Agilent EEsof EDA

Presentation on Error Rate Simulations

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This Seminar provides an introduction to estimating Bit Error Rate (BER) in an EDA simulation environment. Several important issues relating to this task are discussed, including the role of noise in both baseband and RF applications, methods to achieve proper sampling and to determine the number of samples required. Finally, we will discuss a methodology to increase the efficiency of BER simulations.
BIOGRAHPICAL SKETCH

Cory Edelman in an Application Engineer with Agilent EEsof. He has over 10 years of experience in the area of high-frequency EDA, with 20 years of overall industry design experience. Upon joining EEsof in 1988, Cory served as Technical Support Engineer for the ground-breaking OmniSys Systems Simulator. Cory holds a BSEE from California State University, Northridge and resides in Thousand Oaks, California with his wife and two cats. When not preoccupied with the details of RF systems, he enjoys playing the theatre pipe organ, piano and cello.
Problem Statement and Topics

**Problem to be solved:**
BER testing can be difficult, time consuming, and is often inefficient.

**Topics to solve this problem:**

- Understanding System and Receiver Noise
- Modeling System Noise in an EDA Environment
- Configuring BER Simulations in an EDA Environment
- Specifying the Timing and Accuracy
- Fast BER Simulations using *Importance Sampling*

The topics are:
- Receiver Noise: Specifications, Measurements and Assumptions
- How to model noise in both Baseband and RF Systems
- How to configure BER simulations to account for system delays
- How to determine the required number of samples for the desired accuracy
- Using Importance Sampling to make BER simulations more efficient
BER SIMULATION STEPS:
- **Configure a model of your communication system, including all effects except for receiver noise**
- **Control the system noise using a controlled noise source; this sets the Eb/No or Es/No of the system at the detector**
- Set up the BER measurement, accounting for the system timing and delays
- Determine the desired accuracy of the BER measurement, and set the number of simulation points accordingly
- Consider the use of Importance Sampling to reduce the length of the simulation, if appropriate for your type of system
- Perform the simulation and evaluate
While theoretical discussions of BER simulations are not difficult, being based upon an understanding of statistics, practical systems require a deeper level of understanding. In particular, achieving proper control of noise in the system is essential. The choice of simulation method is also a factor in how noise is considered.

You will learn basic concepts of noise in a receiver and how to properly model that noise for estimating BER. In addition, you will learn how to implement BER measurements in an EDA tool such as Advance Design System (ADS).
Noise temperature is often used to describe the noise performance of a receiver. It is helpful to consider the antenna and the receiver as separate entities. Then, we can define a noise temperature for each. The total receiver noise temperature $T_s$ is therefore the sum of the antenna and receiver-only noise temperatures.
**Simplifying Receiver Noise**

- Receiver noise when ambient temperature is at absolute zero (0 Kelvin): \( T_S = T_R \)

*Assume lossless antenna, pointed straight up.*

When the antenna is free of passive losses, is at absolute zero (0 Kelvin) and is pointing straight up at the sky, the antenna has zero noise temperature. In that case, the total receiver noise \( T_S \) is just that due to the receiver itself.
Noise for BER Measurement

- Bit Error Rate or Bit Error Ratio (BER) is defined at a specific signal-to-noise ratio, often expressed as $Eb/No$ or $Es/No$, where:

  $Eb = \text{Energy per bit}$
  $Es = \text{Energy per symbol}$
  $No = \text{Post-detection noise in 1-Hz BW}$

All BER measurements for a practical radio are defined at a certain signal-to-noise ratio. This is often normalized to the bit or symbol time duration to result in the terms $Eb/No$ or $Es/No$, where $No$ is the “noise density” or noise in a 1-Hz bandwidth.
Relating C/N to Eb/No

- In wireless communication systems, we can determine the Carrier to Noise ratio: C/N.
- For BER, we need Eb/No. Are they related?  
  - Yes, if the demodulation linearly translates the RF carrier noise to the baseband signal.

\[
\text{Eb/No} = \text{Carrier power (dBm)} - \text{Noise power (dBm/Hz)} - 10\log(F_b)
\]

- where \(F_b\) is the bit rate in Hz, and Nyquist filtering is used.

Carrier to Noise Ratio or C/N is often used to describe the modulated S/N of a digital radio. The Eb/No can be derived from C/N, assuming that the noise about the RF carrier is linearly translated to baseband during the demodulation process. This is often true of AM modulation (QAM, QPSK, 16QAM) but is generally not true of FM modulation (FSK, MSK). In general, any demodulation which uses hard limiting will not allow this relationship to be used.

Nyquist filtering is discussed next.
Nyquist Filtering Basics

- In a digital radio, **filtering** enables us to transmit as many bits as possible for a given bandwidth.
- The Nyquist or Raised-cosine filter is often used.
  - Bandwidth is 1/2 of data rate

The Nyquist (raised-cosine) filter is often used in digital radios. It is normally set to a bandwidth of 1/2 of the data rate, and provides optimum bit/BW efficiency in most applications.

There are some possible variations in Nyquist filtering which can affect the received noise spectrum:

A) Pulse equalization: Since we transmit using pulses and not impulses, inverse SINC equalization is applied \[ SINC^{-1} = \frac{\sin(f)}{f} \]. This EQ may be applied entirely at the transmitter (typical) or partially at the receiver.

B) Rolloff factor, \( \rightarrow \): Since ideal Nyquist filters cannot be realized, a controlled rolloff or excess bandwidth is specified, indicated by \( 0< \rightarrow <1 \).
Setting noise for BER measurements

For BER, there are two ways to precisely and predictably control the C/N and hence the Eb/No:

1) Determine the receiver Noise Figure and predict the noise power.
   But Eb/No is not controlled except by changing the design.

2) Assume a noiseless system and inject noise to control C/N and Eb/No. This is the best way!

The system noise must be under the control of the simulation so that the desired C/N can be set which then sets the Eb/No or Es/No. There are two ways to do this:

A) We can use the receiver’s noise figure to vary the noise in the system. However, this is often not intuitive and limits the options for modeling various components.

B) We can make the receiver noiseless and inject a known noise signal. This method is often found to be more flexible and is generally preferred.
A typical Baseband System

- First, let’s examine a simple baseband system.
  - Channel includes frequency-dependent distortion but not noise.

Here, baseband signals are sent down a transmission line, cable or wire. The signal may be corrupted by frequency-dependent and dispersive effects, as well as added noise. In this example, there is one noise source, which may be adjusted to define any desired signal-to-noise ratio at the input to BER measurement comparator and error counter.
Here is illustrated a basic baseband BER simulation using ADS. A data signal using +/- 1V (binary) bits is filtered, with separate transmit and receive filters representing the data transmission system. A Gaussian noise source is summed with the data signal to set the S/N and hence Eb/No of the system. A delay is applied to a copy of the original, unfiltered data signal which is equal to the total transmission delay, here set by the filters. This delayed signal becomes the reference input to the BER counter.

Two types of BER measurement counters are available. One measures only the BER, the other also measures the Es/No or Eb/No.
RF System

- Now, let us examine a digital radio. Data are quadrature-amplitude modulated onto a carrier, then transmitted.
  - The signal may be represented as a complex envelope about a carrier

\[ V(t) \times e^{j2\pi f_0 t} \]

Contains I and Q information.

- Noise must be added as a complex envelope...

In an RF system, a carrier is modulated based on the input data and some defined modulation format. In general, this signal may be represented as a complex envelope about the carrier. This offers simulation efficiency not possible if the signal is represented as a baseband signal. However, when adding noise, the complex envelope representation must be considered. Noise should therefore also be added as a complex envelope. Furthermore, it is desirable that the I and Q components of the envelope be uncorrelated.
In the RF system, data are created in the same manner as for the baseband system. Then, they are modulated, often using a quadrature scheme for higher throughput. In this case, noise added at RF should be similarly modulated starting with uncorrelated Gaussian noise sources.
BER SIMULATION STEPS:
- Configure a model of your communication system, including all effects except for receiver noise
- Control the system noise using a controlled noise source; this sets the Eb/No or Es/No of the system at the detector
- **Set up the BER measurement, accounting for the system timing and delays**
- Determine the desired accuracy of the BER measurement, and set the number of simulation points accordingly
- Consider the use of Importance Sampling to reduce the length of the simulation, if appropriate for your type of system
- Perform the simulation and evaluate
Baseband System Timing

- Use delay to synchronize test (system output) data and reference (system input) data

Some simulators may offer an automatic synch mode for BER (in ADS, set DelayBound > 0)

For correct counting of errors, both the test and reference signals must be sampled at the center of each bit or symbol. This can be accomplished by providing an appropriate delay to compensate for the system delay, or by using an automatic synchronization function, such as provided in ADS. The automated delay is given an upper bound for the delay. Then, a routine finds the optimum delay by comparing the two signals.

Some BER measurements also determine S/N and express it in a meaningful way, as Eb/No or Es/No. This is done using the measured power in the test and reference signals, plus the specified bit or symbol time period.

\[
\frac{Eb}{No} = \frac{Es}{No} \cdot \frac{1}{L}
\]

where \(L\) = number of bits/symbol
RF System Timing

- Delay of Analog/RF portions of the system is often not easily found by inspection

Hint: Using a time-domain simulator, observe the system’s response to an impulse

The RF system is seen to be similar to the baseband system, except that noise is injected at RF as a complex modulation envelope, and is uncorrelated with the transmitted signal.

As previously mentioned, the system delay must be accounted for. If an automatic synchronization function is provided, only an upper bound need be specified. If a system is modeled using only digital signal processing functions, including digital filtering, the delay can usually be found by inspection and analysis. However, if the system includes analog or RF models, the delay is often not easily obtained without additional simulation. A possible approach is to excite the system with an impulse (a signal of very narrow, ideally infinitely small width) and observe the output time domain response. Another is to graphically compare the reference and test bit streams.

Note that for an RF system, just as with noise, the impulse source should be amplitude-modulated onto an RF carrier. However, a separate I and Q impulse source is not required. This allows the simulator to sample just the impulse signal’s envelope, not the carrier itself, which is much more efficient.
The Bit Error Counter is essentially a digital comparator, for a simple binary signal. For multi-level QAM-type signals, where there is more than one threshold, the circuit is more complex but is still based on the same concept. In the above figure, an XOR gate compares the Reference and Test data, then outputs a “1” when they are not the same, indicating a bit error. An integrator sums the error signals so that its output is proportional to the number of errors found. The ratio of this output to the total number of samples is the BER.

In a simulation environment, this circuit may be provided or can be build from simple library components.
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**Accurate and Efficient BER Simulation**
BER Accuracy

Bit Error Rate is an \textit{estimate}, not an exact measurement.

- Accuracy depends upon the number of observed samples

- For some systems, a method know as \textit{Importance Sampling} can be used to reduce the required number of samples (covered later)

Measurement of BER is in reality only an estimate whose accuracy depends upon the number of samples considered. It is often referred to as a \textit{Monte Carlo} approach. For a given error tolerance, the accuracy can be predicted when a sufficient number of samples are used.

A method is available to reduce the required number of samples for certain types of digital communication systems. This topic will be discussed later.
How to determine the number of samples required...

- **Rule-of-Thumb:**
  - If the expected BER is known, use $10X-100X \text{ BER}^{-1}$ samples
  - Example: For QAM, $\text{BER}=10^{-6}$, use $10^8$ samples for a relative variance of 0.01 (99% confidence)

- **Observation:**
  - Measure BER vs. Time. Estimate will converge to a nearly constant value (within the variance)

The required number of samples can be predicted using several methods. One is a “rule of thumb” which states that one can use 10 to 100 times the inverse of the expected error rate samples. If a factor of 100 is used, the relative variance is 0.01, which is a reasonable accuracy for most purposes. Another method is to observe the BER vs Time. The estimate will vary a large amount for the first few samples, then will converge to a more constant value. When that value is within the desired variance, it can be concluded that sufficient samples have been taken.
This nomograph shows the required number of samples as a function of the BER and Es/No. The curve labeled “PE” is a familiar “waterfall” curve of the error probability vs. Es/No. “MC” indicates that the *Monte Carlo* method of estimation is being used, which is the type discussed herein.
This graph indicates the BER vs. Time (here the number of symbols is shown on the x-axis) for a digital radio system. The BER estimate varies greatly at first, then settles or converges to a more constant value of about 0.06%.
BER SIMULATION STEPS:

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- Perform the simulation and evaluate.
**Ways to Improve Efficiency**

**Problem:**
Estimating the BER takes a lot of time...

- Standard Monte Carlo techniques require 100 to 1000 more samples than the error rate itself
  - For a typical BER of $10^{-6}$, you would need 10 to 100 million samples!

- In many cases, we need only a small fraction of these samples if we use *Importance Sampling*

BER estimation is often too time-consuming to be practical. The standard Monte-Carlo technique requires 2 or 3 orders of magnitude more samples than the error rate itself. Often, we can use Importance Sampling to reduce the required number of samples to a small fraction of this.
As shown in this nomograph, a system with an error probability of 1 error in 10,000 symbols would require 100,000 simulation samples using Monte Carlo, but only 1,000 samples using Importance Sampling.
A binary signaling system is illustrated here. The probability of a +1V or -1V signal is shown by a Gaussian distribution (Probability Density Function or PDF). The portion of one value’s PDF that overlaps into the other’s space represents the error probability for that value. Sometimes, a signal will exist in that space and thus cause a decision error.
In Importance Sampling, the system characteristics are modified during simulation to change the PDF. In the Conventional Importance Sampling (CIS) approach, the variance of the PDF is changed so that there is a greater probability of an error and at the same time obtain a minimum variance of the BER estimate. In the Improved Importance Sampling method (IIS), the variance of the PDF is unchanged but the PDF is shifted. In this way, error events occur more frequently, and the BER estimation variance is much smaller than that of CIS. For a system with memory (for example, the system includes filters) the IIS method is much better than CIS based on the simulation variance calculation. Therefore, IIS is the preferred method for improving the efficiency of BER measurements.
When can Importance Sampling be Used?

- Improved Importance Sampling is valid only when the system uses an amplitude modulation technique:
  - PAM, QAM, QPSK, DQPSK, Pi/4DQPSK

- Improved Importance Sampling is valid only when the system noise can be considered a linear process:
  - This is true for AM system when the noise is much lower than the signal.
  - This is not true if a limiter or hard-decision detector is used.

The Agilent Ptolemy Improved Importance Sampling method can only be applied to systems which meet certain guidelines. The system must:
- use an amplitude modulation and demodulation method, such as PAM, QAM, QPSK, DQPSK, Pi/4DQPSK
  **AND**
- system noise is not greatly affected by non-linearities in the system

The IS estimator uses a noise source which is keyed to the energy per symbol, Es, found by examining the transmitted signal.
The faster simulation using Importance Sampling is illustrated by these simulation results for a QPSK radio. The IIS method takes only 8 seconds, compared to 182 seconds for Monte Carlo.
This ADS schematic incorporates all of the concepts that we have discussed. An ideal RF system is modeled, with proper injection of complex carrier noise to control the Eb/No, and reference signal delay is applied to synchronize it to the test signal. The delay in this system is due to the filters in the modulation and demodulation process, which is not shown here in detail. The BER measurement method, Monte Carlo or IIS, is selected by using an appropriate measurement “sink”.

BER Simulations - 32
Summary and Review

NOTE: Answers are in the notes page...

- BER simulations require an understanding of system noise effects.
  - Baseband and RF Systems are different!
    1) Review question: In what way are they different?

- BER simulations require precise timing of the measured test and reference signals.
  2) Review question: What is one possible technique for finding the system delay?

Review answers:

1) Noise in baseband systems can be controlled by simply summing Gaussian noise with the data signal. RF systems require that the noise be summed as a complex signal envelope, about the RF carrier.

2) Excite the analog parts of the system with an impulse signal and observe the response using a time-domain simulator.
Summary and Review

Continued...

• BER simulations will be only as accurate as the number of samples allows

  3) Review question: What is a common “rule-of-thumb” used to determine the required number of samples?

• BER simulations can be made more efficient by use of Importance Sampling

  4) Review question: What assumptions must be made when Importance Sampling is applied?

Review answers:

1) The required number of samples is 10 to 100 times the error rate, depending on the desired variance of the BER estimate.

2) IS may be used when the system uses amplitude modulation and noise is not affected by non-linearities.
References

End of Design Seminar...
ADS Project and Exercises (1)

- Project name: BER_IISvsMC_prj
- Exercise 1: Sweeping Es/No for MC BER
  1) Open the design BER_MC
  2) De-activate all Timed sinks and set the berMC parameter berOutput = ber only to reduce the dataset size
  3) Activate the Parameter Sweep item and simulate (hint: use Simulate>Setup to change the dataset name; this retains the original dataset which doesn’t use the sweep - the data display uses BER_MC_vsTime)
  4) Display the measurement b1 on a table (list) to observe BER vs. Es/No or use the data display BER_Sweep. Simulation time is about 280 seconds under Win NT, PIII/650 MHz
Exercise 2: Using the Impulse Response to find the system’s time delay

1) Open the design Impulse_RF_Basic

2) Open the data display Impulse_RF. If no data is shown, simulate the schematic design to observe the impulse response.

3) Adjust the marker (hint: select the marker with the cursor and use the left/right arrow keys to move the marker) to find the nominal system delay (19 usec).

Optional: If the Circuit Envelope simulator is available, activate the sub-network and repeat the test using it instead of the filter and mixer. Note that the impulse response will be inverted.
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