IQ reference
Error vector
Q
$I[n]_{err}$
I
Error
EVM [n]
IQ measured
$Q[n]_{err}$
eference
IQ reference
EVM [n]

Quality Measures for Complex Modulated Signals Reaching for Standardization

The reputation of complex modulation is growing rapidly due to its successful use in optical transmission. It is becoming increasingly adopted, especially in the core networks, due to its superiority over traditional on-off-keying (OOK) in terms of bit transfer efficiency.

Along with these new concepts, a new set of parameters for determining the quality of complex modulated signals and of standardized test conditions is also provided. But why should you get used to new test parameters and install new test setups if you can avoid it? Before you invest in this change, you will probably ask for the proof that any previously used method has severe limitations or even that it does not work.

In some cases where a new quality parameter provides a clear advantage in both ease of use and the cost of test, standardization will follow what is already broadly accepted and implemented.

In this application note, we analyze whether we need a new parameter to quantify complex modulated signal quality and, if so, consider the necessary steps to make this broadly accepted and standardized.

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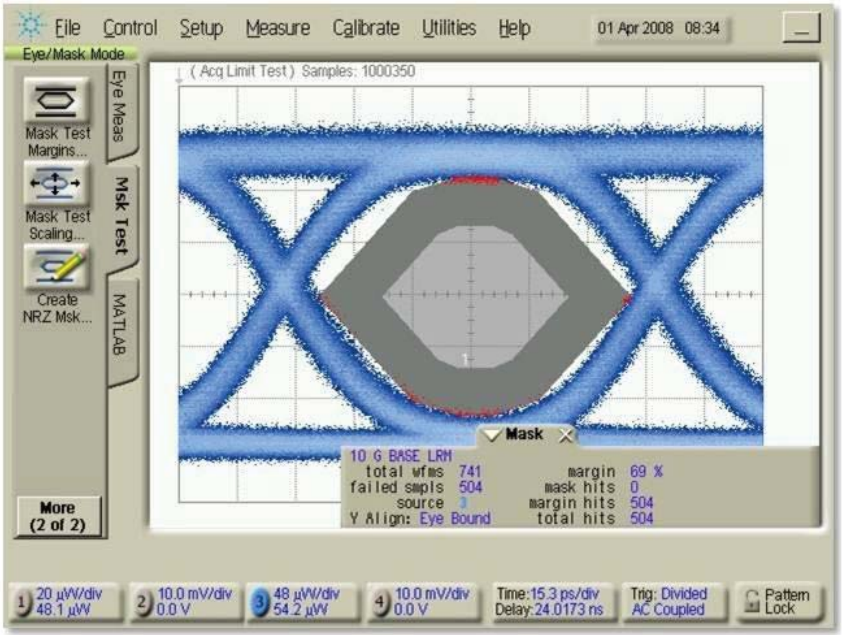
Do we need a new quality parameter for complex modulated signals?

In conventional OOK we only use one dimension to code the information onto the carrier signal, represented by the amplitude of the light. In complex modulation we typically add one more dimension on top of the amplitude — the optical phase. The quadrature phase shift keying (QPSK) modulation scheme is a special case where information is coded only in the phase of the carrier signal, but the signal is still usefully represented in two dimensions. (As dual polarization is more like an additional transmission channel than a 3rd modulation parameter, we do not need to consider this as a third dimension.) This two-dimensional coding already implies an answer to the question: "Do we need a new quality parameter for complex modulated signals?"

Before analyzing this in more detail, let us look at how on-off keying signals are typically specified and analyzed, and and how they are at their limits, when transferring this concept to complex modulated signals.

Figure 1 shows typical parameters that are derived from an eye-diagram of on-off keyed signals. In many cases, an estimate of the bit error ratio (BER) is derived from the noise distribution during the ‚1' and ‚0' amplitude segments of the signal. Assuming a Gaussian noise distribution, the Q-factor can be derived, which is then directly related to the expected BER, based on statistical rules. In addition, a hit ratio of the mask is often determined as another parameter describing the quality of the signal or system. Performance standards specify a limiting number of allowed hits of the mask. This mask is defined in a standard and the relevant influencing factors from measurement receiver behavior are standardized, for example the use of a Bessel-Thompson filter with defined bandwidth at the input of the test instrument.



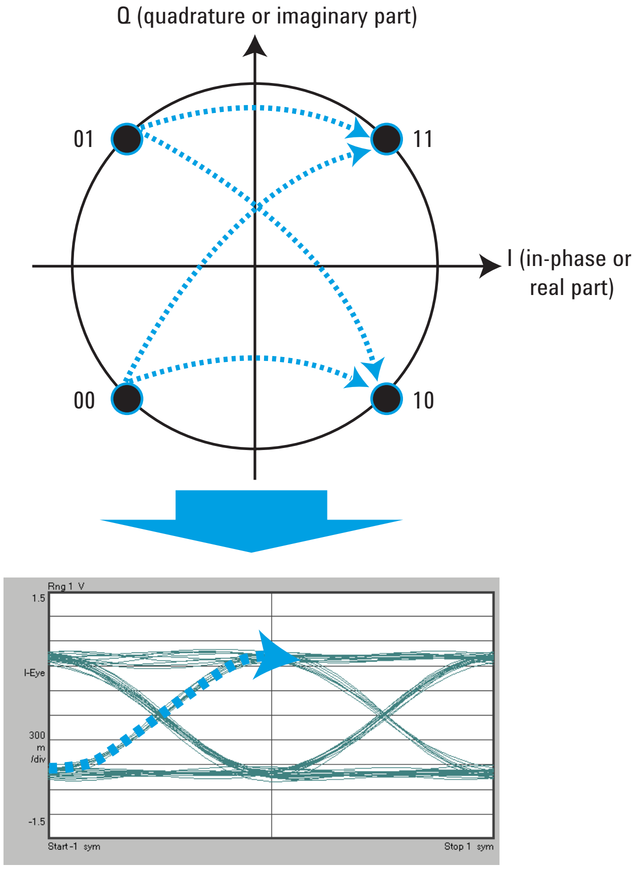
(Acq Limit Test) Samples: 1000350

```
10 G BASE LRM
  total wfms  741            margin  69 %
failed smpls  504         mask hits  0
      source  3         margin hits  504
Y Align: Eye Bound       total hits  504
```

1 20 µW/div 48.1 µW
2 10.0 mV/div 0.0 V
3 48 µW/div 54.2 µW
4 10.0 mV/div 0.0 V
Time:15.3 ps/div Delay:24.0173 ns
Trig: Divided AC Coupled

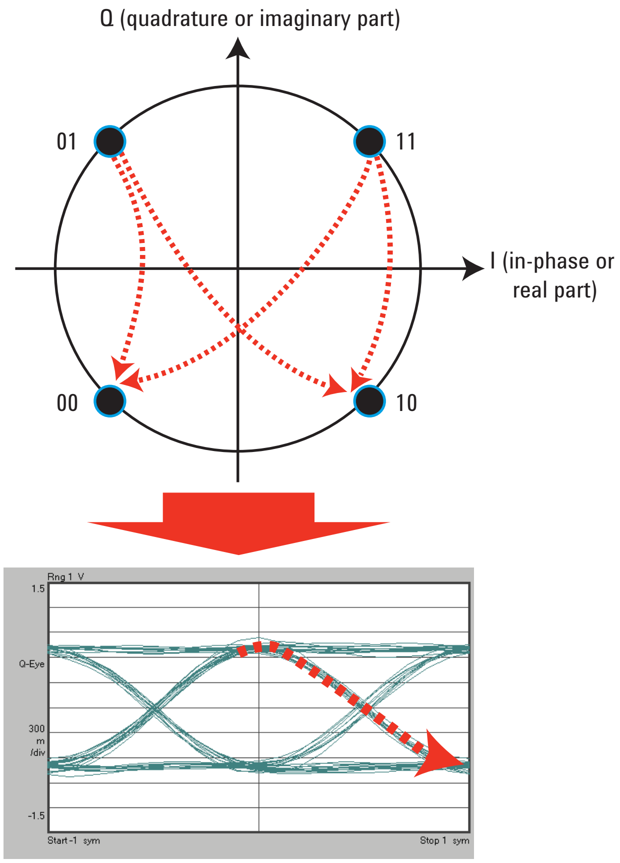
Figure 1. Eye diagram of a signal modulated with on-off-keying

Looking into the details of what an eye diagram represents when applied to a complex modulated signal, we see immediately that these are not really comparable test concepts. We will start with a QPSK signal as used on current 100 Gbit/s transmission systems. Figure 2 illustrates what an eye diagram of a QPSK signal represents. The eye diagram is a projection of the signal to the real axis or to the quadrature axis, resulting in a set of two eye diagrams for complex modulated signals.


Q (quadrature or imaginary part)
01
11
I (in-phase or real part)
00
10
Rng 1 V
1.5
I-Eye
300 m /div
-1.5
Start -1 sym
Stop 1 sym

Only I values versus time are visible

Figure 2. Eye diagram of a QPSK modulated signal



Only Q values versus time are visible

We can see for example that a transition from low to high in the I-graph does not let us distinguish whether this is a symbol transition from ‚01‘ to ‚11‘, from ‚01‘ to ‚10‘, from ‚00’ to ‚11’ or from ‚00’ to ‚10’, as shown in the constellation diagram. For the Q eye we have of course the same ambiguity, leaving doubts about the helpfulness of eye diagrams in characterizing complex modulated signals.

In on-off keying it is usual to determine the best decision level by changing the decision level in small steps and calculating the Q factor or BER at each step. The lowest BER occurs at the optimum decision level. Since a coherent receiver doesn’t decide based on an amplitude threshold, but on a two dimensional search for the nearest symbol in the constellation diagram at a distinct time, the role of the eye diagram in measuring signal quality is also less direct.

The additional complication that we have to distinguish between the eye diagrams of the I and Q projections requires a clear documentation of the assignment in test.

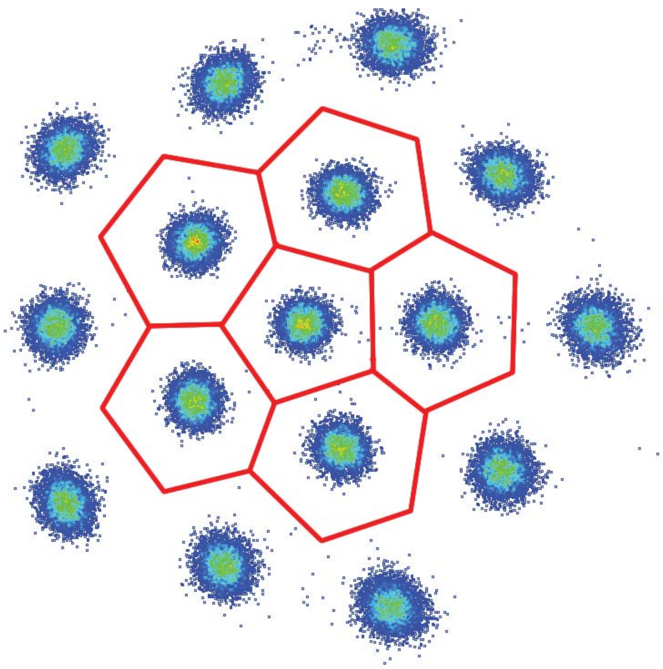


Figure 3. IQ Representation of a 16-QAM signal

Finally, consider the example of Figure 3, showing the result of a special 16-QAM constellation (Reference 1). This QAM signal has a nonrectangular distribution of the constellation points for higher robustness against distortions along an optical link. Looking at the projected axes of this signal makes it immediately clear that any signal quality measure based on eye diagram analysis would fail.

As a conclusion of the previous analysis, we cannot just keep the test concepts we used in on-off keying without severe limitations due to:

- The additional modulation dimension of a complex signal compared to on-off keying,
- The ambiguity of eye diagrams with respect to projections of the I and Q axis and
- The prospect of higher level QAM signals that make the relation between results and the eye measurement parameters nearly intractable.

As QPSK is a special case with only one modulation parameter, there are several approaches on the market, in which the concepts from on-off keying are adopted to complex modulation. This might work well for the time being, but its limitations are on the horizon.

What are the alternatives?

In the optical communication industry we are in a very comfortable situation, as we can learn from what worked well for the RF mobile communications industry, which addressed this issue more than a decade earlier, when switching from pure AM and FM modulation to complex modulation in order to realize higher data rates with digital transmission.

This industry developed the concept of error vector magnitude (EVM), which is common in standards like WLAN and others. It is based on a very simple idea. "What is the deviation of my received signal from the ideal signal?". This is what error vector magnitude measures.

The reason why this concept is broadly adopted in the RF world is that it overcomes the limitations described above.

As we compare the measured signal against an ideal signal, by its nature we can make this comparison at any number of amplitude and phase levels and against any positions of constellation points we define. It leaves no ambiguity as each measured constellation point is related to its nearest ideal neighbor. A false association implies a symbol error in the same manner as it would occur in a real transmission receiver.

This concept also implies that the measurement receiver is only needed to measure the signal at the same time point as a real receiver would use to decide what kind of symbol was received. Any information about the transition is not of interest in this concept. Of course it can be extended to also measure an error vector during the transition, but this would only be at its most helpful if the result is compared to a standardized transition.

Another important point is the fact that the EVM calculated as an RMS value over a statistically significant number of vectors can be used to calculate a Q factor. Therefore EVM has a direct relation to the BER under the same conditions as with on-off keying, namely a Gaussian noise distribution. (Reference 2)

Major EVM dependencies

As described earlier for on-off keying, the major test condition requirement is the Bessel-Thompson characteristic for a reference receiver. For complex transmission receivers we have other influencing parameters like:

- Receiver bandwidth
- Receiver transfer characteristic
- Receiver impairments like skew
- Noise
- Effective number of bits of ADC
- Receiver distortions
- Signal processing algorithm

One of the most discussed parameters is the electrical bandwidth over the path between the PIN diodes and the ADC including of course the ADC itself.

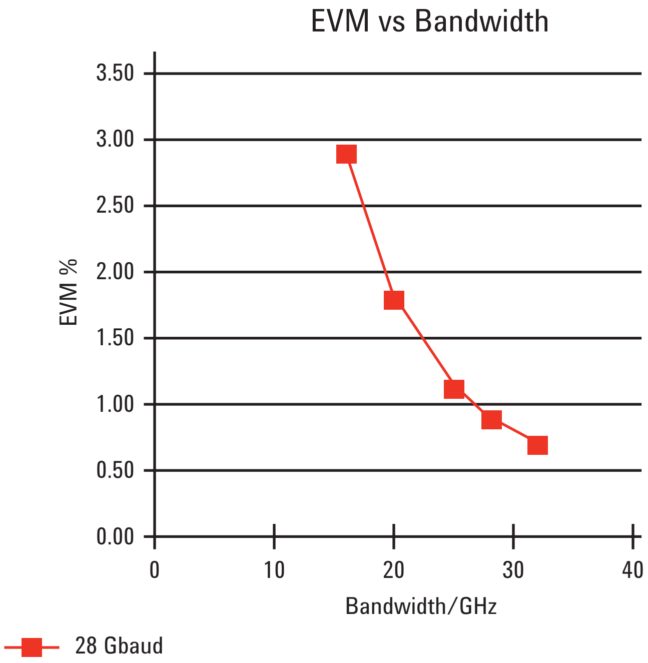


Figure 4. Effects of electrical bandwidth on error vector magnitude

Figure 4 shows, based on a simulation, how electrical bandwidth can influence an EVM measurement result. It is shown that for bandwidths between 22 and 25 GHz, the EVM is influenced in the order of 1% for a 28 Gbaud QPSK signal.

Of course it is not sufficient to evaluate the influence of only one parameter. Phase error, introduced by the manufacturing imperfections of an optical hybrid for a coherent intradyne receiver, is an example for how optical components can degrade receiver performance. Figure 5 illustrates the simulation of the error in phase angle of an optical IQ hybrid.

In version 1.1 of the OIF Implementation agreement for integrated coherent intradyne receivers, a phase angle error of ±5° is allowed for the optical hybrid, which would introduce an EVM error of about 3% according to the simulation.

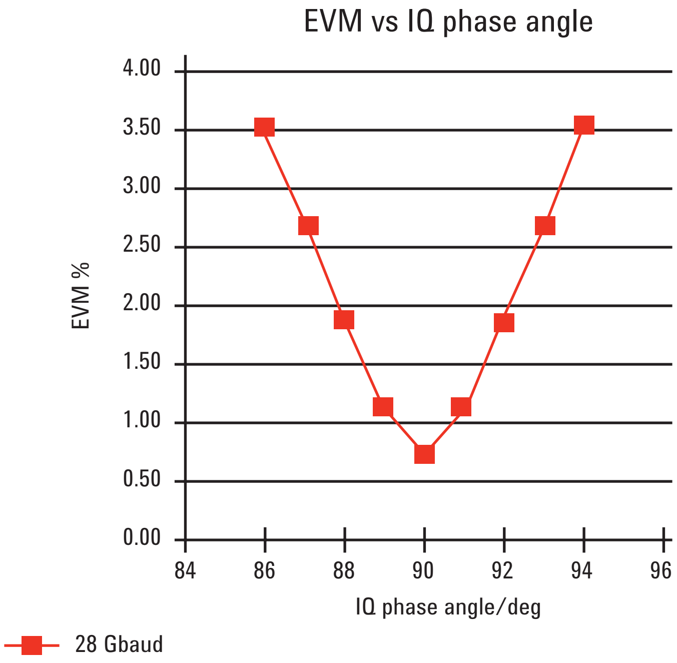


Figure 5. Simulation of the error in phase angle of an optical IQ hybrid

Finally, it should be mentioned that even the way the signal processing – especially phase tracking – is implemented in a coherent optical receiver can lead to differences in EVM measurement results to the order of several percent or more, in the case of signals with high phase noise caused by the transmitter laser.

The above described examples indicate that using EVM as a generally accepted quality parameter might now need more standardization effort than was necessary in the past.

Quality parameters for complex modulated optical signals need either a reference signal that standard institutes can provide as traceable artifacts, or standardization bodies need to provide defined parameters for a reference receiver, including the impairment correction rules and signal processing framework. This signal processing framework does not need to be the same as that which is used in standard telecom receivers, so suppliers of telecom equipment would still be free to implement their own signal processing. In addition, they would benefit from test results of complex modulated optical signal that are comparable between various test instruments, which is beneficial for all engineers.

Status of EVM Standardizations

The concept of EVM is now well known in the optical community. However, it is not really used as „the standard“ for complex modulated signal quality and even less so for BER estimation.

One reason for this might be the fact that without defined measurement conditions for EVM, like in the mask test of on-off keying with a Bessel-Thompson filter, test results cannot be compared easily between different test instruments or telecom receivers using built-in EVM evaluation.

Addressing this situation, the IEC subcommittee SC86C, "fiber optic systems and active devices", has initiated work on this topic. It is circulating a document that, when published, will provide a definition for EVM, adapted to the optical communications industry, and a framework for standardizing its measurement and the necessary conditions. The ITU-T Study Group 15 has also taken up work on this topic to qualify telecom transmitters.

Until we have a defined agreement or a standard for a reference receiver for EVM measurement, as is available in on-off keying with the Bessel-Thomson characteristic for a reference receiver, we will suffer from limitations due to different measurement conditions. The work done so far therefore needs to be continued.
In the meantime, EVM is a helpful quality parameter for your internal tests.

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