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Performance Characterization of Terrestrial and Satellite Telemetry Ground Systems using an Enhanced Functionality Bit Error Rate Tester (BERT)

Introduction

Characterizing the functional performance of today's terrestrial and satellite telemetry ground stations has often employed a daunting and expensive array of stand-alone test equipment. Each item of test equipment, be it microwave spectrum analyzer, RF power meter, modulation analyzer, oscilloscope, wide band noise source, Bit Error Rate Tester, etc., have historically been used to test only one, or a small number of the major subassemblies that make up a telemetry ground station. Recent innovations in digital technology have made it possible to integrate onto a single PC or VME card, some of the diverse test and measurement functions usually found in individual stand-alone test instruments. The specific focus of this paper is to present a new, enhanced functionality Bit Error Rate Tester (BERT) which will become a core element in the test, evaluation, and characterization of any terrestrial or satellite telemetry ground station.

Typical Telemetry Ground Station

A typical satellite telemetry ground station is shown in figure 1. The system in this example has both an uplink and downlink signal path, with a space satellite in between. With regard to the testing of this system, the BERT is, for all practical purposes, "the center of the universe". The BERT is the instrument that generates a special digital test signal, which in turn is modulated onto a subcarrier and then placed onto an RF carrier by the transmitter. The modulated carrier is then translated to a much higher frequency band in the up converter, and finally amplified by a high power amplifier in the up link antenna where it is transmitted to the satellite.

In this example, the transponder in the satellite translates the uplink signal to a different set of frequencies and then re-transmits this signal back down to the ground. The signal is received by the down link antenna, where it is amplified by a Low Noise Amplifier (LNA) and down converted to an Intermediate Frequency (IF). The main carrier on the IF signal is demodulated by the IF Receiver producing a subcarrier containing the original digital test signal created by the BERT. The clock and data of the digital test signal are recovered by the Bit Synchronizer and presented to the BERT. Coming full circle, this recovered down link data is compared with that sent in the up link. The BERT counts the number of bit errors in the recovered signal and provides the operator with a Bit Error Rate, or BER. This BER measurement is one of the fundamental parameters that characterize the overall performance of the telemetry ground station, and of many of its components.

The Concept of BER in More Detail

The basic performance measure of any digital transmission system, of which a telemetry system is an example, is the probability that any transmitted bit will be received in error. These bit errors when they occur can be introduced in many places along the path the signal flows through. Errors introduced into the transmission are often random in nature and are strongly affected by system parameters such as *signal level*, *noise level*, and *timing jitter*. In characterizing a digital transmission system, the notion of *error distribution*, as opposed to total system error rate is also important. In other words, it is important to know where the errors are coming from, and what component subsystem is introducing them. The use of the enhanced functionality Bit Error Rate Tester will help in this regard.

It is important to note that the probability of error for any transmitted bit is a statistical property and has to be treated as such. This means that the resultant BER is actually a probability that will have a statistical variance from the long term mean system bit error rate and will depend upon the size of the sample taken from the population – in this case, the number of errors counted by the BERT during a given period. It is generally accepted that to be statistically significant, the number of errors counted should be at least 100. As an actual measured parameter, the Bit Error Rate

(BER) is defined as *the ratio of the total errors counted in a specific sampling interval and the total number of transmitted bits in the same sampling interval*.

The actual digital test signal generated by the BERT usually employs a Pseudorandom Noise (PN) sequence to simulate traffic and to examine the transmission system for pattern-dependent tendencies or critical timing effects. Selecting the proper PN sequence that will be appropriate for the particular system being tested is important. Some of the key properties of the selected PN sequence that are of importance include: 1) The length of the PN Sequence. 2) The Linear Feedback Shift Register configuration used to implement the PN generator (this defines the binary run properties of the sequence). 3) Spectral line spacing of the sequence (which depends on the bit rate of the sequence). Although there are many, two PN sequence patterns have been standardized by the CCITT(3) for testing digital transmission systems. They are based on 15-stage and 23-stage Linear Feedback Shift Register configurations and are implemented in the enhanced functionality Bit Error Rate Tester.

Some observations(2) regarding the use of the two CCITT patterns are as follows:

- Because the low frequency performance of digital transmission links tested with these patterns is a function of both bit rate and sequence length, it can be argued that the 2^{15}-1 pattern is not long enough for systems operating at bit rates greater than 2 Mbps. (The $2^{23} – 1$ pattern being more appropriate).
- Adequate (i.e., close enough) spectral line spacing is important when testing systems containing relatively narrow band (high Q) clock timing recovery circuits in order to see the jitter contribution, and its effects on error performance.
- The choice of the Linear Feedback Shift Register configuration affects the run properties of the PN sequence, which in turn, affects the jitter performance. This is due to the length of the “zero” block over which phase error is accumulated in the timing recovery circuits of the bit synchronizer. This effect leads to “pattern-dependent” jitter. Using line coding (Bi-Phase), or scrambling are two frequently used methods to control this.

As was previously mentioned, testing of a digital transmission system involves the use of a pattern generator that provides data to the system, and an error detector. The error detector standardized by the CCITT, and implemented in the enhanced functionality Bit Error Rate Tester performs a closed-loop, bit-by-bit comparison of the input data stream against a local reference pattern, both of which are in binary form (i.e., after any line coding or scrambling have been removed from the input data stream). Synchronization between the input data stream and the local reference pattern must be established before error detection can take place. The normal method for achieving synchronization is to open the feedback loop in the reference pattern shift register and feed the input data signal into the register until it is full, close the feedback loop and test for sync.

System Parameters that Determine BER

As was mentioned earlier, errors introduced into the transmission of a digital signal are often random in nature and are strongly affected by system parameters such as signal level, noise level and noise bandwidth, timing jitter, and data rate. The notion that the BER is actually a probability was also introduced. In order to more formally define the BER as a probability, the concept of the system *“E_b/N_0”* will now be presented. The system E_b/N_0 (pronounced ebbno) is the ratio of the energy-per-bit and the noise-power-per-unit-bandwidth of the digital transmission. The E_b/N_0 as a quantity is a theoretical convenience rather than the direct output of a test measurement device. The parameters that do in effect define the E_b/N_0, and that can be directly measured by the enhanced functionality Bit Error Rate Tester are the received carrier power (**C**), and the received noise power (**N**). These measured parameters, in addition to the noise bandwidth (**W**) of the system component being tested and the data rate (**R_b**) of the signal define the system E_b/N_0 in the following relationship**(4)** :

$$\frac{Eb}{No} = \left(\frac{C}{N}\right)\left(\frac{W}{Rb}\right)$$

Equation - 1

With the system E_b/N_0 now defined in terms of measurable quantities, we can now define the BER probability of a digital signal employing bipolar signaling in terms of E_b/N_0 with the following relationship$^{(4)}$:

$$\mathrm{Pe} = \mathrm{Q}\left(\sqrt{\frac{2\mathrm{Eb}}{\mathrm{No}}}\right)$$

Equation - 2

Where $\mathbf{E_b}$ is the average energy of a modulated bit, and $\mathbf{N_0}$ is the noise power spectral density (noise in 1-Hz bandwidth).

The value **Q(X)** is called the Gaussian Integral Function, and for values of *X > 2.15*, **Q(X)** can be approximated by the following$^{(1)}$:

$$Q(X) \approx \frac{1}{X\sqrt{2\pi}}\left(1 - \frac{0.7}{X^2}\right)e^{\left[\frac{-X^2}{2}\right]}$$

Equation - 3

Note: The theoretical results of BER for various modulation methods are based on the assumption that the noise in the channel is purely Gaussian White Noise and that there are no limitations placed on the system bandwidth. If neither of these assumptions is valid, the results of the calculation will overestimate the performance.

It is often helpful to visualize the BER probability function graphically using a double log plot of P_e versus E_b/N_0. Such a plot is shown in figure 2 (Uncoded). It is important to understand that this plot represents the *theoretical* relationship between the BER probability and E_b/N_0. If one were to characterize the *actual* measured BER performance for various values of E_b/N_0 for the system shown in figure 1 for example, a slightly different set of data points would be obtained. For the actual system, for any given value of P_e, the resulting value of E_b/N_0 will always be slightly *higher* in value than the theoretical. The overall performance of the system is thus compared to the best-case theoretical performance and is expressed in terms of the difference, or deviation from theory. As E_b/N_0 is a dimensionless quantity and is expressed in terms of dB, the performance of the system is often expressed as, “so many dB from theory”.

Measuring Carrier & Noise Power

As was mentioned previously, the parameters that define the E_b/N_0 (see equation-1), and that can be directly measured are the carrier power (**C**), and the noise power (**N**). The two types of stand-alone test instruments that have historically been used to measure RF power are the Spectrum Analyzer, and the RF/Microwave Power Meter. Of the two instruments, the spectrum analyzer is undoubtedly the most generally useful piece of test equipment in the RF & Microwave field today. A good spectrum analyzer will measure RF power, frequency, noise, sensitivity, modulation, distortion, and a number of other useful measurements required to characterize a particular component. The RF/Microwave Power Meter, a more specialized and much more accurate instrument for measuring all types of RF & Microwave energy is the preferred test instrument for making carrier and noise power measurements. The term "*power meter*" actually refers to two devices, a measuring device, or meter, and a separate power sensor.

Two types of power sensor technologies have been used in the past. The *thermocouple* type sensor is formed when two wires of different materials are joined together. A differential voltage exists across this junction and is a function of temperature. The more RF energy that flows through the junction, the higher the temperature, and thus the higher the differential voltage. The measuring device, or meter, reads this voltage and displays the corresponding power. The *thermistor* type sensor consists of a tiny bead of semi-conductor material that bridges the gap between two fine, closely spaced, parallel supporting wires. The resistance of the thermistor has a negative temperature coefficient of resistance (an increase in temperature results in a decrease in resistance). As RF energy flows through the thermistor, it's resistance changes. These changes in resistance are measured by the meter portion of the power meter and are displayed as a corresponding power.

The Enhanced Functionality Bit Error Rate Tester

The block diagram for the enhanced functionality BERT is shown in figure-3. The major functionality of this design is implemented in three sections: 1) The BERT integrated circuit performs all programmable test pattern generation, data reception, and analysis functions. 2) The PCM Decoder/Encoder & Convolutional Encoder integrated circuit processes data generated by the BERT chip, or from a separate external data source, and provides SYNC, CLOCK & DATA outputs. 3) The internal white noise source and RMS Power Meter provide calibrated levels of Gaussian white noise that can be summed with the DATA for testing system components such as bit synchronizers and Viterbi decoders at varying E_b/N_0 levels.

The timing that drives the BERT is provided from an internal 120 MHz source that can be phase locked to an external 10 MHz reference oscillator if desired. To explore and test the effects of clock jitter on the device under test, the BERT also provides the capability of "jittering" the internal clock with an external modulation signal. This enables the user to create digital test signals with very precise levels of jitter.

The enhanced functionality BERT provides an internal noise source and has provisions for the use of an external, user supplied noise source. A separate noise only output is also provided.

The enhanced functionality BERT need not be removed from the telemetry ground station during its normal operation. A separate Baseline input is provided for normal data flow. This enables the BERT to be completely, or partially bypassed during normal station operation. The Baseline input also performs another very important test function. By connecting the Baseline input to a very low frequency external sine wave source, it is possible to create a resulting PCM Out signal that is, in effect, riding on top of a very slow sine wave. This reproduces the phenomenon known as, *"baseline gallop"*, where the DC level of the signal slowly rises and falls with time. This is often a very important issue with some Bit Synchronizer designs, and the ability to create this condition during testing is one of the features of the enhanced functionality BERT.

Enhanced Functionality BERT At a Glance

The specific operational specifications for the enhanced functionality BERT are summarized in the following table:

Tabel – 1: Enhanced Functionality BERT Specification & Functions

Bit Rate	1 bps to 30 Mbps NRZ codes (15 Mbps non-NRZ codes) with 1 bps resolution
Stability	± 2 PPM
Inputs	Receiver Clock (TTL, RS-422, ECL) Receiver Data (TTL, RS-422, ECL) Baseline (Analog, 200 ohms)

	FM Jitter (Analog, 1K ohms) External 10 MHz Ref (TTL, Analog 50 ohms) External Noise input (Analog, 50 ohms)
Outputs	Transmitter Data (TTL, RS-422, ECL) Transmitter Clock (TTL, RS-422, ECL) 2 Times Clock (TTL, RS-422, ECL) (NRZ output to 15 Mbps) or 3 Times Clock (TTL, RS-422, ECL) (NRZ output to 10 Mbps) Pattern Sync (TTL, RS-422, ECL) PCM Output (Analog + Noise, 50 ohms) 100 MHz Noise Output for use with upconverted modulated signals
PCM Output	0.1 V p-p to 5 V p-p into 50 ohms in 4096 steps.
Noise Output	Calibrated noise from 1 kHz to 60 MHz ± 1 dB with programmable filters. Filter Fc's: 60 MHz, 25 MHz, 10 MHz, 5 MHz, 2 MHz, 1 MHz, 500 kHz, 250 kHz, 100 kHz, 50 kHz, 25 kHz, 10 kHz, 5 kHz, 2.5 kHz, 1 kHz Output variable from 0 to 40 dB in 4096 steps.
Transmitter PCM codes	NRZ-L,M,S; BI0-L,M,S; DM-M,S; MS-M,S; RZ; 11 BIT & 15 BIT Randomize (Fwd & Rev) & V.35 Randomize. Convolutional Encoding Rate ½ & 1/3
Patterns	2^3-1, 2^4-1, 2^5-1, 2^6-1, 2^7-1, 2^9-1, 2^{10}-1, 2^{11}-1, 2^{15}-1, 2^{17}-1, 2^{18}-1, 2^{20}-1, 2^{21}-1, 2^{22}-1, 2^{23}-1, 2^{25}-1, 2^{28}-1, 2^{29}-1, 2^{31}-1 & other PN patterns; Alternating 1010; User defined pattern to 32 bits.
Receiver PCM codes	NRZ-L, 11 BIT & 15 BIT (Fwd & Rev) Derandomizer. 75 ohm single ended or 120 ohm differential input. 10 k ohms optional. Polarity - Manually selectable
Sample Interval	Programmable 10^3 to 10^9
Baseline Input	Z_{in} = 200 ohms, Gain = 0 dB, Bandwidth = 10 MHz
Frequency Modulation Input	Zin = 1 K, Mod. = 1%/V, Bandwidth = 1 MHz, AC coupled
Error Count	Error counts to 2^{31} errors. Bit Error rate calculated in sample mode . Accumulate mode shows total number of errors.
Error Insertion	Insert bit error for error rates of 10^{-1} to 10^{-7}.

Implementation of the Enhanced Functionality Bit Error Rate Tester
SBS Berg Telemetry Systems has implemented the enhanced functionality BERT in both VME and PCI form factors. Designated as the BSI **4419-V** and **4419-P** respectively, both integrate onto a single card, some of the diverse test and measurement functions usually found in individual stand-alone test instruments. For example, all of the functions historically performed by a stand-alone BERT are performed in the 4419 by a *single* integrated circuit chip manufactured by Dallas Semiconductor. The block diagram of the Dallas Semiconductor DS2172 BERT chip is shown in figure 4. The DS2172 chip is a software programmable test pattern generator, receiver, and analyzer useful in a wide variety of digital transmission system test scenarios. The DS2172 generates two categories of test patterns (Pseudorandom and Repetitive) that conform to CCITT standards O.151, O.152, O.153, and O.161. and operates at clock rates ranging from DC to 52 MHz. The DS2172 consists of four functional blocks: the pattern generator, pattern detector, error counter, and control interface. The DS2172 can be programmed to generate any pseudorandom pattern with a length up to 2^{32-1} bits or any user programmable bit pattern from 1 to 32 bits in length. The DS2172 can insert single errors, or continuous 10^{-1} to 10^{-7} bit errors to verify equipment operation and connectivity. The transmit and receive sections of the DS2172 can operate completely independently of each other, thus allowing more flexible test performance. The advanced synchronization circuits of the DS22172 enable it to detect and sync to test patterns with bit error rates of up to 10^{-2}.

The remaining digital functions of the 4419 BERT are performed in a custom developed, Field Programmable Gate Array, or (FPGA). The functions implemented in the Xilinx FPGA include: 1)

Rate ½ and Rate 1/3 convolutional encoding, 2) PCM encoding of the output data [codes include: NRZ-L,M,S; BI0-L,M,S; DM-M,S; MS-M,S; RZ; 11 BIT & 15], 3) Derandomization for NRZL11 & 15 and also V.35, and 4) Error totalization.

The software implementation for the 4419-P BERT is based on the industry standard Microsoft Windows95/NT operating system and consists of a simple, yet powerful Graphical User Interface, or GUI. Figure 7 and figure 8 shows this GUI in more detail. The BERT menu tab shown in figure 7 allows the user to setup and configure the 4419-P by entering parameter values and selecting operating modes defined in Table-1. The BERT Plot tab shown in figure 8 is a very simple, yet powerful display that shows the user, at-a-glance, the exact results of the test currently underway. The data presented on this graphic is very similar to the, "*waterfall*" plot shown in figure 2, and displays two curves: one for the theoretical, best-case performance, and a second curve representing the actual measured probability of error as a function of E_b/N_0 level. By placing the mouse cursor on any measured data point on the curve, the exact probability value (P_e), the E_b/N_0 level and the deviation from theory for that point will be displayed. Figure 8 also shows a very powerful feature of the 4419-P software. This is the automated test feature in which the user enters the starting and ending E_b/N_0 levels, and an E_b/N_0 increment value. The test begins with the 4419-P establishing the initial E_b/N_0 level, followed by a BER measurement at that level. Then the E_b/N_0 level in increased by the increment value and the BER is measured again. This process continues until the ending E_b/N_0 level is reached. The results of the test are presented as described above.

Applications of the Berg 4419 BERT

A typical application of the Berg 4419 BERT is shown in figure 6. In this example, all of the functional blocks shown in figure 3 are employed to test and characterize a bit synchronizer equipped with an on-board Viterbi decoder. In this test scenario, the 4419 will create a noisy (specific E_b/N_0 levels), jittery test signal of user specified length that will undergo convolutional encoding (rate ½), and Bi-Phase-L line encoding prior to transmission to the bit sync. The bit synchronizer under test will acquire this signal, recover the clock and data from the signal and then employ Viterbi decoding to correct any random errors introduced into the signal. The recovered clock and data is then passed back to the 4419 BERT where the test signal is synchronized with the transmitted pattern. After sync lock has been established, the 4419 BERT counts the number of any uncorrected errors and presents the bit error rate for the selected E_b/N_0 level to the user via the computer bus. A complete characterization of the bit sync/Viterbi card can thus be performed at a variety of different E_b/N_0 and jitter levels.

References:

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2. Feher, K., *Telecommunications Measurements, Analysis, And Instrumentation*, Prentice-Hall Press, Englewood Cliffs, NJ, 1987, ISBN 0-13-902404-2.

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5. IRIG 106-93, *Telemetry Standards*, Secretariate, Range Commanders Council, U.S. Army White Sands Missile Range, New Mexico.

6. IRIG 119-88, *Telemetry Applications Handbook*, Secretariate, Range Commanders Council, U.S. Army White Sands Missile Range, New Mexico.

7. Beyer, W., *CRC Standard Mathematical Tables, 28th Edition*, CRC Press, Boca Raton, FL, 1987, ISBN 0-8493-0628-0.

SIDEBAR What is "Telemetry"

The Federal Communications Commission (FCC), in its Rules & Regulations, Part 2, defines telemetry as the, "*use of telecommunication for automatical indicating or recording measurements at a distance from the measuring instrument*". Expressed more plainly, we could say that telemetry systems are a means by which physical data (such as a pressure, air speed, voltage level, temperature, etc.) is gathered in a remote location (such as a missile, an airplane, or satellite) and then transported (i.e., transmitted) to a user at a central location. The data or information that is transported is referred to as ***telemetry*** and the process by which this data is gathered is called telemetering. An excellent tutorial overview of telemetry systems can be found in reference (1).

In the early 1950s, a committee composed of telemetry engineers from all major Department of Defense test ranges in the United States formed the *Inter-Range Instrumentation Group*, or **IRIG**. The purpose of the group was to establish and publish standards for telemetry equipment and systems. These *IRIG Standa*rds are updated frequently and collectively represent a reasonably current outline of the state of the art in telemetry. The IRIG standard for telemetry, as revised in 1993 is IRIG *106-93*(5), and is considered by many to be the, *"Telemetry Bible"*. An equally important companion to IRIG 106-93 is the *Telemetry Applications Handbook*(6) also published by the IRIG. This handbook is filled with a wealth of practical, real-world information on telemetry.

Note: For those readers with internet access and a good web browser, the IRIG 106-93 document is available online at: http://tecnet0.jcte.jcs.mil:9000/RCC/manuals/tmstd/titlepg.htm

SIDEBAR More About The Gaussian Integral Function(4)

The Gaussian integral function, or "Q-Function" as it is often referred to is used a great deal in communication system theory for defining the performance of different modulation schemes. The exact mathematical definition for the Q-function is shown in equation 4 below.

$$\boxed{Q(y)=\frac{1}{\sqrt{2\pi}}\int_y^{\infty} e^{\left(\frac{-x^2}{2}\right)}dx}$$

Equation - 4

Unfortunately, this equation has no closed form solution, but can only be solved numerically. By using the following substitution,

$$x=z\sqrt{2}$$

and employing the ***Complementary Error Function*** erfc(y), a more useful equation can be written for the Q-Function:

$$\boxed{erfc(y)=\frac{2}{\sqrt{\pi}}\int_y^{\infty} e^{-z^2}dz}$$

Equations 5a & 5b

$$\boxed{erfc(y)=2Q\left(y\sqrt{2}\right)}$$

$$\boxed{Q(y)=\frac{1}{2}erfc\left(\frac{y}{\sqrt{2}}\right)}$$

Equation - 6

The complementary error function also has no closed form solution, but has been extensively tabulated in numerical form in a variety of math and science handbooks(7).

Typical Telemetry Ground Station Test Setup

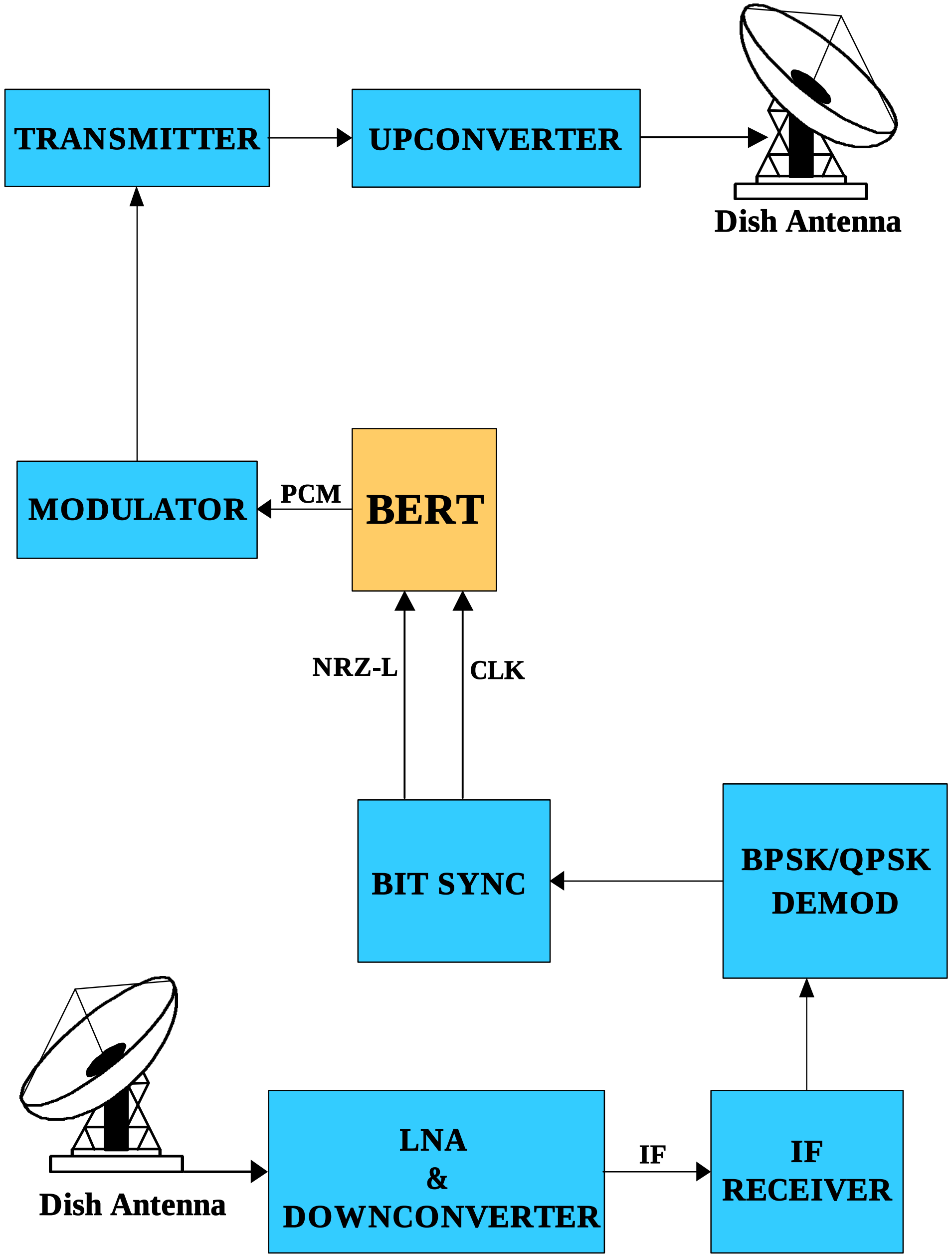


Figure - 1

V1.0

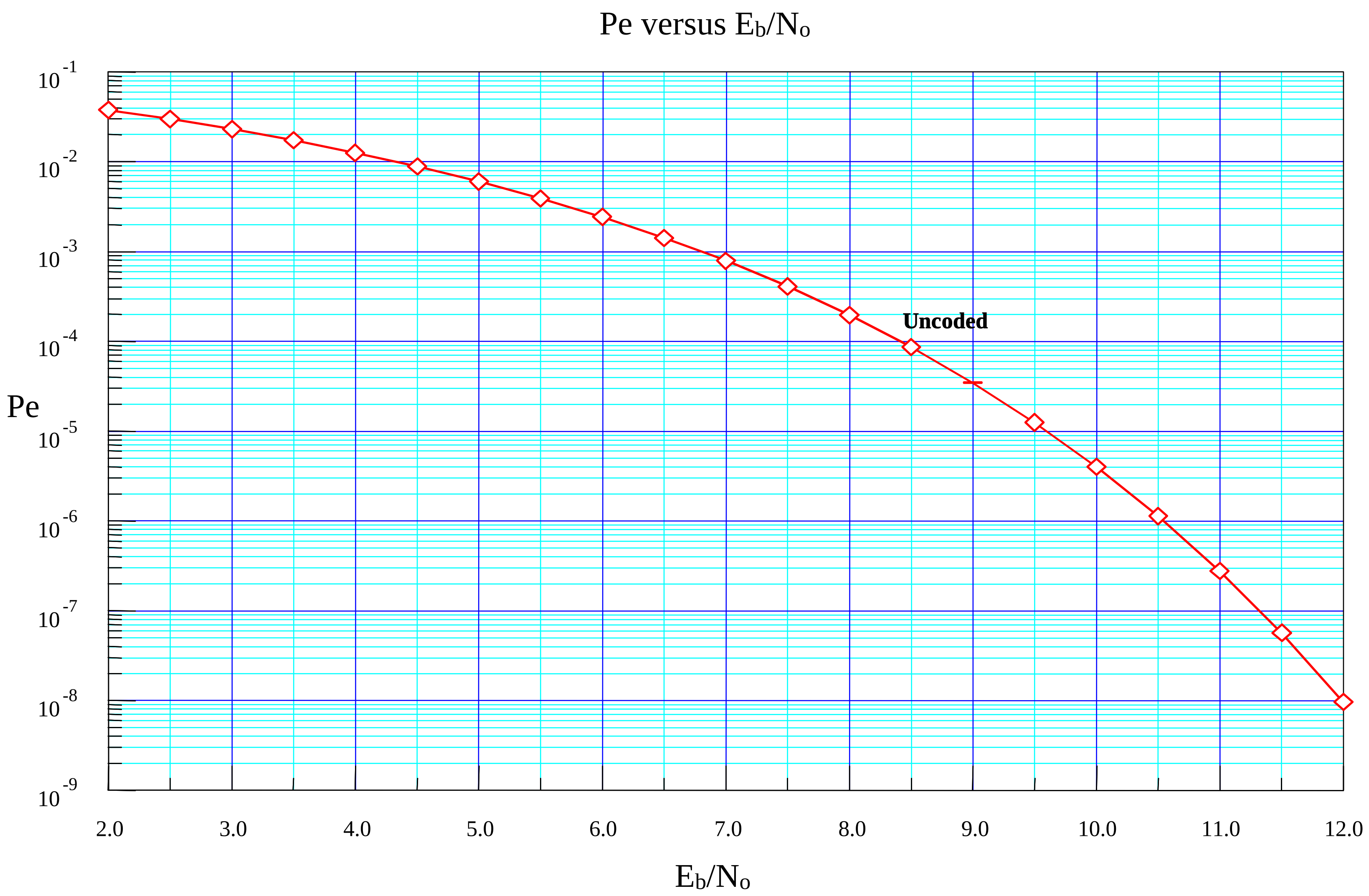

Pe versus Eb/No
Pe
10 -1
10 -2
10 -3
10 -4
10 -5
10 -6
10 -7
10 -8
10 -9
Uncoded
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
11.0
12.0
Eb/No

Figure - 2

Telemetry Ground Station
Enhanced Functionality
Bit Error Rate Tester (BERT)
Block Diagram

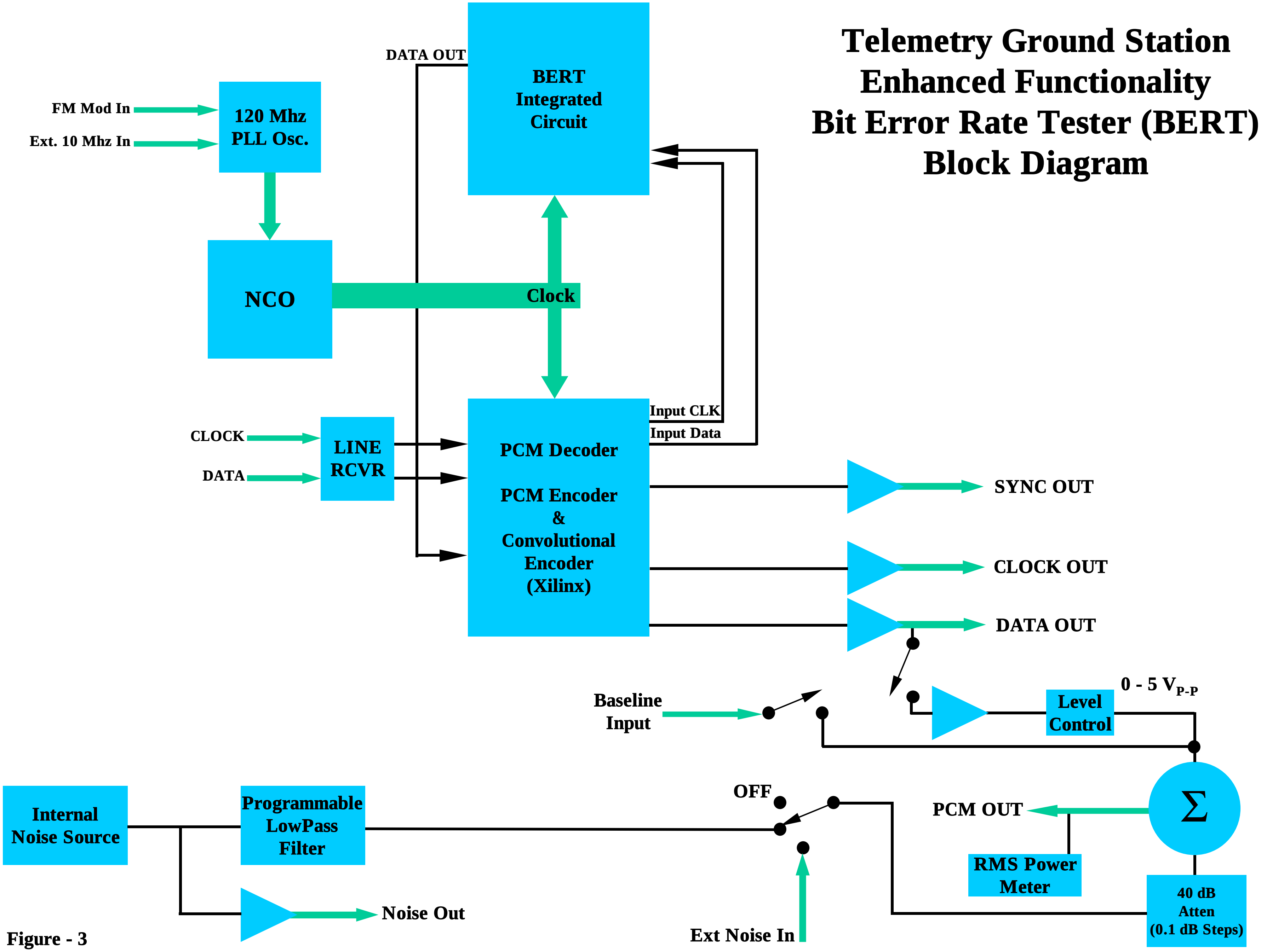
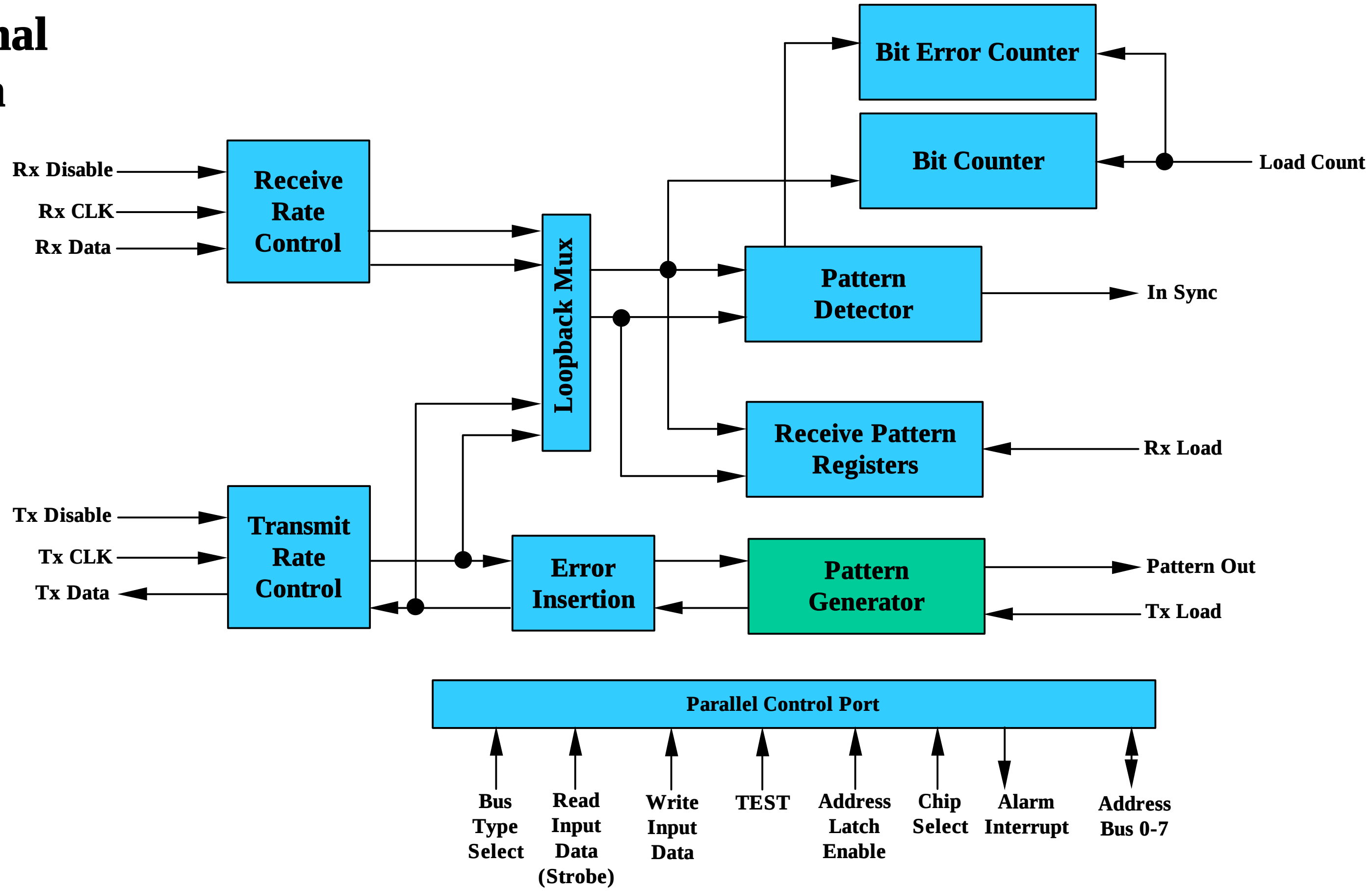


Figure - 3

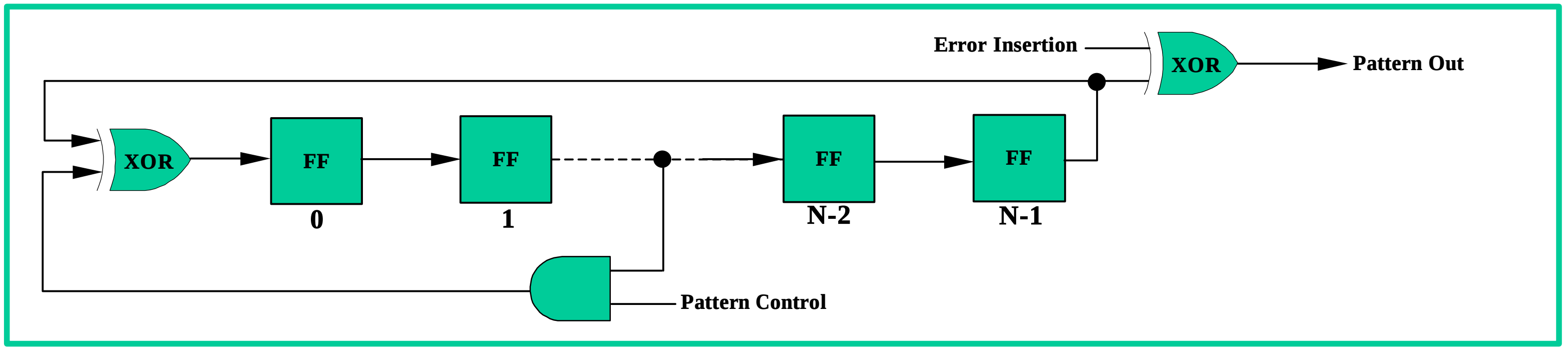
V1.2

Figure - 4

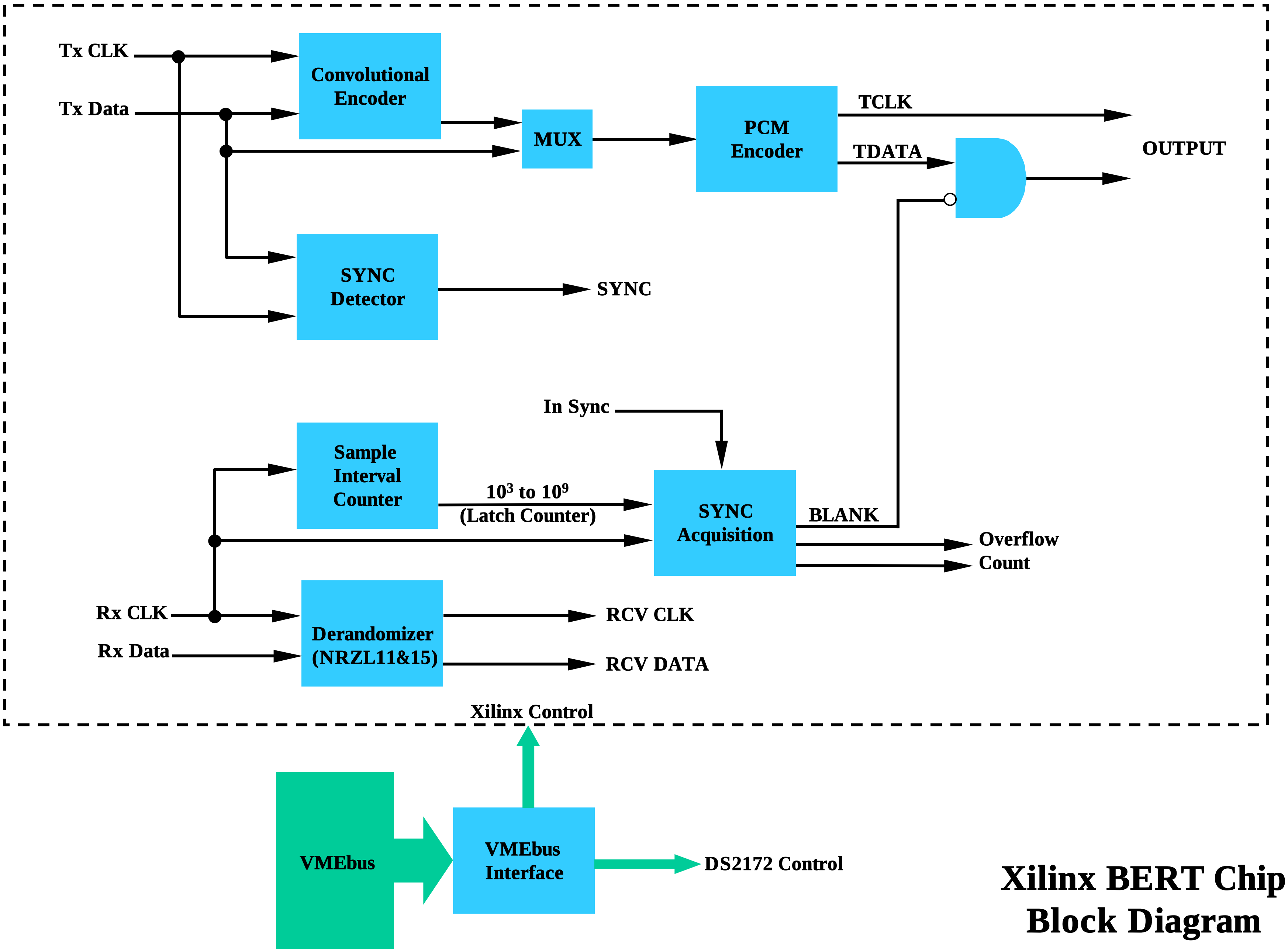
Dallas Semiconductor DS2172 Functional Block Diagram



Pattern Generator



V1.0

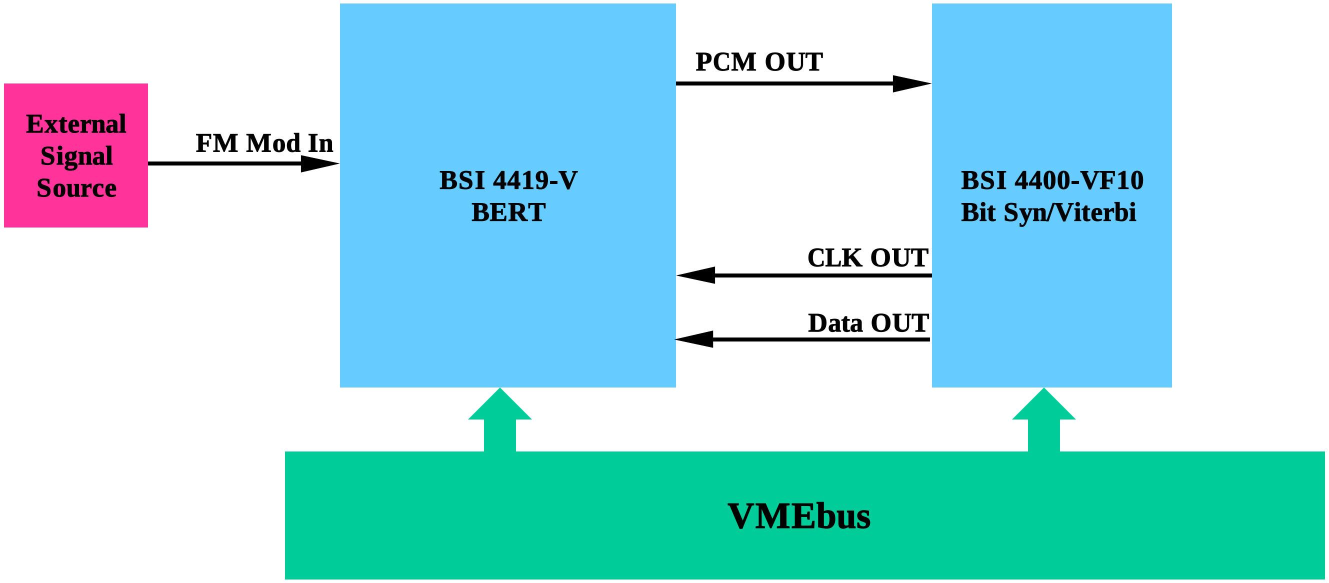


Xilinx BERT Chip Block Diagram

Figure - 5

V1.0

Characterization
of Bit Synchronizer
with On-board Viterbi Decoder



External Signal Source

FM Mod In

BSI 4419-V BERT

PCM OUT

CLK OUT

Data OUT

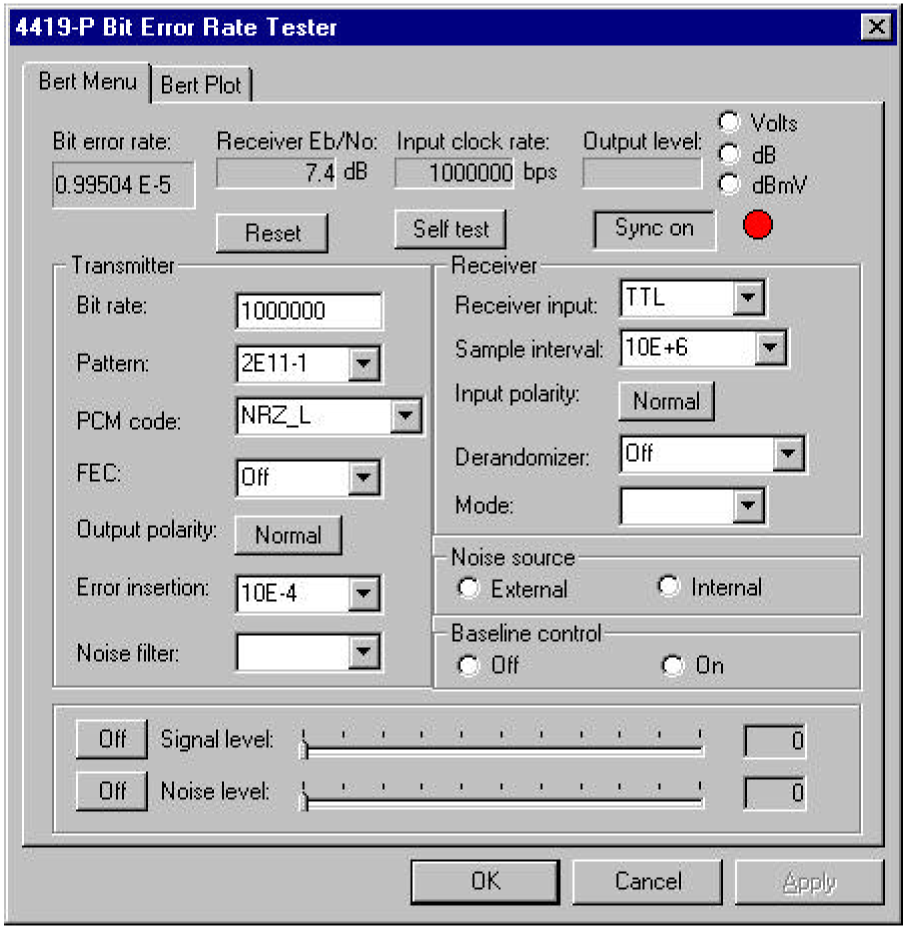
BSI 4400-VF10 Bit Syn/Viterbi

VMEbus

Figure - 6

V1.0

BSI 4419-P Graphical User's Interface
(Setup Screen)



Bit error rate: 0.99504 E-5

Receiver Eb/No: 7.4 dB

Input clock rate: 1000000 bps

Output level:

○ Volts
○ dB
○ dBmV

Transmitter

Bit rate: 1000000
Pattern: 2E11-1
PCM code: NRZ_L
FEC: Off
Output polarity: Normal
Error insertion: 10E-4
Noise filter:

Receiver

Receiver input: TTL
Sample interval: 10E+6
Input polarity: Normal
Derandomizer: Off
Mode:

Noise source

○ External ○ Internal

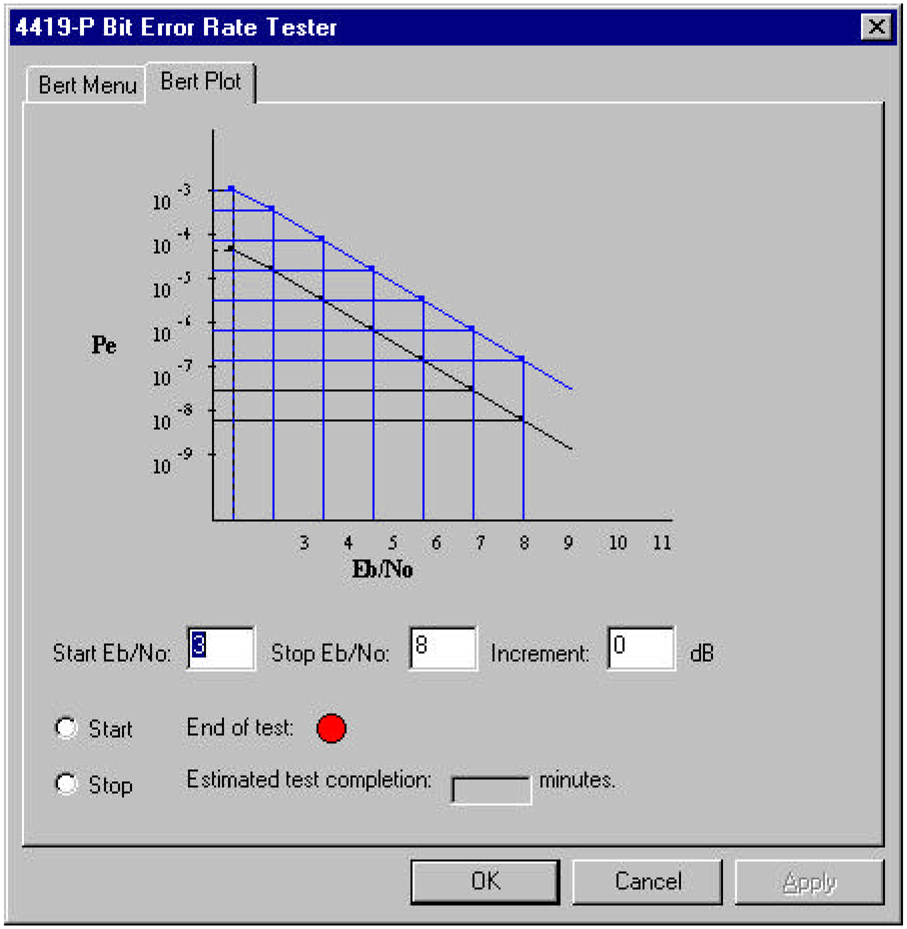
Baseline control

○ Off ○ On

Off Signal level: 0
Off Noise level: 0

Figure - 7

BSI 4419-P Graphical User’s Interface
(BERT Performance Results Screen)



Start Eb/No: 3 Stop Eb/No: 8 Increment: 0 dB

Estimated test completion: minutes.

Figure - 8