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Tutorial

Optimizing Link Performance, Cost and Interchangeability by Predicting Residual BER: Part I - Residual BER Overview and Phase Noise

The demand to put more data through the channel has driven the industry to complex modulations that require low phase noise oscillators and low distortion power amplifiers. While design tools such as link power budgets are excellent for predicting performance at threshold, a different analysis is needed for 'normal' receive power levels. Residual bit error rate (BER) prediction allows the radio designer to determine the phase noise and linearity requirements for a given quality of service.

Quadrature amplitude modulation (QAM) bit error rate performance is thus related to key analog metrics that drive cost. The recent growth of the broadband market has created much interest in this little understood topic. This two-part tutorial begins with an introduction to the residual BER problem by identifying the primary causes, and goes on to further characterize the phase noise component. Part II will continue with the characterization of amplifier nonlinearity, concluding with the techniques for putting together a system budget and optimizing cost.

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The following quiz often helps to create interest in the subject of residual BER. Imagine you are making an expensive microwave high capacity broadband point-to-point data link, encountering these problems in final test and see what your answers would likely be.

A digital radio "dribbles" errors. The modem is then looped back on itself and is error free. Therefore the RF must be bad. True or False?

The dribbling radio's power amplifier (PA) is swapped into an error free radio link, which then begins to dribble. The PA is thus the cause of the errors. True or False?

It is possible with intermodulation distortion (IMD) and phase noise to predict if a QAM radio will dribble errors. True or False?

Phase noise has less of an effect than distortion. True or False?

Now that you have taken a minute to answer these questions, how often did you choose "false?" Actually, all of the above statements are false. Do not worry if your answers are incorrect, however; this tutorial should help clear up your questions.

This tutorial starts with a brief introduction to the residual BER problem. In addition, QAM digital radio is reviewed for those unfamiliar with the basic technology. Next, a basic noise and error probability model that is commonly found in many textbooks will be reviewed. This will serve as a foundation for the residual BER budget process. Similarly, a review of common nonlinear distortion models is helpful before trying to begin to put the concepts into a composite system. This is followed by a discussion of composite effects. Finally, an example system budget is presented to tie all the material into a practical form for the system engineer. Frequently, radio engineers find they have been exposed to all this material but rarely have they seen it applied to the residual BER budgeting process.

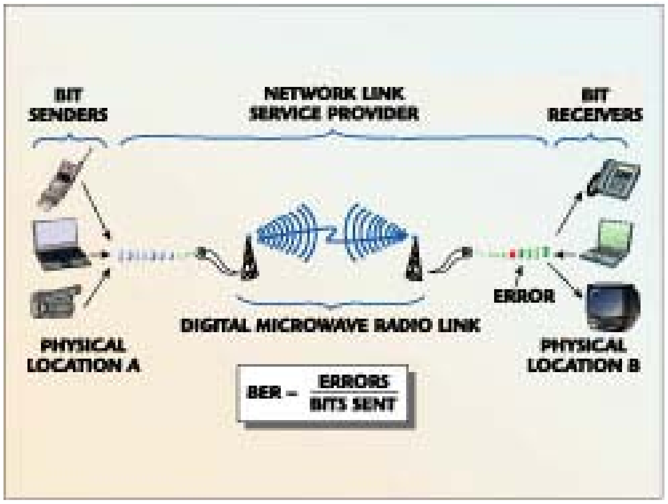


Fig. 1 What is bit error rate (BER)?

QAM Digital Radio

In any digital communications link there are bit senders and bit receivers that are physically separated. These devices are linked together through a network link, often provided by a third-party service. The network links can be wire, coaxial cable, fiber optic, microwave or some combination.

One very important measure of the quality of service (QoS) of the network link provider is the ratio of bits sent correctly to bits received in error. This ratio is called the bit error rate (BER) (see Figure 1).

Different levels of service quality are required, depending on the type of network data being transported between locations. Voice traffic will tolerate much higher error rates than data traffic. Digitized voice can tolerate bit errors as high as 1 bit per thousand bits sent or 10-3 BER. Computer data demands bit error rates of 1 per million to 1 per trillion or BERs of 10-6 to 10-12 depending on content. For example, Internet surfing does not demand the same quality of service as bank fund transfers or nuclear power plant control. BER is thus an important part of the network operator's service offering.

What is "residual" BER? In a microwave data link the BER is a function of the received signal level (RSL) sometimes called received signal strength (RSS). Very weak signals cause many bit errors. The transition from few errors to many at low power is called "threshold." A considerable body of knowledge exists on predicting threshold because it is a key factor in determining the maximum physical distance of the data link and its availability to transport data due to atmospherics. As the received signal strength increases, the error rate will fall to a very low level or error floor. This error floor is called the "residual" bit error rate or residual BER, as shown in Figure 2 . It is the "normal" operating performance of the data link. As the received power is increased, the receiver will ultimately reach an overload point where the error rate increases quickly. This article focuses on a somewhat different approach for predicting residual BER, from those traditionally used at threshold.

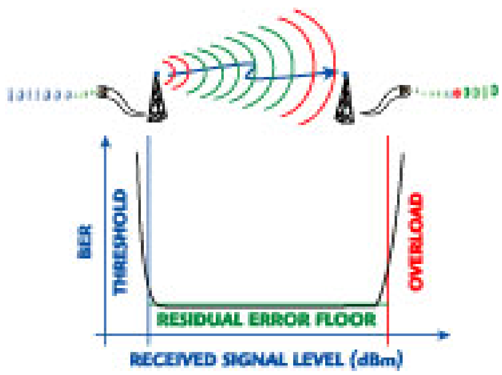


Fig. 2 What is residual BER?

Why is residual BER important? The network provider's customers demand a certain QoS based on the type of data payload being carried. The better the QoS, the bigger the potential market. Thus the network provider uses residual BER as a measure of the quality of the equipment he has purchased. Unlike threshold and dispersive fade margin, key availability metrics, residual BER characterizes the radio in its "normal" operating RSS range. This is the performance the network provider will experience most of the time. Residual BER measures the combined effect of the digital radio's modulator, transmitter, receiver and demodulator. It is thus a combined evaluation of the entire link. In essence, it is a single measure of a broadband radio link's QoS. Residual BER is a metric defining the service performance, similar to the link budget's fade margin, that defines the availability of the service (99.99 percent of the time).

Residual BER is a key performance metric, but why is it so valuable to be able to predict it? Residual BER prediction guarantees that modem and RF will integrate together to deliver a consistent error floor performance. The measurements used to confirm residual BER prediction budgets allow the technician to separate modulator, transmitter, receiver and demodulator issues, where loop-back and error vector magnitude (EVM) techniques cannot.

Many vendors are now providing products with capacity upgrade paths by increasing the complexity of the radio's modulation. Residual BER prediction allows manufacturers the ability to upgrade modems in the future with confidence that the present RF will support it, since the residual BER budgets assure interoperability between different receivers or transmitters. Equally important, a residual BER budget is essential for assuring that consumer premise equipment (CPE) units won't dribble errors when deployed years after the base station. Residual BER budgets are an essential element for cost optimization of the sources and power amplifier, two of the most expensive pieces of any radio link. The most important contribution of residual BER prediction is that it relates key analog metrics to digital bit errors. This bridges the gap between the network provider's QoS metric and the radio engineer's analog metrics.

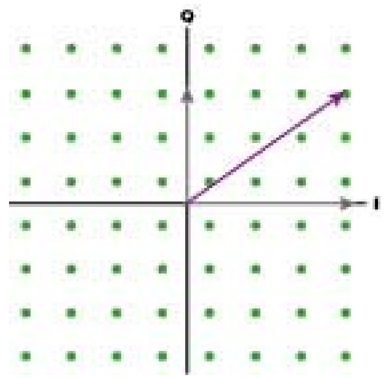


Fig. 3 Digital radio QAM.

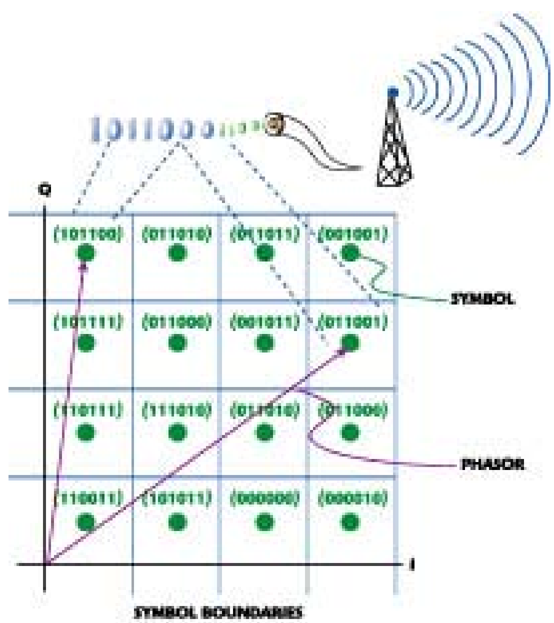


Fig. 4 The QAM constellation (only one quadrant is shown).

Most modern digital radios use QAM or some form of it. It is created by taking two vectors which are 90° apart and amplitude modulating them, then summing them together to form a resultant vector. The resultant vector can be modulated in both amplitude and phase. This vector, or "phasor," can be directed to any number of points, which represent a symbol constellation, as shown in Figure 3 . Typically, the number of points in the constellation is related to a power of 2 (2n) to make digital processing easier. In the remainder of this tutorial the 64 QAM symbol constellation will be used in the examples (the techniques are equally applicable to other QAM configurations). Often for simplicity, only a single quadrant of the 64 QAM constellation is shown. Each symbol represents several bits, allowing more information to be sent with each sample of the vectors position, as shown in Figure 4 . Sending several bits with each sample has the advantage of decreasing the rate at which the vector is modulated, thus decreasing the RF bandwidth required to transmit a given amount of information. Decreasing the RF bandwidth requirements provides high spectral efficiency, which is often a concern with broadband modulations. On the receive side, the vector is matched up with the symbol that it best fits and bit values are reassigned.

A review of the process in shown in Figure 5 . In a typical digital radio, bits come to the modulator and are mapped to a symbol point. The vector is then driven to that symbol point. The signal is then up-converted to a high frequency (filtering has been omitted), which radiates easily and where sufficient bandwidth exists to carry the required data rate. The up-converted signal is boosted in power with the power amplifier (PA) and directed out through the antenna towards the receiver. The signal then travels to the receiver suffering attenuation and some distortion from the path. Upon receiving, the signal is amplified and down-converted to a frequency where signal processing is least costly. The demodulator then compares the phase and amplitude of the vector, and makes a decision on which symbol fits best, followed by assigning the representative bits.

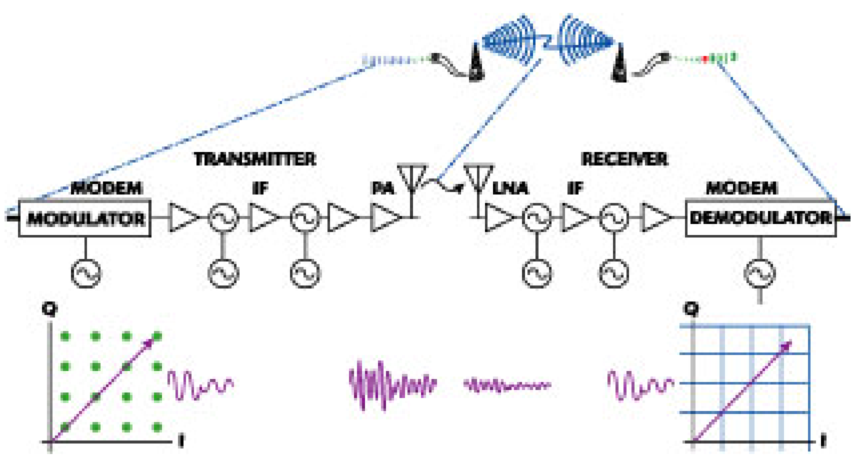


Fig. 5 System diagram using a typical double conversion transceiver.

Ideally, at the receive demodulator, a single infinitesimally small sample point would be found in the center of the symbol boundary area. Unfortunately, this ideal case never occurs because there is always noise, distortion and interference components present. Random noise has the effect of creating a distribution of sample points. Phase noise is similar to random noise but is only on the angular axis. AM/AM distortion causes the symbol point to fall short of the desired point on the radial axis based on vector length. AM/PM distortion causes the symbol point to take on an angular error based on the vector length.

Delay distortion (sometimes called inter-symbol interference (ISI)) causes the symbol point to be distorted based on the previous symbol point. Finally, spurious interference will cause the point to take on a circular shape. These different types of receive problems are illustrated in Figure 6 .

These are all unwanted signal impairments, which make the symbol decision process imprecise and result in bit errors. Many of these receiver problems are usually dominated by several key system elements. Generally, they fall in two categories, noise sources and distortion sources (see Figure 7).

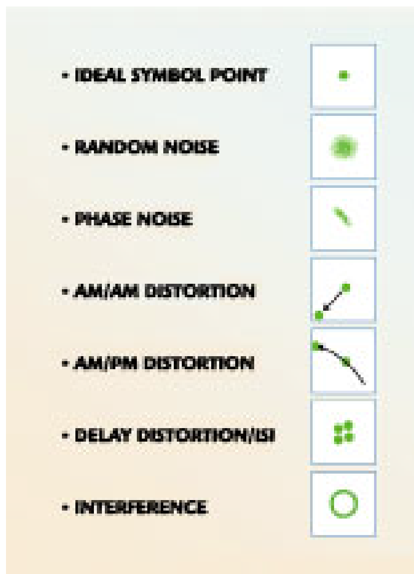


Fig. 6 Types of receive problems.

Fig. 7 Primary noise and distortion elements.

Local oscillators used in modulation and demodulation, as well as the up- and down-conversion LOs, are primarily responsible for the phase noise component. The receiver noise figure is a primary cause of the random noise. The transmitter power amplifier and the receiver first mixer are the most common sources of distortion components, such as AM/AM and AM/PM.

It is interesting to note that these components often represent the majority of the cost of a broadband wireless link. Typically 60 percent or more of a radio cost is in the sources and power amplifier. Each of these sources of constellation problems has a unique impact on the BER performance, as shown in Figure 8 . At threshold, receiver noise dominates the BER error mechanisms. At overload, receiver distortion, primarily in the first mixer, dominates the BER error mechanism. The residual error floor is dominated by a combination of the phase noise from all the sources and the PA's distortion.

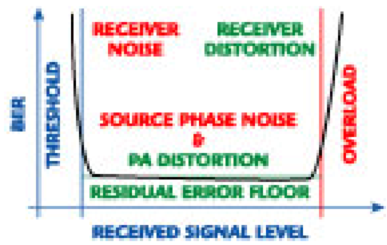


Fig. 8 Primary BER influences.

The remainder of this article focuses on the residual BER floor. It is important to note that the techniques to follow are equally applicable to overload and threshold. The dominant component(s) of error differ based on the received signal level. Thus, the error versus received signal level curve is really made up of three composite terms (threshold, residual and overload). Most systems engineers are familiar with threshold calculation:

$$\text{Threshold} = C/N + NF + BW + kT \qquad (1)$$

where

C/N= carrier to noise ratio
NF = noise figure
BW = bandwidth
k = Boltzman constant
T = temperature

If C/N= 28 dB, NF = 5 dB, BW = 28 MHz and kT = -174.1 dBm at 273°K, then threshold = 28 + 5.0 + 74.4 - 174.1 = -66.7 dBm

At first glance, this may not seem related to the techniques described in this tutorial but the carrier-to-noise ratio for a given error rate embodies the analogous statistical relationship presented in this tutorial. The other parameters are used to scale the noise power level to traceable standards.

Noise and Error Probability

Now that a brief review of QAM radio has been made, let's examine a common noise and error probability model. Errors occur when the received phasor sample falls outside the intended symbol boundary. The addition of Gaussian noise creates a distribution of sample points about the mean or "ideal" symbol point. If sliced on a single axis, the probability density function (PDF) is clearly visible. This distribution, shown in Figure 9 , is similar to the "bell-shaped curve" of test scores.

The PDF area under the curve beyond the symbol boundary represents the probability of that type of error. It can be calculated by integrating the area from the symbol boundary to minus infinity.

$$P(V_Q < a) = \int_{-\infty}^{a} \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left[\frac{(v_Q - \mu)^2}{2\sigma^2}\right] dv_Q \qquad (2)$$

The central limit theorem can be used to normalize the curve to a Gaussian PDF where the standard deviation σ is used to determine the probability of an error. Error probability can then be expressed in terms of the standard deviation of samples. Thus, the primary question becomes how many sigma (σ) are there to the symbol boundary? Counting the number of standard deviations to the symbol boundary provides a means to determine the probability of a symbol error. If there is only a single standard deviation to the symbol boundary (σ = 1), then the probability of that boundary error is 3.5×10^{-1} or 35 percent. If there are seven sigma to the boundary (σ = 7), then the probability of an error is 2.7×10^{-10} , which is quite small. This is illustrated in Figure 10 .

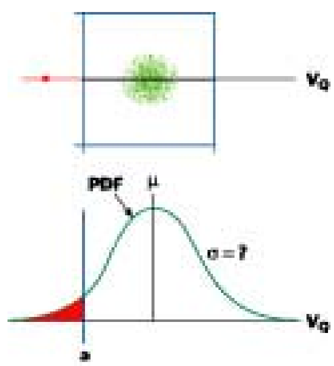
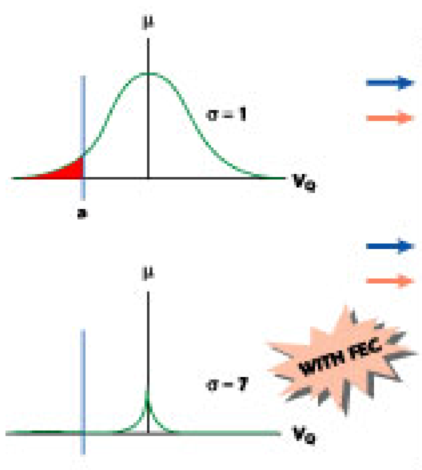


Fig. 9 Error probability.



σ	P(V>a)
1	3.5E-01
2	1.3E-01
3	1.8E-02
4	8.7E-04
5	1.6E-05
6	1.1E-07
7	2.7E-10
8	2.4E-13
9	8.2E-17
10	1.0E-20
11	4.6E-25
12	7.6E-30
13	4.7E-35
14	1.1E-40
15	8.8E-47

Fig. 10 Symbol error rate.

In practice, many higher performance wireless broadband systems compete with the low end of the fiber optic communications. Often, these broadband systems are held to the same QoS requirements as the fiber, where residual BER rates of 10^{-12} are commonplace. Raw, uncorrected BER rates of 10^{-10} are usually sufficient to achieve 10-^{12} after correction, thus providing a wireless service of the same quality as that of the fiber. The typical number of sigma to the boundary for a high quality wireless system is usually between seven and eight.

(Note: The previous paragraph is the only place in this tutorial where the effects of forward error correction (FEC) are discussed. The improvement, achieved by turning on FEC, is predictable and fixed for low error rates, hence its effects are easily factored into the raw error rate. The remainder of the discussion deals with raw uncorrected error rates.)

The preceding discussion was for a simplified random noise model often found in textbooks for the analysis of threshold noise. This model is the basis for threshold effects, which are random in all directions and only relevant at low power.

This article is concerned with "normal" operating power levels where oscillator phase noise is the dominant source of noise. Local oscillator phase noise is always present and, unlike threshold noise, is random on the angular axis. The preceding analysis was simplified to examine only a single type of boundary error. In reality, as shown in Figure 11, errors can occur on both symbol boundaries, so a "two tailed" probability model is required. The integration of both "tails" is sometimes seen as a 3 dB factor.

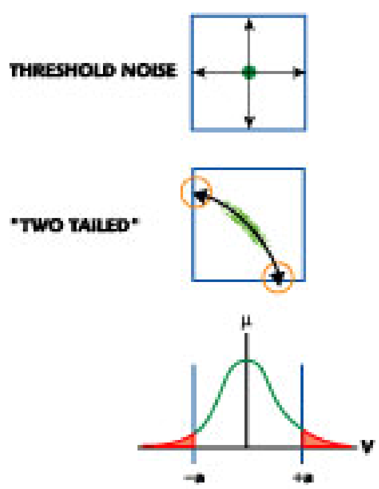


Fig. 11 Phase noise effects.

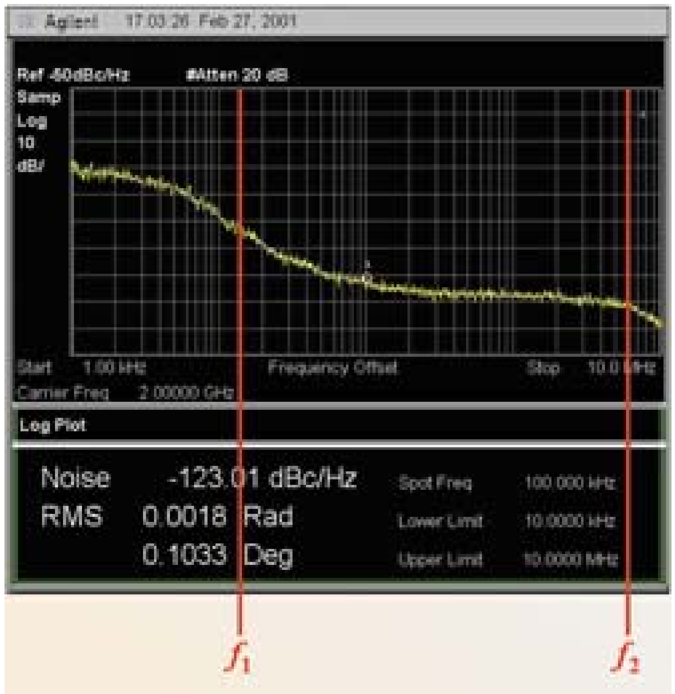


Fig. 12 RMS phase noise.

So how does one characterize and account for phase noise in the probability model? First, the fact that phase noise is a measure of the source's (local oscillator's) spectral purity or how perfect the sine wave is produced, must be understood.

The frequency (f) is the rate of change of phase with time. Phase noise is the deviation in phase from the mean rate of phase change (center frequency). Side-band noise power is rarely flat Gaussian with frequency offset and therefore must be integrated to obtain phase noise. The random nature of side-band noise necessitates the need for a root mean squared (RMS) characterization. Hence, by integrating side-band noise (the difference between the mean power and the side-band power, dBc) in an RMS fashion, phase noise is expressed as an RMS angular error in either degrees or radians (see Figure 12).

$$\Delta\phi_{RMS} = \sqrt{\int_{f_1}^{f_2} 2\,L(f_o)^2\,df_o} \qquad (3)$$

It is important to note that the limits of integration should start just outside the carrier recovery tracking loop bandwidth for the lower limit and stop at the symbol rate bandwidth for the upper limit.

One key relationship is that the one-sigma distance happens to be identical to the RMS error, as shown in Figure 13 . Often statistics courses are taught in such a way that the connection between RMS and sigma are never clearly stated to the engineer.

If there is one element of this article to come away with, it is this relationship between sigma and RMS. As will be seen, this relationship makes it possible to calculate the probability of a BER from analog metrics.

Integrating the side-band noise power over the appropriate limits gives the RMS angular phase noise in degrees ($\Delta\phi_{RMS}$) that will affect the modulation. This RMS error ($\Delta\phi_{RMS}$) represents the amount of angular degrees that are contained in one-sigma ($\sigma = 1$) of standard deviation. Knowing the angular magnitude of the one-sigma and the constellation geometry it is possible to calculate the number of sigma to the symbol boundaries, as shown in Figure 14 .

Given the number of sigma to the boundary, the normalized PDF yields the probability of that boundary error. Thus, it is possible to calculate the probability of a symbol error for each possible boundary error type in the constellation. Hence, the effect of oscillator phase noise on residual symbol errors can be calculated.

$$\boxed{\sigma = 1 \iff \text{RMS}}$$

$$\sigma = \sqrt{\sum_{i=1}^{n} (x_n - \mu)^2 \bullet P(X = x_i)} \qquad \Delta\phi_{RMS} = \sqrt{\int_{f1}^{f2} \bullet\, 2\, \mathcal{L}(f_0)^2 \bullet df_0}$$

Fig. 13 Standard deviation and RMS noise.

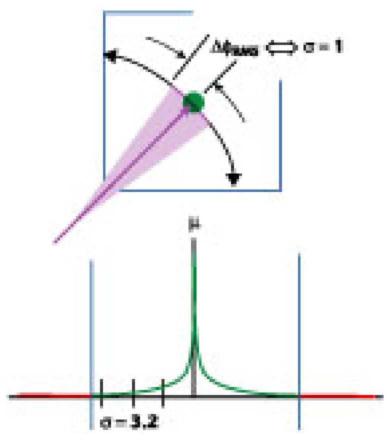


Fig. 14 Phase noise and error probability.

Summary

In the first part of this two-part tutorial, the economic case from the network operator's perspective was reviewed. It was discovered that as the residual BER performance improves, the market space is expanded. Next, the residual BER performance was found to be primarily a function of the combination of the system's sources phase noise and power amplifier nonlinearity impairments.

A Gaussian symbol distribution resulting from random noise was related to the probability of a symbol error using the standard deviation s. This was refined for the phase noise specific case by the realization that the RMS phase noise integrated over the appropriate limits is equivalent to the standard deviation. Thus, it is possible to characterize and account for the phase noise impairments effect on the symbol error rate, one of the two primary influences on residual BER.

In the next article, the effect of AM/PM distortion will be examined as to how it can be properly quantified. A system model will be assembled with an example system budget. This will provide the basis for understanding the cost ramifications involved with specifying the source phase noise and power amplifier linearity. How common mistakes in the residual BER budgeting can easily make a system's cost non-competitive will be shown, as well as why residual BER characterization with golden modems or EVM measurements cannot typically characterize the residual error floor and how to avoid deployment problems with point-to-multipoint systems.

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