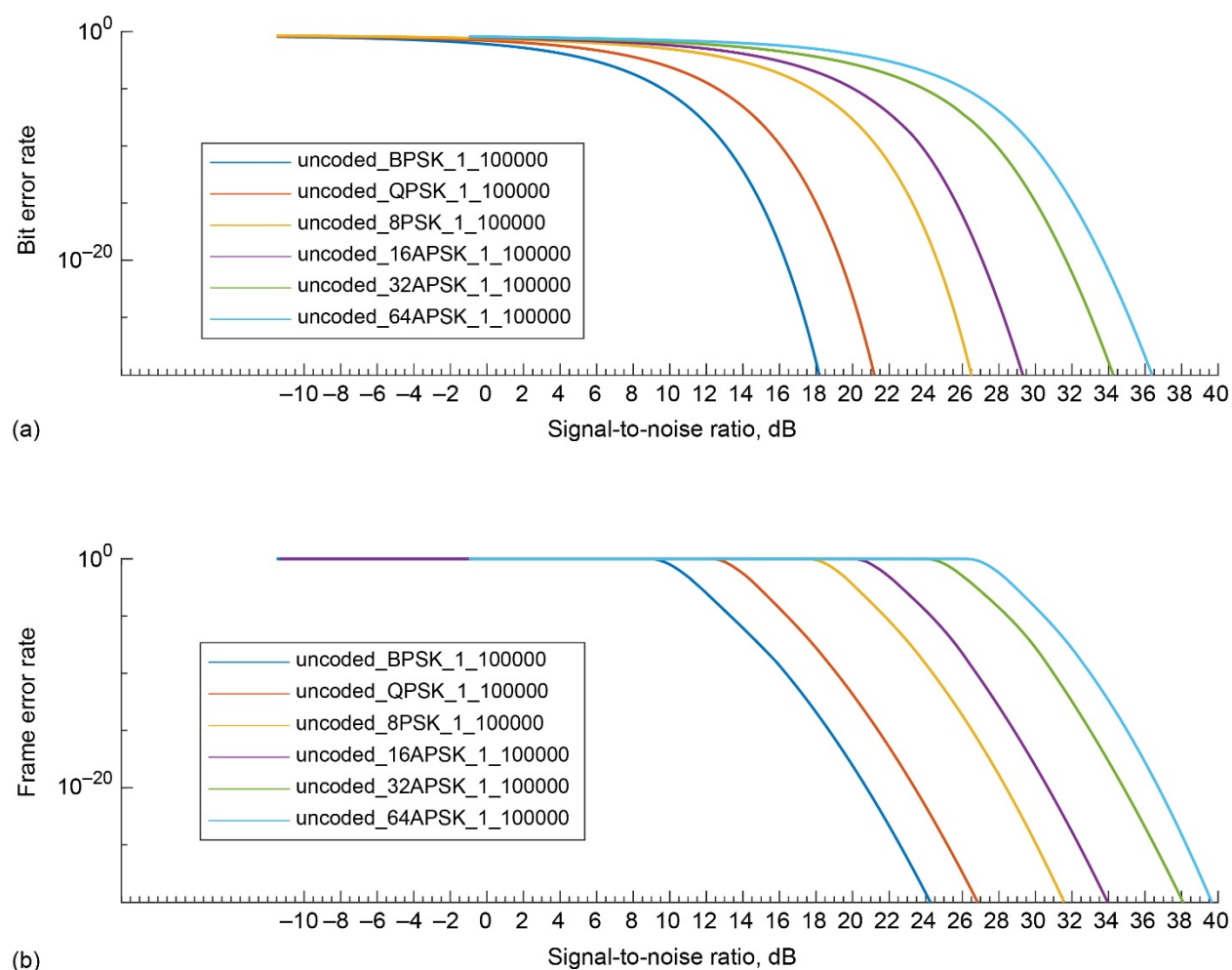

(a)

(b)

Figure 9.—Uncoded group with 100,000 frame size, including six modulations. (a) Bit error rate versus signal-to-noise ratio (SNR). (b) Frame error rate versus SNR.

Figure 10 illustrates the convolutional coding scheme. As expected from a coded system, the error correction performance should improve compared to uncoded system, as indicated by lower SNR. As is the case, convolutional has a lower SNR requirement compared to that in Figure 9. The slope, however, for both BER and FER is about the same and less steep, which means that the improvement in the error rate is not very significant as SNR increases.

Figure 11 pertains to an LDPC coding scheme across the six modulation schemes. The figure shows a significant error performance compared to both uncoded and convolutional coding schemes, as indicated by lower SNR for both BER and FER, and a steeper slope in the waterfall region of the curve.

Figure 12 pertains to a turbo coding scheme across the six modulation schemes. The required SNR to match the same BER and FER is very close to that of the LDPC but with a much steeper slope. The rate of improvement in error performance is much faster than that of LDPC.

Figure 13 pertains to a Reed-Solomon coding scheme across the six modulation schemes. The error performance is between that of convolutional and LDPC or turbo. The rate of improvement in error performance is significantly better than that of convolutional.

Figure 14 pertains to a concatenated Reed-Solomon convolutional scheme across the six modulation schemes. The error performance is slightly better than that of LDPC and turbo. The rate of error performance is about the same as turbo.
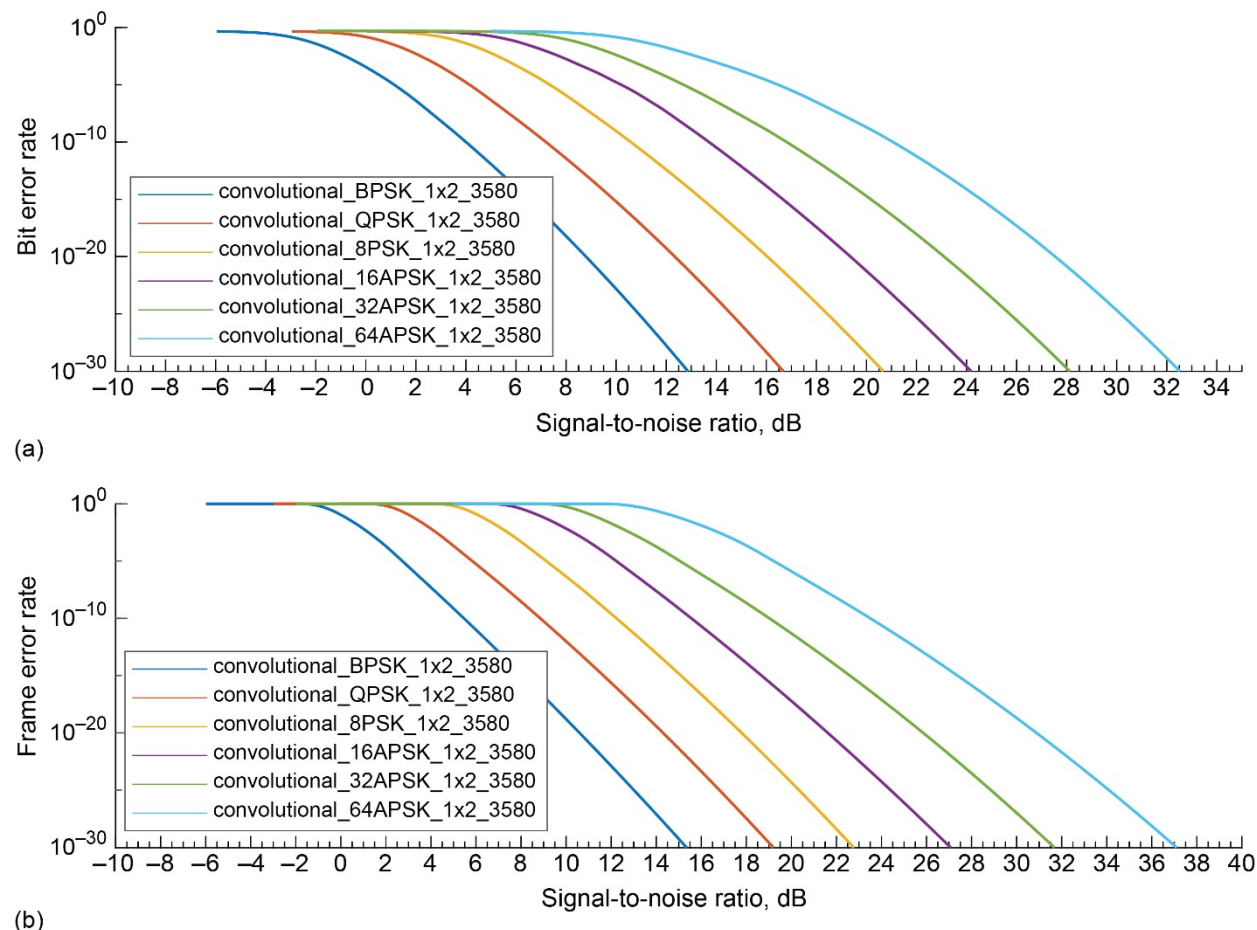

(a)

(b)

Figure 10.—Convolutional coding scheme with 3,850 frame size, including six modulations. (a) Bit error rate versus signal-to-noise ratio (SNR). (b) Frame error rate versus SNR.
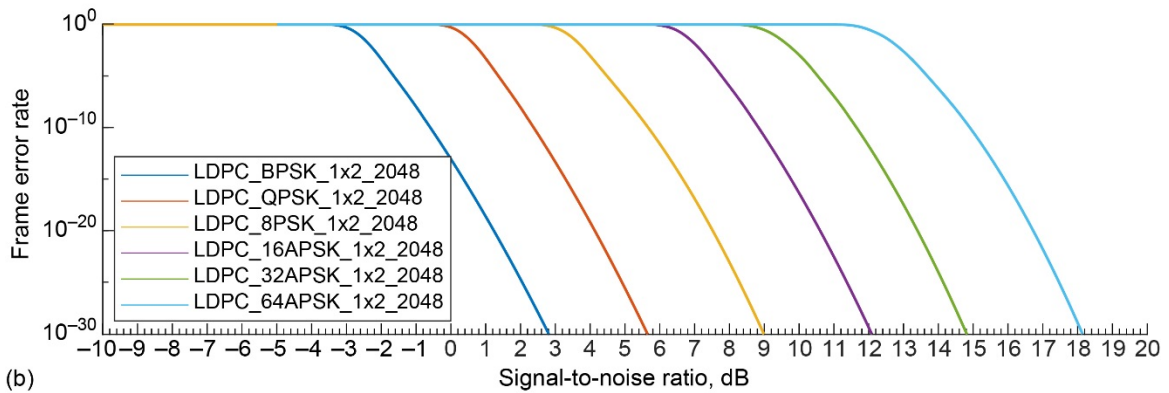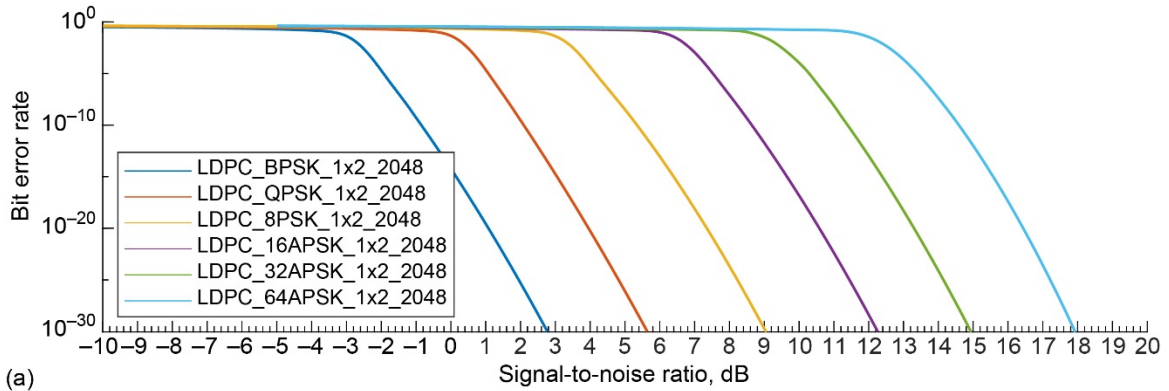
Figure 11.—Low-density parity-check coding scheme for 2,048 frame size, including six modulations. (a) Bit error rate versus signal-to-noise ratio (SNR). (b) Frame error rate versus SNR.
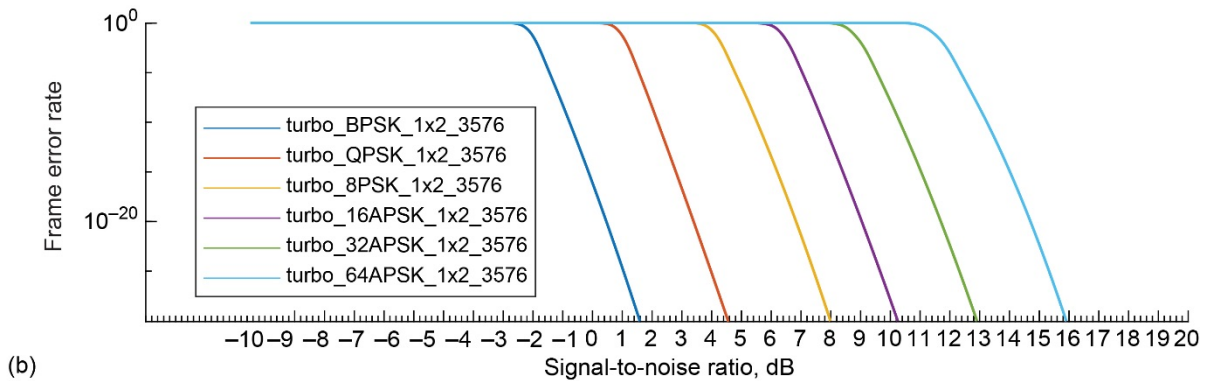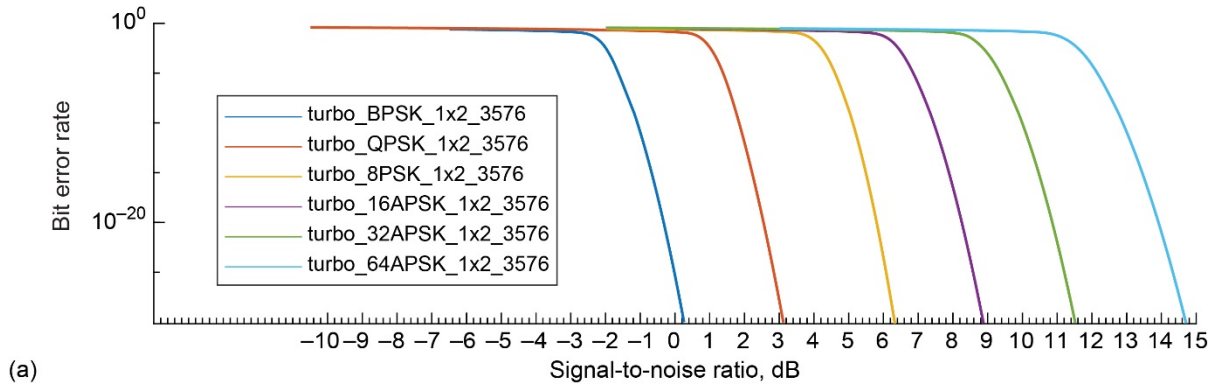

Figure 12.—Turbo coding scheme for 3,576 frame size, including six modulations. (a) Bit error rate versus signal-to-noise ratio (SNR). (b) Frame error rate versus SNR.
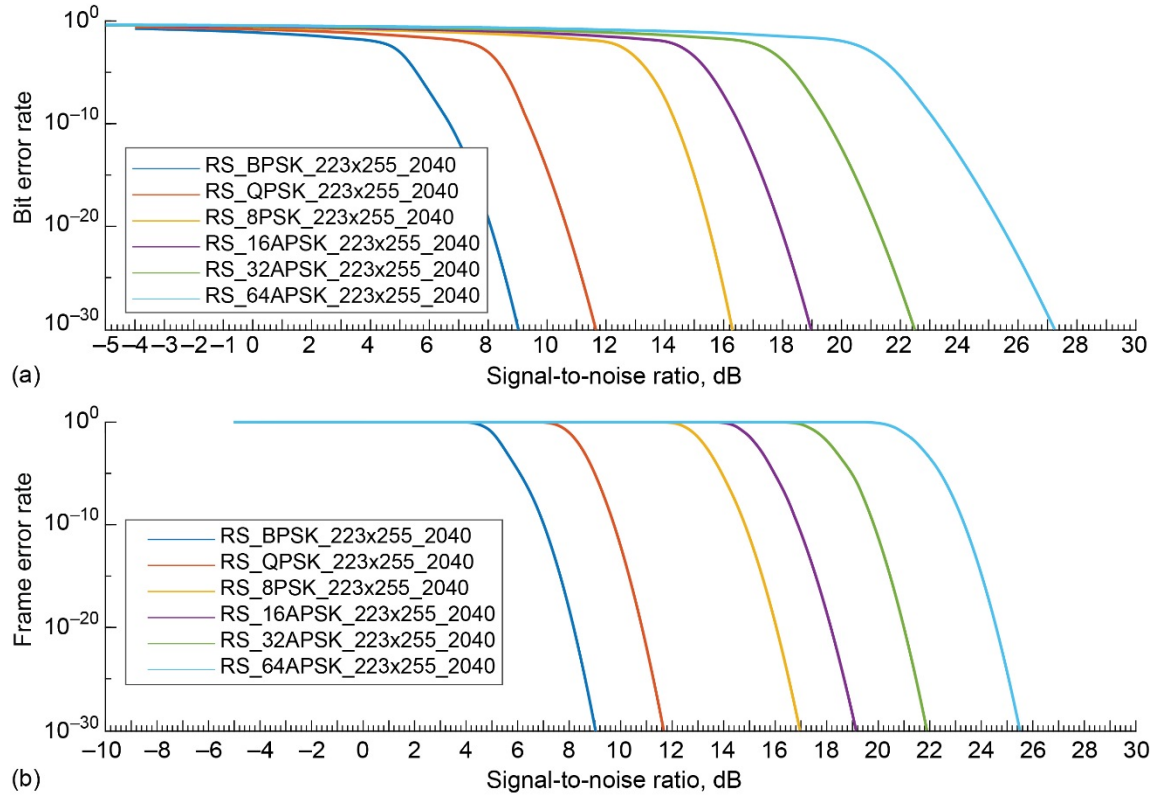
Figure 13.—Reed-Solomon coding scheme for 2,040 frame size, including six modulations. (a) Bit error rate versus signal-to-noise ratio (SNR). (b) Frame error rate versus SNR.
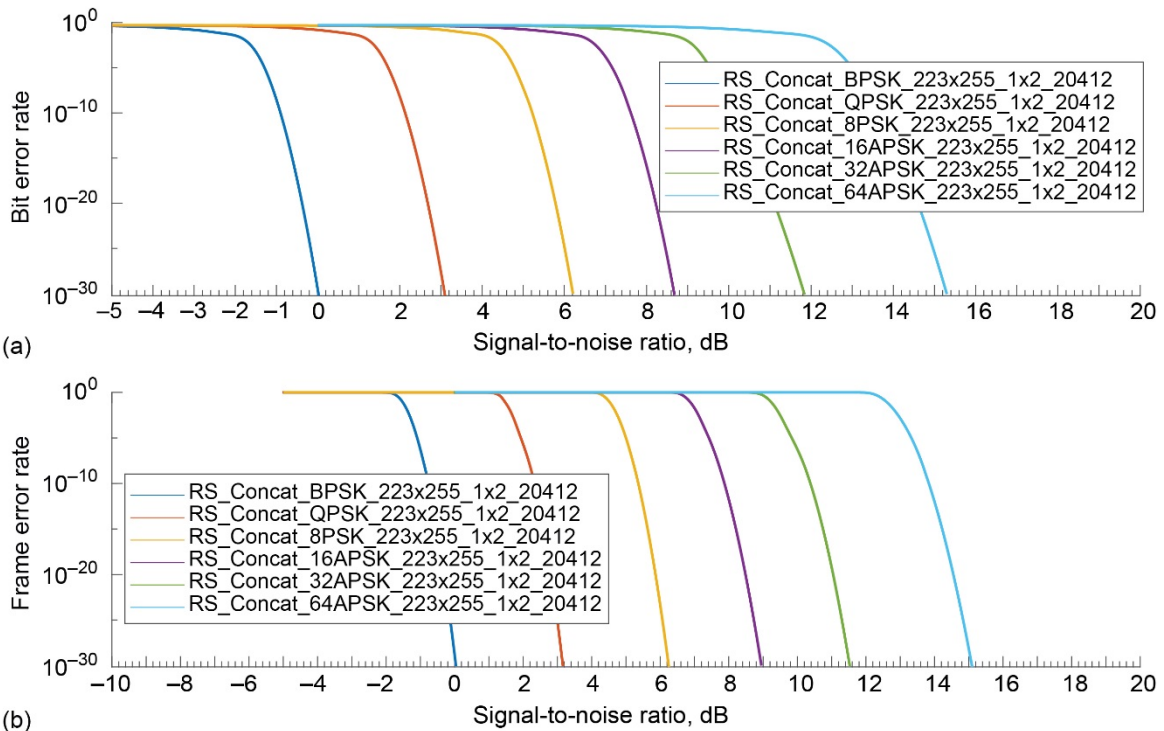

Figure 14.—Concatenated Reed-Solomon convolutional coding scheme for 20,412 frame size, including six modulations. (a) Bit error rate versus signal-to-noise ratio (SNR). (b) Frame error rate versus SNR.

Lastly, Figure 15 pertains to the BCH coding scheme across the six modulation schemes. The error performance is slightly better than the uncoded and with a similar rate of error performance.

Other results obtained from the data extracted from curve fitting include coding gain, FER_BER SNR delta, coded optical SNR BER, and coded optical SNR FER. The last two pertain to the theoretical and simulated data for the optical link.

Figure 16 shows the coding gain result for one sample calculation. For the same BER values (yellow and red curves), the uncoded_BPSK_1_100000 is in the higher level of SNR compared to LDPC_BPSK_ 2x3_1536. In this particular configuration, the resulting coding gain curve, shown in blue, illustrates the improvement of the LDPC coding scheme, compared to uncoded link operations. This result will be used to calculate the coded optical SNR BER.

Figure 17 depicts a BER curve in blue, an FER curve in red, and the resulting difference of the two curves in yellow. Both BER and FER were discretized at fixed error rates to obtain the corresponding SNRs at those discretized error rates. The discretized BER curve was subtracted from the discretized FER curve to obtain the FER_BER SNR delta values.

The varying parameters from a set of coding type, coding rate, and frame size to produce an average delta are the three modulations: BPSK, QPSK, and 8PSK. Figure 18 shows the three deltas and their average.

Figure 19 illustrates the uncoded optical SNR BER in blue, coding gain in red, and the resulting coded optical SNR BER in yellow. The discretized BER is used to obtain the corresponding SNRs for coding gain and uncoded optical SNR BER, and the difference resulted in the coded optical SNR BER.

Lastly, for the optical link, Figure 20 illustrates the curves for coded optical SNR FER in yellow. The average delta shown in Figure 18 earlier is added to corresponding parameters in coded optical SNR BER obtained in Figure 19. This process repeats for all the datasets.
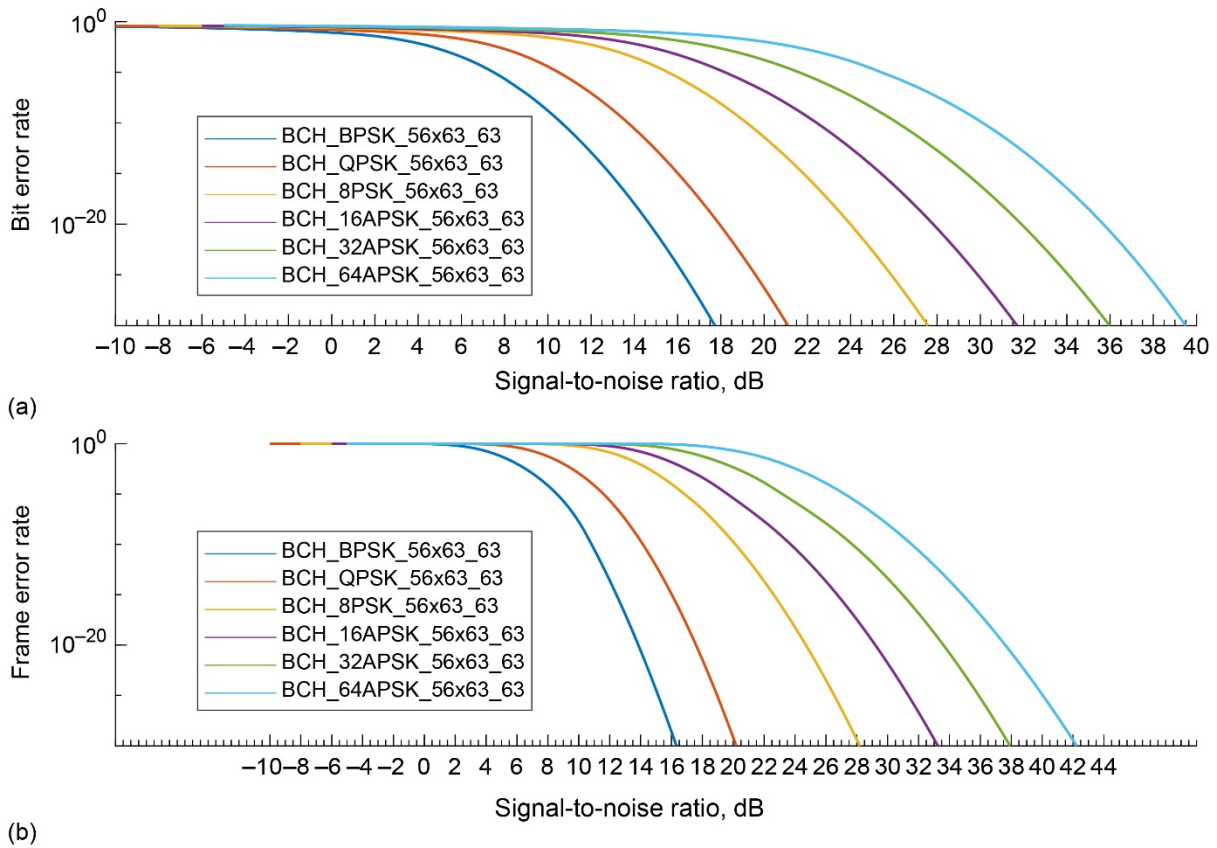

(a)

(b)

Figure 15.—Bose-Chaudhuri-Hocquenghem coding scheme for 63 frame size, including six modulations. (a) Bit error rate versus signal-to-noise ratio (SNR). (b) Frame error rate versus SNR.
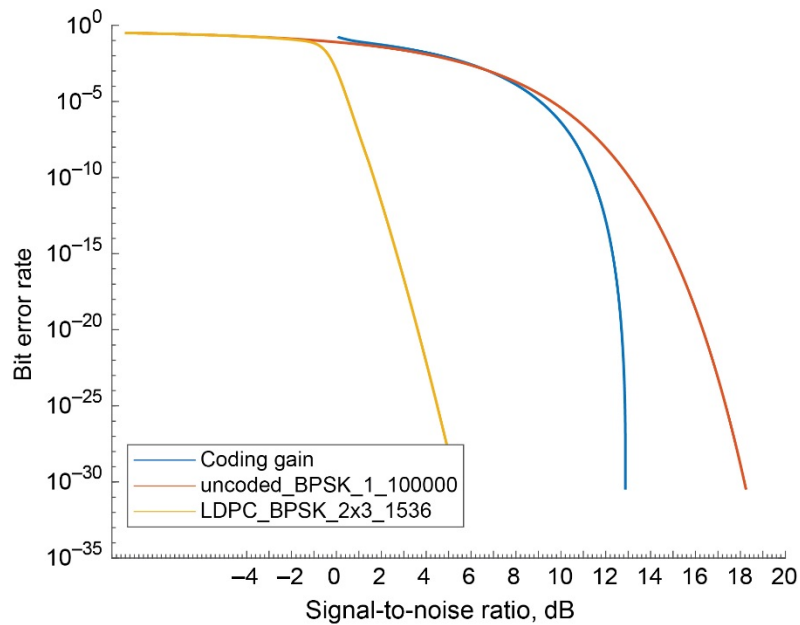
Figure 16.—Coding gain result and difference between uncoded binary phase shift keying (BPSK) and low-density parity-check BPSK.
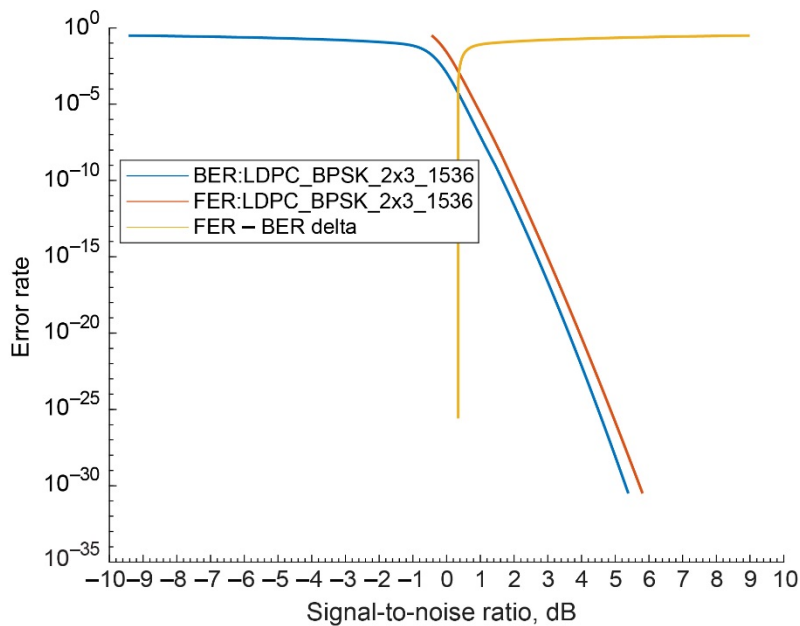

Figure 17.—Frame error rate (FER), bit error rate (BER), and FER – BER delta curves.
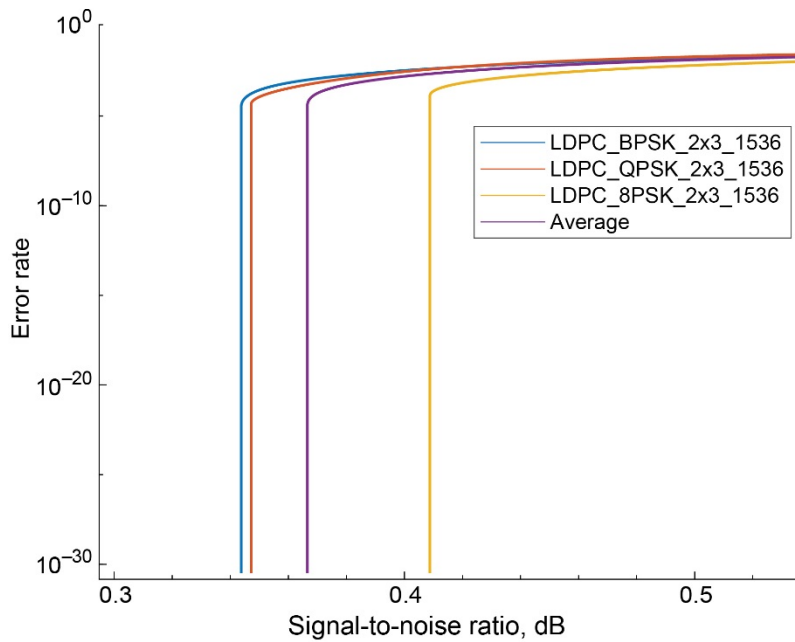
Figure 18.—Individual delta of binary phase shift keying, quadrature phase shift keying, eight phase shift keying, and their average.
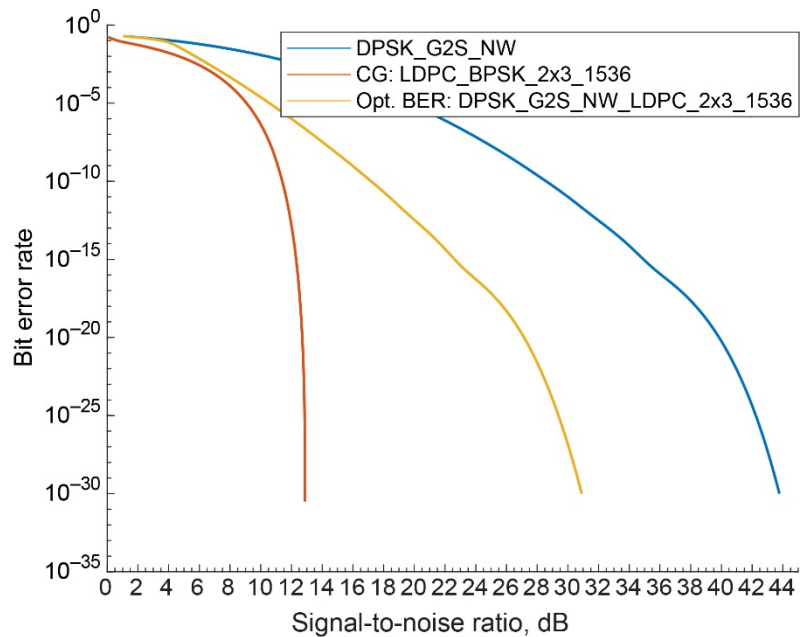

Figure 19.—Coded optical (opt.) bit error rate (BER) versus signal-to-noise ratio, where CG is coding gain.
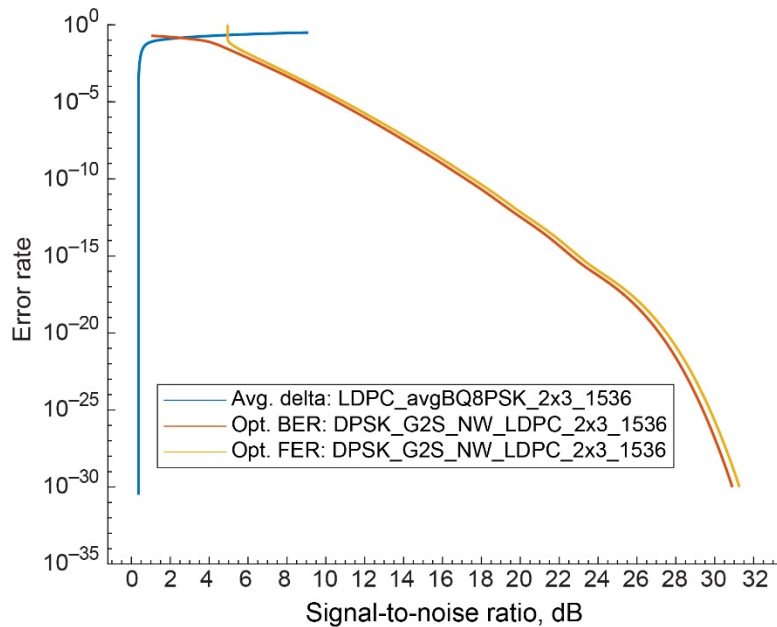
Figure 20.—Coded optical (opt.) frame error rate (FER) versus signal-to-noise ratio, where BER is bit error rate.

Conclusions

The curve fitting technique used in this project enabled the expansion of bit error rate (BER) and frame error rate (FER) simulation data beyond the computing capacity and time allowable in the scope of the current phase of the project. The curve fitted simulation data from various parameters, including coding type, signal modulation, coding rate, and frame size, were used to build the foundation for the upcoming capabilities of the Strategic Center for Networking, Integration, and Communications (SCENIC) user interface (UI), which adds the network protocol and link encryption augmentations of communication system analyses to the SCENIC capability. These capabilities would help users select and model the appropriate network-level standards and protocols for establishing connections between two endpoints as well as integrity of end-to-end data transmission. Such capabilities were modeled based on the data extracted from the curve fitted datasets and implemented in various search routines to enable efficient look-up capabilities to compare signal-to-noise ratio (SNR) with BER and FER. Furthermore, the data extracted from the curve fitted data allow the expansion of the ECC schemes in the radio frequency (RF) domain toward the optical link domain.

Because data have grown considerably due to the different parameters in the simulation data, keeping a consistent naming convention would greatly help in the identification, archival, and retrieval of these data. Moreover, a consistent naming convention would greatly reduce the program code expansion and management necessary to access these data.

Appendix.—Nomenclature

8PSK	eight phase shift keying
16APSK	16 amplitude and phase shift keying
32APSK	32 amplitude and phase shift keying
64APSK	64 amplitude and phase shift keying
BCH	Bose-Chaudhuri-Hocquenghem
BER	bit error rate
BPSK	binary phase shift keying
DL	decision line
DSN	Deep Space Network
DVB-S2	Digital Video Broadcasting-Satellite-Second Generation
ECC	error-correcting code
FCS	frame check sequence
FER	frame error rate
LDPC	low-density parity-check
LERCIP	Lewis' Educational and Research Collaborative Internship Project
NEN	Near Earth Network
OSI	Open Systems Interconnection
QPSK	quadrature phase shift keying
RF	radio frequency
SCaN	Space Communications and Navigation
SCENIC	Strategic Center for Networking, Integration, and Communications
SN	Space Network
SNR	signal-to-noise ratio
UI	user interface

Symbols

B	binary
CG	coding gain
$\mathbf{S}$	signal vector
$\mathbf{N}$	noise vector
Q	quadrature

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