Q Factor: The Wrong Answer for Service Providers and NEMs

White Paper

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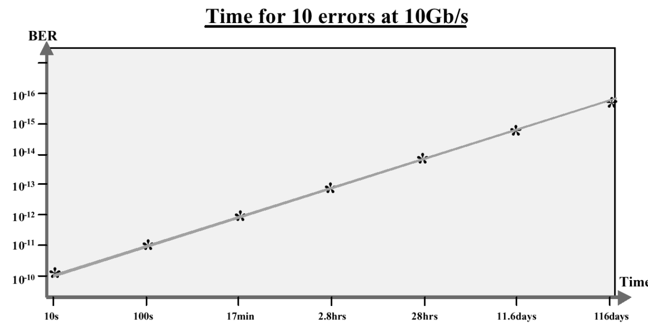
Current market conditions – throughout the economy in general and within the telecommunications industry in particular – are forcing network operators and network equipment manufacturers (NEMs) to look for every possible way to both trim costs and boost operating efficiencies. One obvious strategy for achieving both goals is to install and roll out new services quicker than before. By shortening installation times and turning up end-user services faster, network operators and their network equipment vendors hope to earn revenues more quickly. However, this strategy presents them with another time-related challenge. The service level agreements (SLAs) and quality-of-service (QoS) agreements that apply to most installation tests and equipment handovers are partly based on bit-error-ratio (BER) measurements. Given the industry-wide requirement for very low error ratios, e.g., from 10^{-12} to 10^{-15} , conducting BER tests can slow down the effort to deploy new services more quickly. Even at line rates of 2.5 Gbps and 10 Gbps, a BER test takes a considerable amount of time to achieve statistically valid results for error ratios of 10^{-12} as specified by the ITU-T and for Gigabit Ethernet or even 10^{-15} for financial transactions and banking. These measurements are typically made over 24 hours or 72 hours, depending on the line rate and individual company procedure.



This paper discusses a particular alternative to the long term BER test outlined above and is an attempt to stimulate debate about the value of this alternative method until an accurate and universally acceptable alternative is developed.

Understandably, industry players want an acceptable method that can determine error ratios faster than the traditional BER test can. One alternative to emerge thus far is Quality-Factor, or "Q-Factor," testing, which can basically be used to calculate the theoretical BER of a transmission system.

This "quick and dirty" test in fact provides a small incremental benefit in that it saves time. However, some network operators and NEM installers are discovering that Q factor, for a variety of technical reasons discussed in this paper, can be an inconclusive measurement of BER. Consequently, some who use Q -Factor testing may base their operational decisions - and hence their competitive position in the market – on misleading assumptions. Even those whose Q-Factor calculations are verified by an eventual BER test will have paid a great deal for that small incremental benefit of time saved. Indeed, the significant extra cost of adding Q-Factor test functionality is causing many service providers and equipment installers to reconsider its value and cost effectiveness, simply because they know they must eventually conduct traditional BER measurements. The BER test is not only reliable; it also is mandatory, given that the entire industry uses it as the standard measure of transmission-system quality. If, for example, the cost of a 2.5Gb/s BER tester to perform the mandatory test is $45,000 and the cost of Q-Factor test functionality is an additional $15,000, can the relatively small time savings be justified by that substantial extra investment?

Q factor Theory

To better understand what Q-Factor testing can and cannot do, it is helpful to examine first exactly what Q factor theory is. Q factor measures the quality of an analog transmission signal in terms of its signal-to-noise ratio (SNR). As such, it takes into account physical impairments to the signal – for example, noise, chromatic dispersion and any polarization or non-linear effects – which can degrade the signal and ultimately cause bit errors. In other words, the higher the value of Q factor the better the SNR and therefore the lower the probability of bit errors.

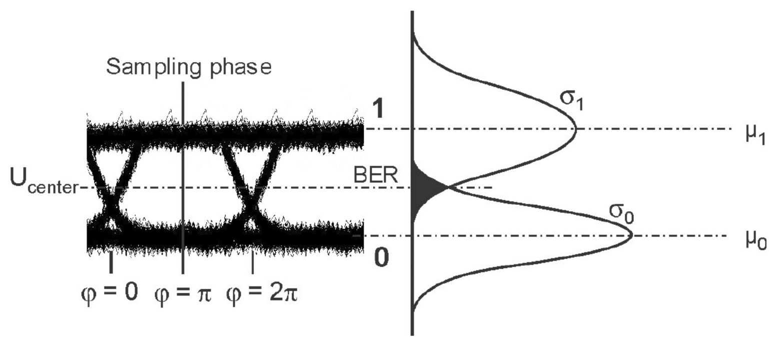
Specifically, Q-Factor represents the quality of the SNR in the “eye” of a digital signal – the “eye” being the human eye-shaped pattern on an oscilloscope that indicates transmission-system performance. The best place for determining whether a given bit is a “1” or a “0” is the sampling phase with the largest “eye opening.” The larger the eye opening, the greater the difference between the mean values of the signal levels for a “1” and a “0”. The greater that difference is, the higher the Q-Factor and the better the BER performance.

Defined in mathematical terms from the solution of $dBER(V_{th})/dV_{th} = 0$
where

$$BER\,(V_{th}) = \tfrac{1}{2}\left(\mathrm{erfc}\left(\frac{|\,\mu_1 - V_{th}\,|}{\sigma_1}\right) + erfc\left(\frac{|\,V_{th} - \mu_0\,|}{\sigma_0}\right)\right)$$

Q factor is the difference between the mean values of the signal levels for a ‘1’ and a ‘0’ (μ_1 and μ_0), divided by the sum of the noise values (ó$_1$ and ó$_0$) at those two signal levels assuming Gaussian noise and the probability of a ‘1’ and ‘0’ transmission being equal {i.e. P(1) = P(0) = ½}

$$Q = \frac{\mu_1 - \mu_0}{\sigma_1 + \sigma_0}$$



Reference 1

As illustrated above (see Ref 1), the width of the curves represents the noise in the signal. The lower the noise, the narrower the distribution curve and therefore the smaller the overlap. Indeed, the overlap area on the distribution curves is what determines the BER, for that is where the receiver has a greater chance of interpreting a ‘1’ as a ‘0’ and vice versa - misinterpretations that produce bit errors.

However, that overlap area also is the section that deviates from true Gaussian or normal signal distribution, primarily because of transmission impairments and measurement inaccuracies. This deviation from the theoretical leads to the inaccuracies in estimating BER. Various ITU-T work/study groups are trying to determine how to extrapolate the distribution curves more accurately, so as to predict the extent of this deviation more accurately and make the BER estimation more accurate. Unfortunately, until they succeed, network operators and NEM installers cannot be certain their Q-Factor measurements are producing accurate BER estimates.

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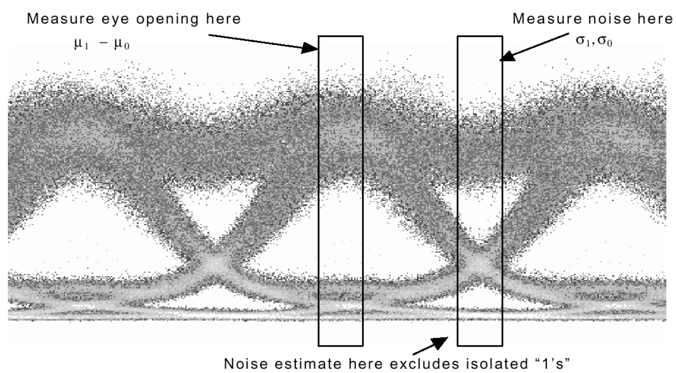
1 ITU-T Temporary Document 25 (WP 1/4) 19 April 2002
Draft New Recommendation 0.qfm

In fact, in one measurement technique (see Ref 2) the SNR is artificially impaired at the receiver to more quickly measure BER and then extrapolated to give the BER at zero impairment. However, a small change in the impairment leads to a large change in the BER, e.g. a change of 1dB in the impairment level leads to a change of three orders of magnitude at a BER level 10^{-15}.

If the estimated BER is inaccurate and the decisions based on it include replacing cards or postponing testing, then this will result in significant and unnecessary costs and delays in turning up new revenue earning services – the two things operators most want to avoid.

Q-Factor Measurement Methods Raise More Doubts

Adding to the uncertainty of what is actually measured in the Q-Factor approach are the questions about how to measure Q factor. These questions in turn raise even more doubts about the accuracy of BER estimates. There are various ways to measure Q factor today, but the two most common ones are the voltage-histogram method and the variable optical-threshold method. The first technique (see Ref 2) estimates Q factor by using a digital sampling scope to measure both voltage histograms at the center of the eye diagram and the standard deviation of the noise at both signal levels.



Reference 2

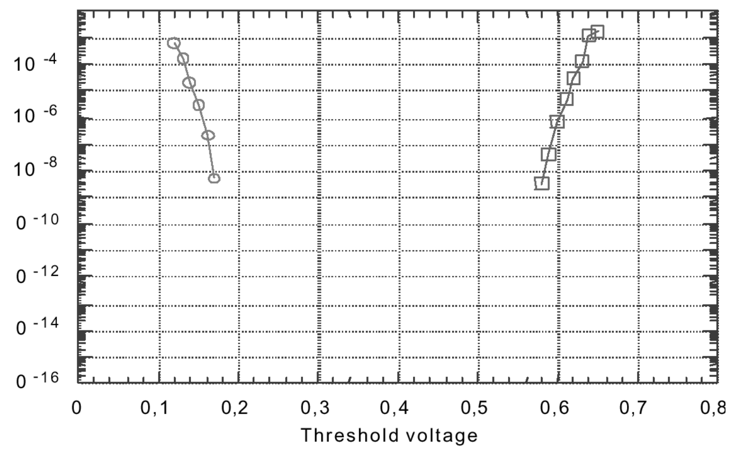
One of its limitations is the fact that the sampling rate of the scope allows only a small portion of the high bit rate to be sampled. For example, when used to measure a 10-Gbps signal, a scope with a sampling rate of 1M/sample(s) can sample only one bit out of every 100,000 bits, meaning the Q-Factor measurement is based only on a very small portion of the data stream. To make matters worse, the front end of the scope adds noise that can distort the real noise value and thus significantly skew the Q-Factor measurement.

Finally, the voltage-histogram method does not take into account the effects of intersymbol interference (ISI), or dispersion, which causes pulses to spread out so they appear in adjacent time slots. Because ISI effects can obviously broaden the estimated noise values, they can further skew the Q-Factor measurement. Although network operators and NEM installers can use a specific 1010 pattern to eliminate the ISI, they typically test their systems with PRBSs (pseudo-random bit streams) that closely approximate live traffic. Consequently, ISI effects, along with the other limitations mentioned earlier, make the voltage-histogram method a less-than-ideal choice for measuring Q-Factor – and for calculating that critical BER – in real transmission systems.

International Electrotechnical Commission IEC 61280 -2-8 Fibre Optic Communication Subsystem Basic Test Procedure
Part 2-8 Test procedures for digital systems Determination of low BER using Q-factor measurements

Variations on the Variable Decision-Threshold Theme

The other method often used to measure Q factor is the variable-decision-threshold technique, which as its name implies, uses a receiver with a variable-decision threshold to measure the BER at different decision thresholds. In reality, there are two possible methods of conducting this technique. There is a single-decision-threshold method, which network operators and NEMs run on an out-of-service basis that uses a PRBS. Alternatively, the dual-decision-threshold method is based on a dual receiver, with one input serving as the reference path and the other as the variable decision-threshold input. These two paths can be compared for bit errors. Because this type of measurement is not dependent on the data pattern, technicians can use the dual-decision-threshold method as an in-service test. In either case, the variable-decision-threshold method measures the values of the threshold voltages relative to a number of BERs in the 10^{-4} to 10^{-10} range.



Reference 3

This data is then converted to a plot of SNR against voltage threshold, using the following mathematical formula:

$$BER\,(V_{th}) = \tfrac{1}{2}\left(\mathrm{erfc}\left(\frac{|\,\mu_1 - V_{th}\,|}{\sigma_1}\right) + erfc\left(\frac{|\,V_{th} - \mu_0\,|}{\sigma_0}\right)\right)$$

in which 'm' is the mean level and 's' is the standard deviation for the '1' and '0' levels, and the complementary error function (erfc) is given by:

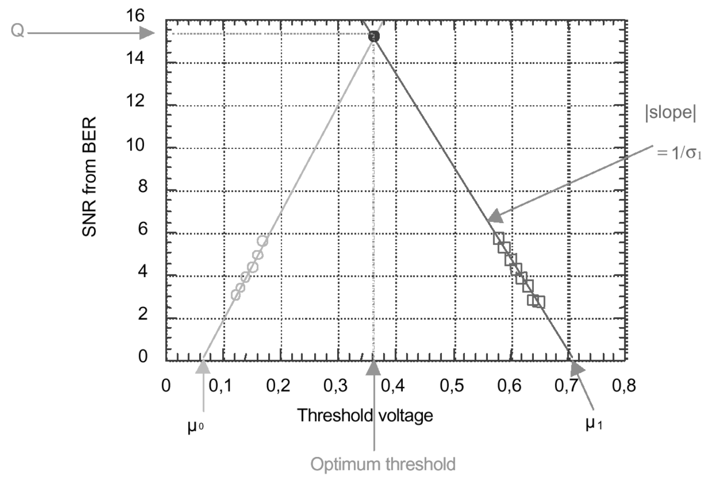
$$erfc(x) = \frac{1}{\sqrt{2\pi}} \int_x^{\infty} \mathrm{e}^{-\beta^2/2}\, d\beta \equiv \frac{1}{x\sqrt{2\pi}}\, e^{-x^2/2}$$

The first term in the BER equation is the probability of a '0' being determined when a '1' has been sent, and the second term is the probability of a '1' being determined when a '0' has been sent. These relate to the overlap part of the distribution curves where errors are likely to occur. When these values are plotted, it is possible to obtain the optimum threshold voltage and Q factor from the intersection. Because the minimum BER occurs at the optimum threshold voltage, they can calculate the value of this BER by using the following:

$$BER_{\text{optimum}} \equiv \frac{e^{-(Q^2/2)}}{Q\sqrt{2\pi}}$$

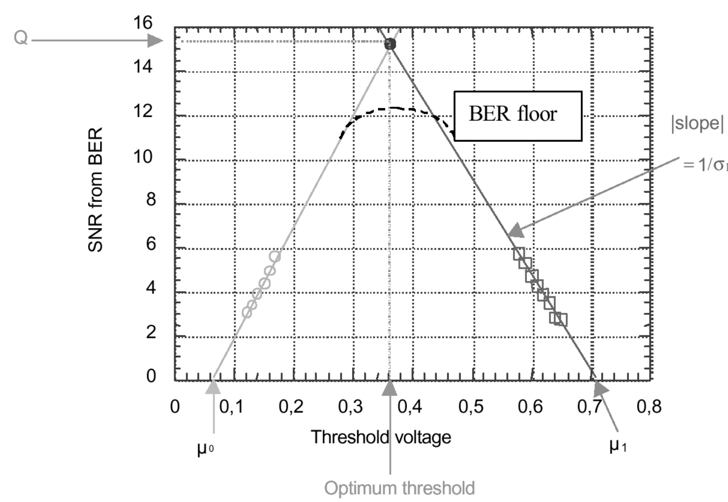
As a result, they can use a measurement of Q factor at the optimum threshold voltage to estimate the BER.

3 ITU-T G.976 (10/2000) Series G Transmission Systems and Media, Digital Systems and Networks Test methods applicable to optical fibre submarine cable systems



This is a complex measurement that needs to be carried out with dedicated test equipment, not by optional additions to existing BER test sets if real accuracy is to be achieved.

This measurement of Q factor requires an accelerated error ratio in the range 10^{-4} to 10^{-10} to achieve the short measurement times which will swamp any residual background BER. Under error free conditions, the above BER expression can be used for signal characterization although there are practical difficulties discussed in the next section. However, where there is a BER floor caused by systematic or random bit errors in the digital electronics because there is no predictive mechanism in Q measurement, it is not possible to predict the BER floor. Without carrying out a long-term BER measurement, you cannot know there is a BER floor, thus, carrying out a Q-factor measurement alone could indicate a BER that is lower than the actual.



From an Operators and Installation/Maintenance point of view, Q would be measured after the electrical to optical conversion. In this case, if there were systematic or random errors prior to this, a Q measurement would not correctly predict this value as the swamping effect would disguise the residual BER.

However, these errors are a result of a digital error in the electronics of the DUT and this would typically be a design problem which would be detected at manufacturing or conformance test and hence would not be an issue by the time the element was installed. Therefore, the BER floor issue is more a manufacturing issue rather than one for operators. It does however indicate the potential problem of this measurement.

The fact that Q measurement is only applicable to analyze a single link single direction at any one time is more of an issue for operators. End-to-end performance cannot therefore be predicted in one measurement. However, it is possible to sum the predictions from multiple sections and obtain an estimate of end-to-end performance.

Test Equipment Is Another Issue

At first glance, the variable-decision-threshold method of Q-Factor measurement would seem to solve the problem of reducing the time needed to make BER measurements on very-low-BER systems. Unfortunately, it cannot reliably replace the long-term BER measurement for all applications.

First, the receiver of the Q-Factor tester and the receiver of the system being tested will have different bandwidth and sensitivities. Secondly, they will have different characteristics, in light of the fact there is not a global standard for equipment receivers. Finally, until test set receiver requirements are standardized, the incompatibility between different test equipments will produce varied results. To clarify, if the NEM installers measure Q factor with one receiver and a service provider measures it with another receiver, they may get different results.

Consequently, the use of different Q factor test sets to calculate the BER will result in different BER values.

Yet another problem stemming from the Q-Factor receiver is the fact that it introduces even more uncertainty and difficulty, simply because it is not part of the transmission system. For in-service testing, for example, the Q-Factor test set receiver can operate at amplified optical-monitoring points; however, those monitoring points must have the appropriate dispersion compensation. Alternatively, for out-of-service testing situations such as with DWDM systems, the Q-Factor tester can operate as a replacement for the system receiver; however, an optical channel filter would be required to select the desired bandwidth.

In either scenario, test personnel must first characterize that Q-Factor tester in measurement terms, again, because it is not part of the transmission system under test. It is the only way they can know exactly how that particular piece of equipment will affect the eventual Q-Factor measurement and, ultimately, the theoretical BER.

Unfortunately, technicians do not have the necessary skills to make accurate Q-Factor measurements, even without compensation techniques or optical channel filters being considered. Such tasks require experienced engineers, a fact that further increases the cost of Q-Factor testing.

Q factor Does Have a Role to Play

In spite of the limitations of Q-Factor testing as a way to estimate BER in transmission systems, it can play an important role in manufacturing operations. For example, a manufacturer obtains greater Q-Factor accuracy by using “golden” transmitters and receivers, and calibrated equipment that takes into account the noise contributions and other limitations of test receivers. If there is any doubt as to the accuracy of the Q-Factor measurement, the manufacturer simply can substitute the “golden” receiver for the test receiver and then check the results.

Another application (see Ref 3) that lends itself to Q-Factor testing is optical-fiber submarine cable systems. Measurement techniques that have proven to be adequate during the development process are likely to verify the interface specifications for the amplified sections, which obviously do not represent the entire transmission link. Such indirect parameters include Q factor and optical SNR and accumulated chromatic dispersion. The results, when included as part of the full commissioning tests over the required stability period, can be useful as reference data for future operation, maintenance and repair of the system. However, the recommendation clarifies the Q-Factor measurement is an additional parameter representative of the amplifier margin and is not compulsory.

It's About SLA and QoS Compliance

Although service providers and NEM installation teams understandably are seeking a faster way to determine BER so they can roll out new services faster, many have decided that Q-Factor testing is neither a sufficiently accurate nor a cost-justified solution – at least not yet. As previously stated, making decisions using inaccurate BER estimates based on Q-Factor measurement must be avoided especially when it leads to unnecessary and significant extra costs and delays. In fact, even the strongest advocates of using Q factor as a means of estimating low BER – the manufacturers of Q-Factor testing equipment – concede that only a BER test can ensure the performance quality part of SLA and QoS compliance. Such a test provides actual performance results and does not rely on any assumptions, extrapolations and/or theoretical models.

Nevertheless, because the industry does need to improve operating efficiency and expedite the rollout of new services, it also needs to find an accurate short-term measurement to complement or replace the full long-term BER test. Until such a measurement emerges, however, the ITU-T recognizes the BER test as the only valid QoS method available today for evaluating the performance of a transmission system.

Accordingly, for the application of measuring the performance quality of optical systems, the author recommends that the long term BER test continues to be the method used. Although there is currently no practical alternative to Q factor measurements, they should not be used for the above purpose due to the issues raised in this discussion document.

Biography

Keith Willox has worked with Agilent/HP in the metrology, product and sales marketing departments and is currently a business development engineer for the Transmission Test group.

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