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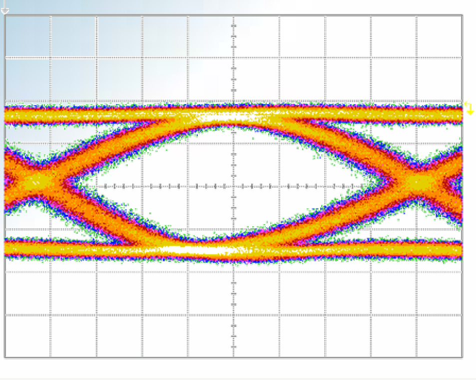
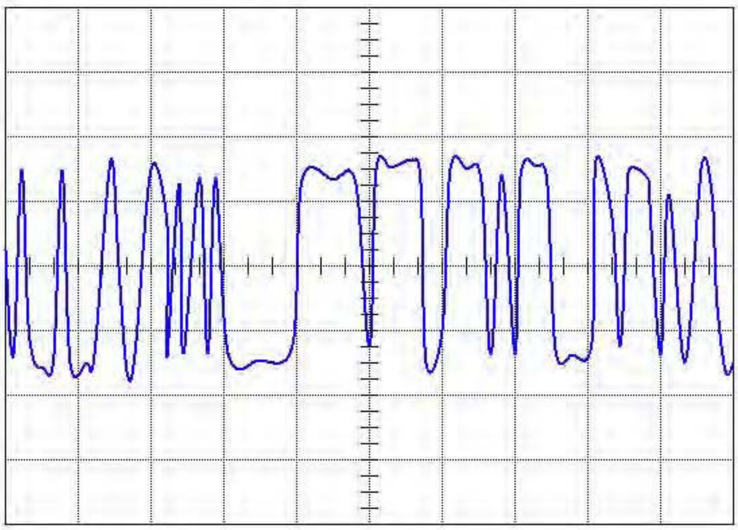


Tutorial Note #3

Broadband Communication Signals



This application note describes the signals that are used for measurements in high speed communication systems. It describes the generation of the signals as well as the analysis of these signals.

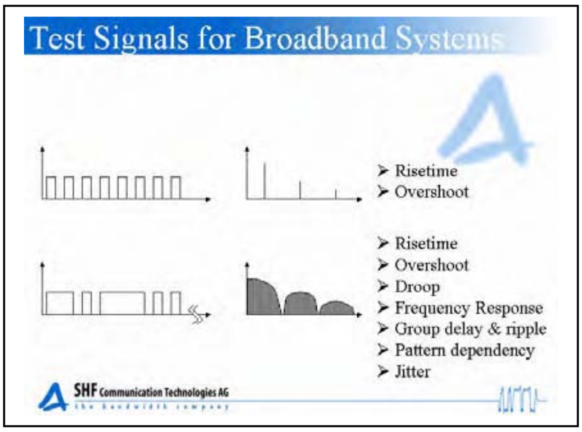
When testing high speed communication systems or components the test signals should be as similar as possible to the signals the system or component has to transmit when it is deployed.

Real life signals are completely random – in frequency domain this translates to a continuous spectrum.

As a measurement should be reproducible the test signals have to be standardized, a truly random generator might not be a good idea.

The solution to this are pseudo random bit sequences (PRBS). PRBS signals have a very long periodicity (very dense discrete spectral components) and are therefore very similar to completely random signals. On the other hand PRBS signals can be reproduced anywhere in the world without any ambiguity.

If you were to test with a sequence like 010101…. you would be testing with a spectrum consisting of a spectral line at half the data rate and its odd harmonics. Such a test signal is sufficient to measure rise time and overshoot but you would not get any information about pattern dependency, jitter and group delay and the impact of parameters like droop and low frequency cut off. To evaluate these effects you have to have a test signal with spectral components that are distributed over the entire transmission bandwidth.



Test Signals for Broadband Systems

- Risetime
- Overshoot

- Risetime
- Overshoot
- Droop
- Frequency Response
- Group delay & ripple
- Pattern dependency
- Jitter

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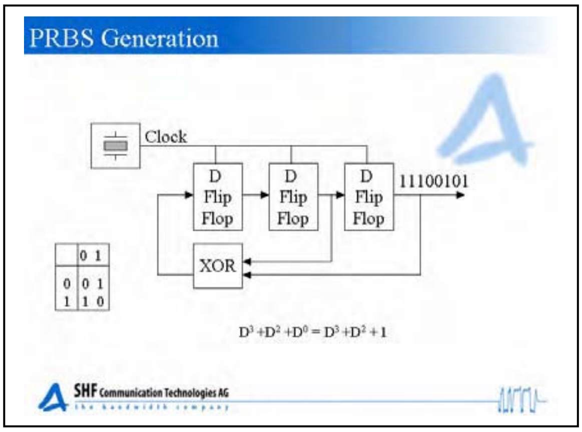
Pseudo random bit sequences (PRBS) are generated by shift registers: Some outputs of the registers are fed back via an XOR to the input. Depending upon the length of the shift register and the outputs that are fed back you will get different output patterns. For some possible combinations you will get a pattern with a maximum period before it repeats.

The maximum period is 2^n-1; where n is the amount of registers. The –1 is because a pattern consisting of n- times zeros is not possible, as it would produce only zeros. The output may or may not be inverted. The circuitry – and thus the output pattern – can be mathematically expressed by a polynomial. If we want to tap only one register output in addition to the last register output, the following polynomials give a PRBS:

(The polynomials that are commonly used and that are employed in our pattern generator are underlined.)



PRBS Generation

	0	1
0	0	1
1	1	0

$D^3 + D^2 + D^0 = D^3 + D^2 + 1$

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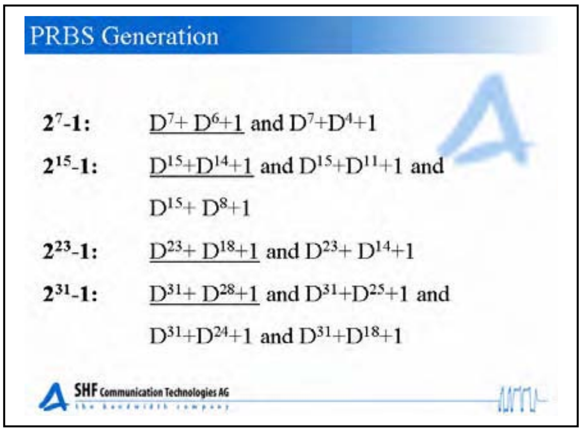

PRBS Generation

2^7-1: $D^7 + D^6 + 1$ and $D^7 + D^4 + 1$

2^{15}-1: $D^{15} + D^{14} + 1$ and $D^{15} + D^{11} + 1$ and $D^{15} + D^8 + 1$

2^{23}-1: $D^{23} + D^{18} + 1$ and $D^{23} + D^{14} + 1$

2^{31}-1: $D^{31} + D^{28} + 1$ and $D^{31} + D^{25} + 1$ and $D^{31} + D^{24} + 1$ and $D^{31} + D^{18} + 1$

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A PRBS- Signal in the frequency domain has a ${\frac{\sin(x)}{x}}^{2}$ envelope. The first zero occurs at the clock frequency.

The spacing of the individual spectral lines is the reciprocal of the period of the PRBS sequence.

Let’s calculate an example:

40 GBit/s; PRBS with 2^{31}-1

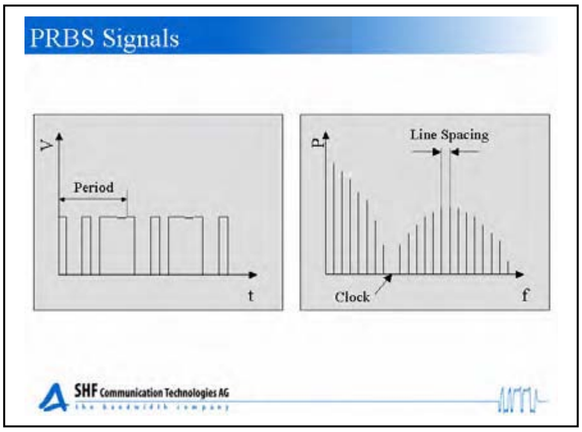
PRBS length = 2^{31}-1 Bits

= 2 147 483 647 Bits

PRBS duration = PRBS length / 40 GBit/s

= 53,69 ms

Line Spacing = 1/ PRBS duration = 18,63 Hz



PRBS Signals

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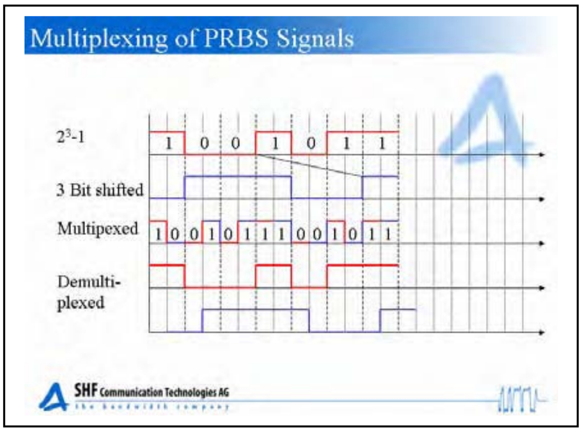
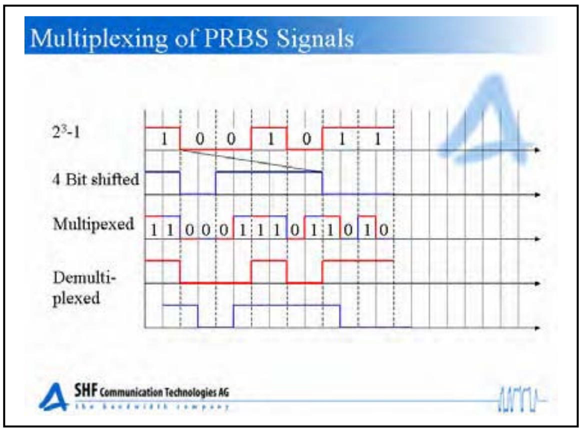
To get higher bit rates you have to clock your PRBS Generator faster or you have to multiplex the signals.
For very high bit rates, such as 10 GBit/s and 40 GBit/s multiplexing is the only practicable approach.
If done properly the PRBS characteristic of the input pattern will be maintained by the multiplexing.



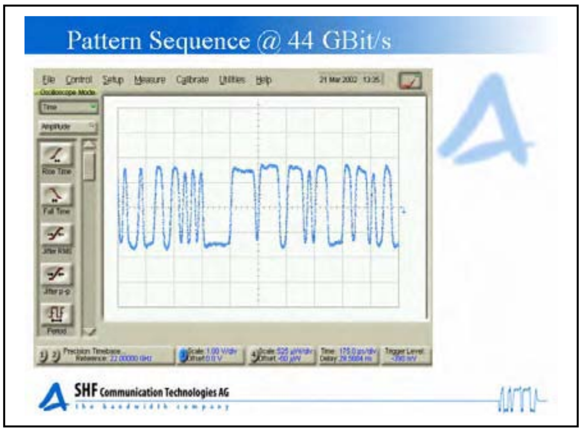
Multiplexing of PRBS Signals

When the shift of the two bit streams that are multiplexed is not correct, you will not get true PRBS at the higher (multiplexed) bit rate. Note that even if you do not have true PRBS at the multiplexed, high-speed data stream, the de-multiplexed data streams will be two true PRBS pattern again!

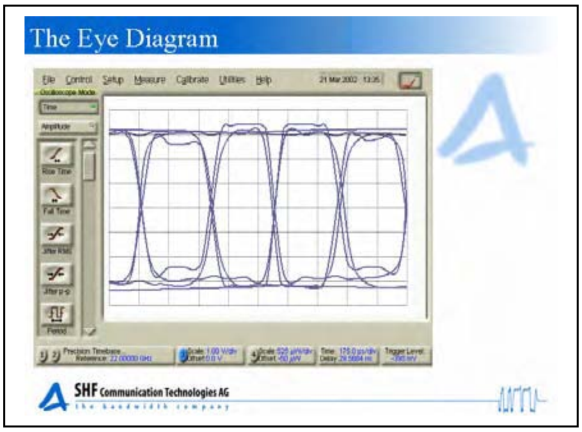


Multiplexing of PRBS Signals

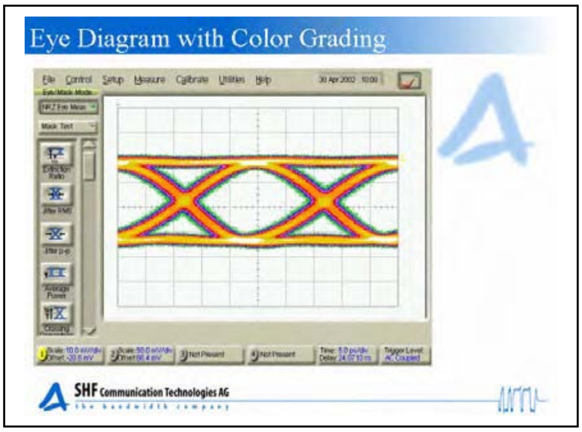
If we measure a broadband communication signal with an oscilloscope and trigger on the word frame, our signal would look as shown. As in practice the memory depth of oscilloscopes is not sufficient to capture the entire pattern, we can only see a portion of it. Of course we could increase the delay of the oscilloscope to scroll through the pattern, but for long patterns this becomes impractical and beside this, the jitter of the oscilloscope will increase with an increase of the delay.


Pattern Sequence @ 44 GBit/s

An alternative way of displaying a digital signal is the eye diagram. Here we trigger the oscilloscope with the clock of the PRBS generator or a subrate of the clock signal and superimpose many measurements.
This diagram gives a complete picture of the overall signal quality: Effects like droop, overshoot, ringing, noise, jitter and pattern dependencies can be seen on an eye diagram display.


The Eye Diagram

A further enhancement is the color grading: The color of a pixel is dependent upon the number of samples that were taken at this particular position.


Eye Diagram with Color Grading

Continuous random variables (like voltage or current) have the probability that their value lies within the interval x…x+dx according to their probability density function. A very common distribution of the probability density function is the Gaussian distribution:

$$\varphi(\lambda) = \frac{1}{\sigma\sqrt{2\pi}} \cdot e^{-\frac{\lambda^2}{2}}$$

where:

$\lambda = (x - \mu)/c$

$\varphi(\lambda)$ =Probability Density Function

μ = Mean Value

σ = Standard Deviation

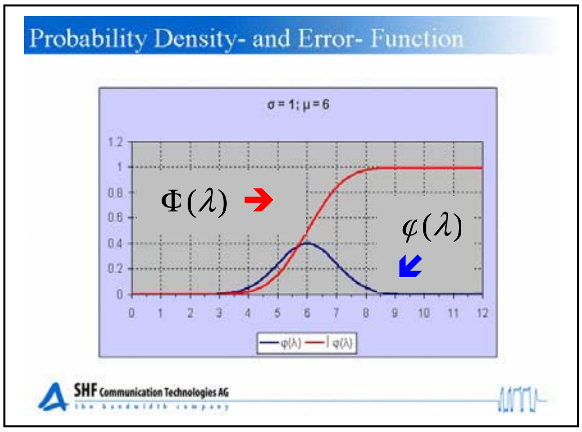
The integral of the Gaussian distribution gives the probability that x is smaller than a certain threshold x_0 .This function is also called the Error Function:

$$\Phi(\lambda) = erf(\lambda) = \int_{-\infty}^{\lambda} \varphi(t)dt$$

As this integral can only be solved by approximation or numerically there are tables for the error function.

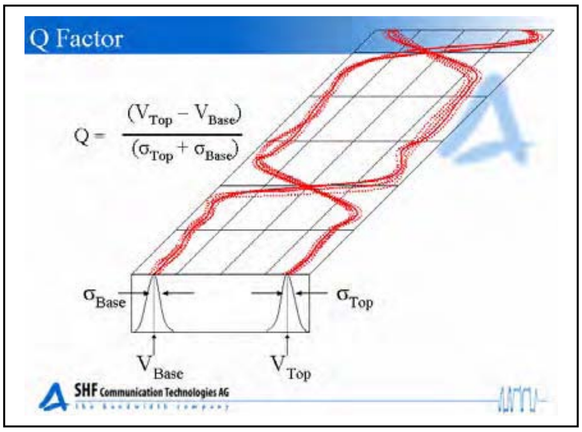
The probability that the sample is within a certain interval is:

Interval	Probability
± 1σ	68.27%
± 2σ	95.45%
± 3σ	99.73%



Probability Density- and Error- Function

This is the definition of the Q- Factor: It is based on the histogram of the amplitude. It is a measure for the quality of an eye diagram, as noise, overshoot and ringing will increase the standard deviation and therefore decrease the Q- factor.



Q Factor

$$Q = \frac{(V_{Top} - V_{Base})}{(\sigma_{Top} + \sigma_{Base})}$$

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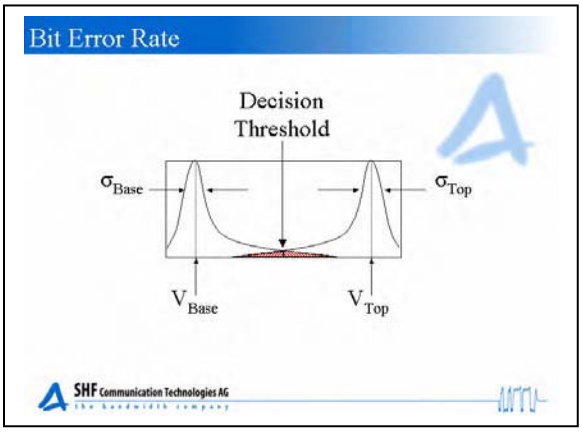
The above histogram gives a good intuitive understanding, where bit errors come from: The amplitude probability functions intercept somewhere near the decision threshold, the common area represents the errored bits. Unfortunately noise is not the only source of errors. Jitter, waveform perturbations such as ringing and non-linear effects like inter-symbol interference influence the bit error ratio (BER).



Bit Error Rate

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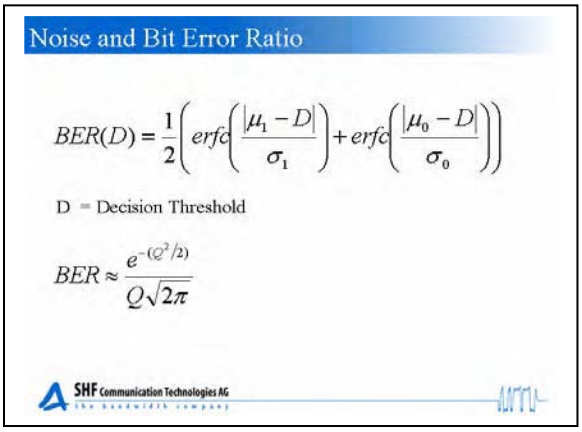
Here is a more mathematical description about the relation between noise and BER.
[erfc(x) = 1-erf(x)]
If the noise in the two logical states has identical properties and if the decision threshold is right between the high and low level the expression can be simplified.
This relationship can be used for approximation of the BER if noise with a Gaussian distribution is the predominant term.



Noise and Bit Error Ratio

$$BER(D) = \frac{1}{2}\left(erfc\left(\frac{|\mu_1 - D|}{\sigma_1}\right) + erfc\left(\frac{|\mu_0 - D|}{\sigma_0}\right)\right)$$

D = Decision Threshold

$$BER \approx \frac{e^{-(Q^2/2)}}{Q\sqrt{2\pi}}$$

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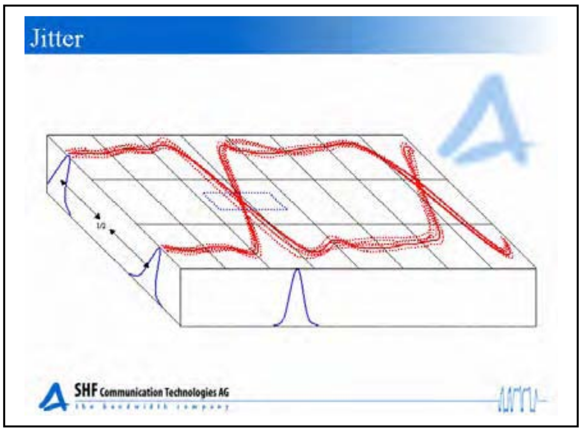
Similar to the top and base of the eye, the jitter is determined by a statistical method:
At a certain threshold (usually the crossing point) the variations of the rising and falling edge are measured and a histogram analysis gives the jitter. There are two jitter specifications: Jitter RMS and Jitter peak to peak.
Jitter RMS is the 1σ crossing; Jitter p-p is in practice the 6σ crossing (99.9999997% of the samples are within this window).
When measuring low jitter, please make sure that the oscilloscope has lower jitter than the device under test (DUT).
If the jitter of the scope approaches the jitter you want to measure correct the influence with the following formula:
$\text{Jitter}_{DUT} = \sqrt{(\text{Jitter}^2_{Total} - \text{Jitter}^2_{Scope})}$
Note: This formula is only valid for jitter with a Gaussian distribution!



Jitter

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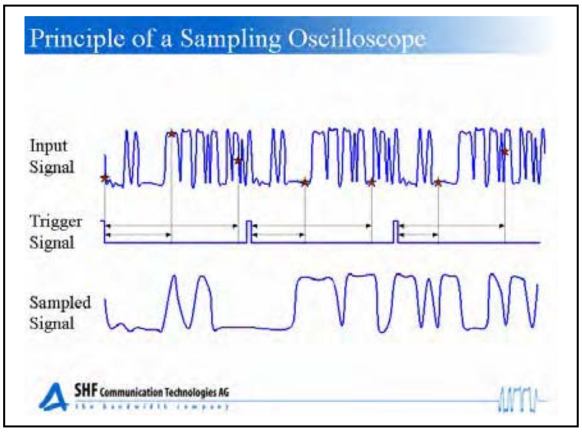
A sampling oscilloscope measures the input signal by sampling it with a relatively low sampling rate, typically around 200kHz. The samples are digitized with high resolution and the time at which the sample was taken relative to the trigger is carefully measured. By this sampling process it is possible to reconstruct the input signal with high resolution, provided that the input signal is periodical.

The disadvantage is the sampling rate: If you try to measure a bit error rate of 10^{-12} it will take you almost 80 years to measure this assuming you want to measure the BER with 100 errors and 5 samples/bit.

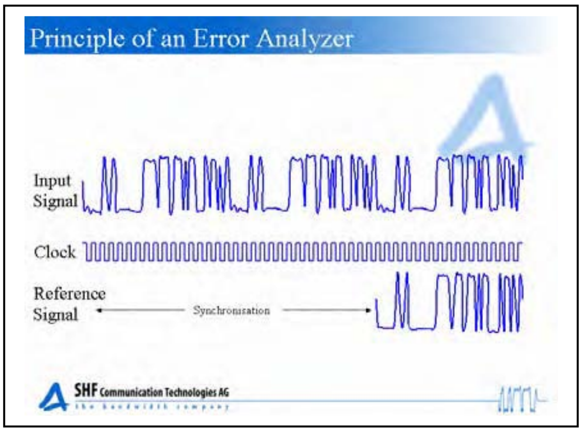


Principle of a Sampling Oscilloscope

The operating principle of an error analyzer is completely different: The error analyzer synchronizes to the incoming bit stream, once synchronization has been established it compares every bit with an internally generated reference signal. This comparison is done in real time.

In order to synchronize and to generate the internal reference signal the error analyzer has to know what PRBS signal is to be measured.

The benefit is the speed of the measurement: To measure a BER of 10^{-12} with 100 errors at 40 GBit/s will take only 42 minutes!

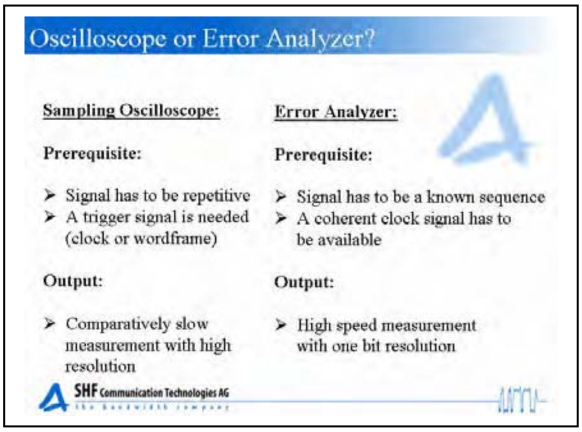


Principle of an Error Analyzer

To summarize: The sampling oscilloscope requires a repetitive signal and a synchronous trigger. As a result it will display the input signal with high vertical resolution.

An error analyzer requires a repetitive, know PRBS sequence and a coherent clock. It measures erroneous bits in real time.

As the decision point (where input data and reference data are compared) can be varied in time and amplitude the error analyzer can provide you with much more information than only the BER.



Oscilloscope or Error Analyzer?

Sampling Oscilloscope:

Prerequisite:

- Signal has to be repetitive
- A trigger signal is needed (clock or wordframe)

Output:

- Comparatively slow measurement with high resolution

Error Analyzer:

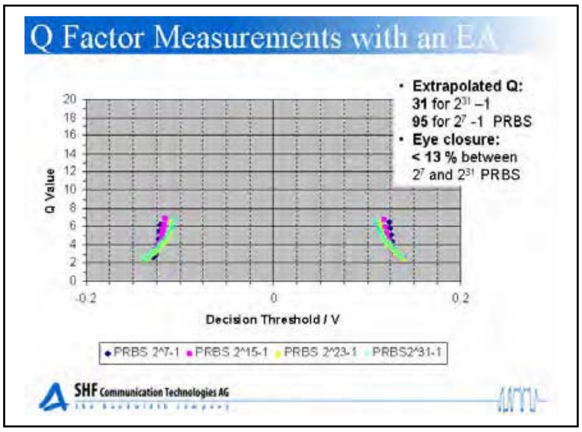
Prerequisite:

- Signal has to be a known sequence
- A coherent clock signal has to be available

Output:

- High speed measurement with one bit resolution

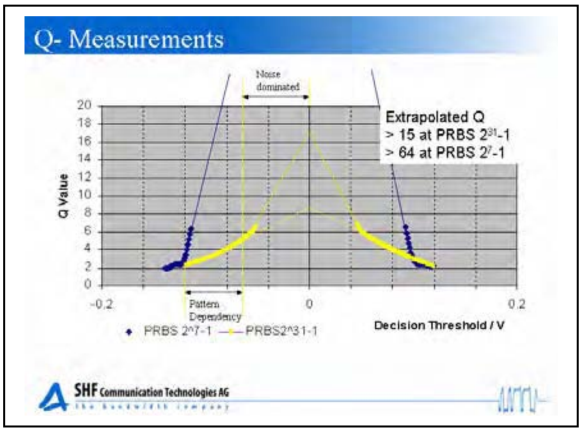
When measuring the BER versus decision threshold we see the distribution at a particular delay setting.
The measured BER can be converted to the Q factor giving you the shown diagram.
If this measurement is done for different PRBS sequences the pattern dependency can be measured



Q Factor Measurements with an EA

- **Extrapolated Q:**
  31 for $2^{31}-1$
  95 for 2^7-1 PRBS
- **Eye closure:**
  < 13 % between
  2^7 and 2^{31} PRBS

When measuring the Q factor with a oscilloscope you can not distinguish between the contribution of noise and the contribution of pattern dependency.
The measurement of Q factor versus decision threshold gives you an insight: If the decision threshold is somewhere in the middle between the high and low values the Q factor is predominately determined by noise. If the decision threshold is placed close to the high or low value pattern dependency will be the predominant term.
Of course you can make similar measurements with a fixed decision threshold and by varying the delay: This will provide you with information about the jitter behavior.



Q- Measurements

Extrapolated Q
> 15 at PRBS $2^{31}-1$
> 64 at PRBS 2^7-1