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Bit Error Rate: Fundamental Concepts and Measurement Issues

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This tutorial describes the principles of bit-error rate, the factors that affect it, and the methods for its measurement, but with a recommendation that readers do further study of its mathematical basis

One of the changes that modern digital communications systems has brought to radio engineering is the need for end-to-end performance measurements. The measure of that performance is usually bit-error rate (BER), which quantifies the reliability of the entire radio system from "bits in" to "bits out," including the electronics, antennas and signal path in between.

On the surface, BER is a simple concept—its definition is simply:

$$BER = Errors / Total\ Number\ of\ Bits$$

With a strong signal and an unperturbed signal path, this number so small as to be insignificant. It becomes significant when we wish to maintain a sufficient signal-to-noise ratio in the presence of imperfect transmission through electronic circuitry (amplifiers, filters, mixers, and digital/analog converters) and the propagation medium (e.g. the radio path or optical fiber).

Any in-depth analysis of the processes that affect BER require significant mathematical analysis. I will not attempt to do that in this short introduction and overview.

Noise and BER

Noise is the main enemy of BER performance. Noise is a random process, defined in terms of statistics. The noise introduced by the circuitry is described with a Gaussian probability density function, while the signal path is usually described with a Rayleigh probability density function. A Rayleigh, or fading, signal path is not "noise" in the intuitive sense of the familiar hissing sound of "white noise," but it is a random process that is analyzed in the same manner as Gaussian noise.

Without going into detail, the mathematical representations of these functions allow the analysis of a system to help predict its performance. Further study of noise and statistical signal analysis is highly recommended.

Quantization errors

Quantization errors also reduce BER performance, through incorrect or ambiguous reconstruction of the digital waveform. This is also a described by a probability function that defines the likelihood that a digital transition or edge detection error will occur. These errors are primarily a function of the accuracy of the digital-to-analog and analog-to-digital conversion processes, and are related to the number of bits used at these points in the circuit.

The accuracy of the analog modulation/demodulation process and the effects of filtering on signal and noise bandwidth also affect quantization errors.

E_b/N_o and BER

BER can also be defined in terms of the probability of error (POE),

$$POE = \frac{1}{2}(1 - erf)\sqrt{E_b / N_o}$$

where *erf* is the error function, E_b is the energy in one bit and N_o is the noise power spectral density (noise power in a 1 Hz bandwidth). The error function is different for the each of the various modulation methods. What is more important to note is that POE is proportional to E_b/N_o, which is a form of signal-to-noise ratio.

The energy per bit, E_b, can be determined by dividing the carrier power by the bit rate. As an energy measure, E_b has the unit of joules. N_o is in power (joules per second) per Hz (seconds), so E_b/N_o is a dimensionless term, or simply, a numerical ratio.

Factors Affecting BER

One way to lower the spectral noise density is to reduce the bandwidth, but we are limited by the bandwidth required to transmit the desired bit rate (Nyquist criteria). We can also increase the energy per bit by using higher power transmission, but interference with other systems can limit that option. A lower bit rate increases the energy per bit, but we lose capacity. Ultimately, optimizing E_b/N_o is a balancing act among these factor.

BER Measurement

While the basic concept of BER measurement is simple—send a data stream through the system and compare the output to the input—its execution is not trivial. Over an infinitely long period of time, we can assume that a data transmission is a random process. However, we don't want to wait forever to make a BER measurement! So a *pseudorandom* data sequence is used for this test. We call it "pseudo" random because we cannot create a truly random signal using deterministic (mathematical) methods. Fortunately, some smart mathematicians have worked out sufficient approximations of random behavior so we can quickly make accurate BER measurements.

The next measurement issue is a practical one—we don't want to completely install our system to make the test. It would be far too costly and time-consuming to build entire radios and install them with transmission lines, towers and antennas, just to test the bit-error rate performance of a particular filtering scheme or demodulation circuit.

Let's go back to the subject of noise. Radio noise is Gaussian in its spectral power density. This includes semiconductor junction noise (in full conduction) and thermal noise in resistors. Specially-designed "noise diodes" can be used to generate noise with predictable spectral characteristics, which can be added to the signal path in a controlled laboratory environment.

It is also possible to add Rayleigh (fading) characteristics to the signal, using multiple channels with variable time delays to simulate changing path conditions. The combination of Gaussian noise and Rayleigh fading have become extremely important in the development of new digital communications equipment and systems, since they allow convenient testing. The mathematical nature of digital signal transmission also allows computer simulation, but with the practical limits imposed by production variations in system components.

How do we use BER data?

When BER threatens the usefulness of a system, there a many courses of action. First, the troubleshooting process must identify the cause of the errors. Is it circuit-related or path related? What is the cost of the remedy? Should we improve the hardware, pursue changes to the transmission environment, or choose a different modulation format?

Sometimes the solution is software-based error correction. These techniques have been used for many years in terrestrial and satellite communications.These come at a cost of lower data throughput, but they can effectively reduce BER.

This short introduction cannot describe all issues related to BER, but we hope it encourages you to do additional reading and study on this important topic.