Design Considerations for Compliance Testing of EDC Receivers

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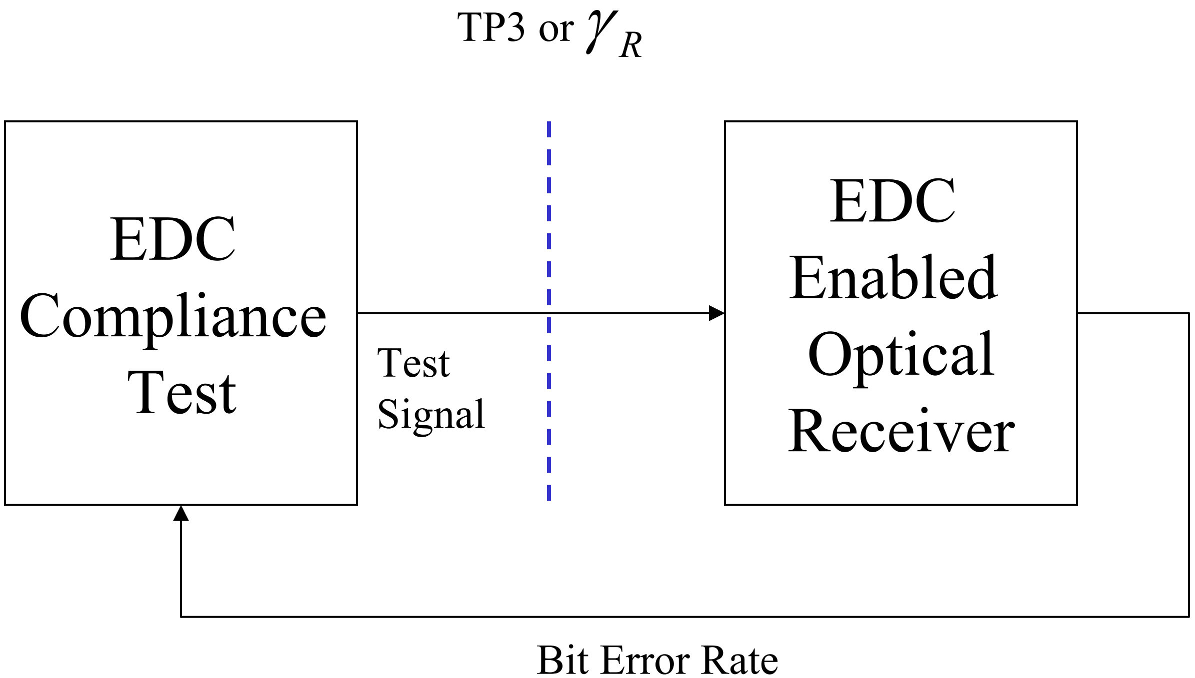
Motivation for Compliance Test

- For a given launch condition, bandwidth of a multimode link varies widely with fiber process and manufacture date.
- Performance of an EDC varies with EDC implementation and characteristics of noise.
- Other than extensive field testing, there is no available mechanism today to satisfy an EDC implementer that they have tested the product on worst-case DMD.
- These factors lead to unpredictable distance improvement that can be achieved with EDC in the field.
- A standardized test will enforce a uniform and worst-case compliance condition on all EDC-enabled receivers. A high confidence level by users is essential for broad market potential.

What is an EDC Compliance Test?

- It is a test to verify that an optical receiver enhanced with Electronic Dispersion Compensation is able to operate with target error rate in the presence of a severely bandwidth limited and noise-borne signal. In essence, it's an extended version of the stressed receiver sensitivity test.



Guiding Principles

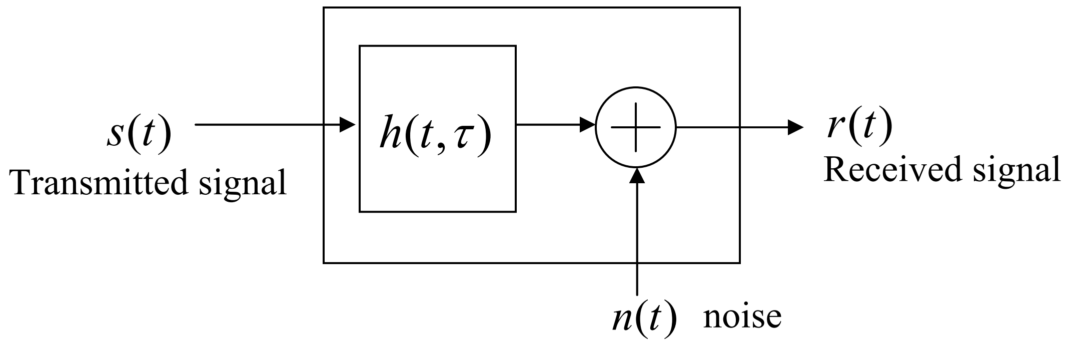
- Define a worst-case optical test signal at TP3 for extended-distance links. Be conservative, without trying to emulate the worst fiber ever made.
- Support a test consistent with the selected fiber types and link lengths.
- Emulate key elements of multimode channel that guide EDC implementation – impulse response, noise, jitter and SNR.
- Emulate the irregular and possibly time-varying impulse response resulting from the combination of launch condition and anomalous DMD.
- Take into account RIN, Modal Noise, Interferometric Noise, and Mode Partition Noise.
- Ensure sufficient SNR at TP3 to make it feasible for an EDC-enhanced receiver to meet the objective of BER = 10^-12 cost-effectively.
- Prefer to eliminate the need for mode conditioning patch cord?

Changing Nature of MMF Impulse Response

- Temperature, vibration, etc. cause a change in the optical power weighting function across mode groups. To the EDC, it may appear as if the impulse response of the fiber is time-variant.
- Slow variations can be tracked by EDC. Variations too fast to be tracked by EDC behave as noise and degrade SNR.
- The definitions of “slow” and “fast” are determined by the tracking loop bandwidth of EDC. A certain loop inertia is required for proper functioning of EDC.
- A compliance test, in order to impose a uniform test condition, should emulate impulse response variations and define the test value of this tracking bandwidth. One possible implementation is to vary the coefficients of a transversal filter. (See page 9. More study required.)

Channel Model for Multimode Fiber

- Linear time-variant channel with additive noise.



Here $n(t)$ represents sum of all noise terms, and $h(t,\tau)$ represents time-varying impulse response. Multimode fiber impulse response can be modeled as that of a multi-path channel.

$$h(t,\tau) = \sum_{1}^{M} a_k(t)\,\delta(\tau - \tau_k)$$

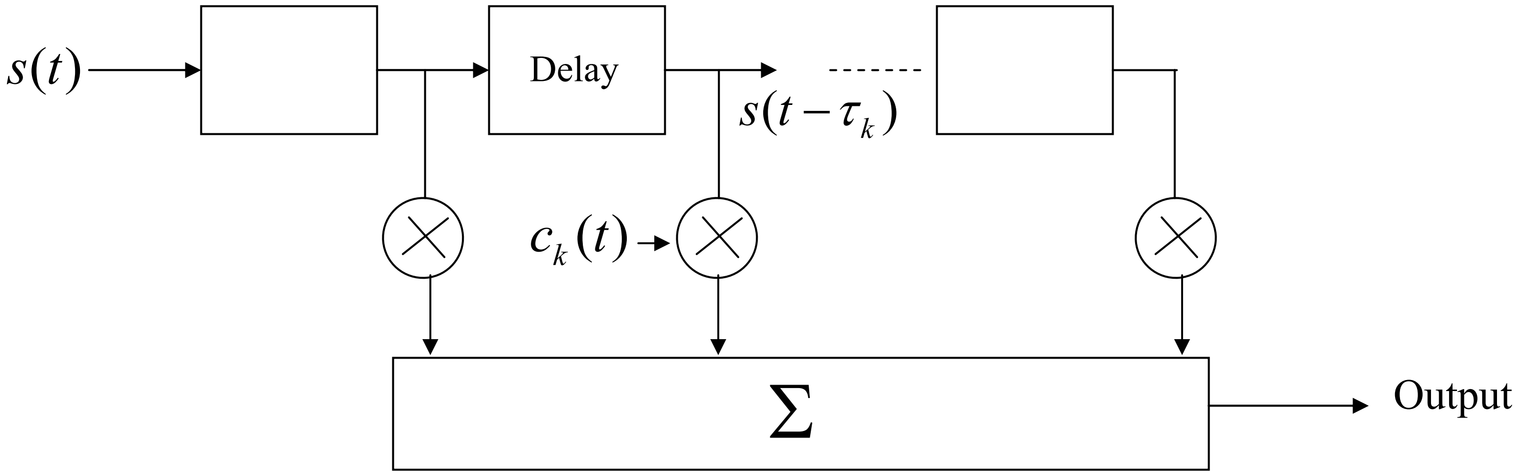
Where $\{a_k(t)\}$ represents possibly time-varying coefficients of power among M mode groups, and $\{\tau_k\}$ represents DMD.

$$\therefore \quad r(t) = \sum_{k=1}^{M} a_k(t)\, s(t - \tau_k) + n(t)$$

Note: Although convolution is not applicable to time-varying systems, the convenient form of impulse response here permits a simple result for r(t).

Compliance Test: Filter Architecture

Build a transversal filter (FIR) such that $g(t,\tau)$ is approximately equal to $h(t,\tau)$.

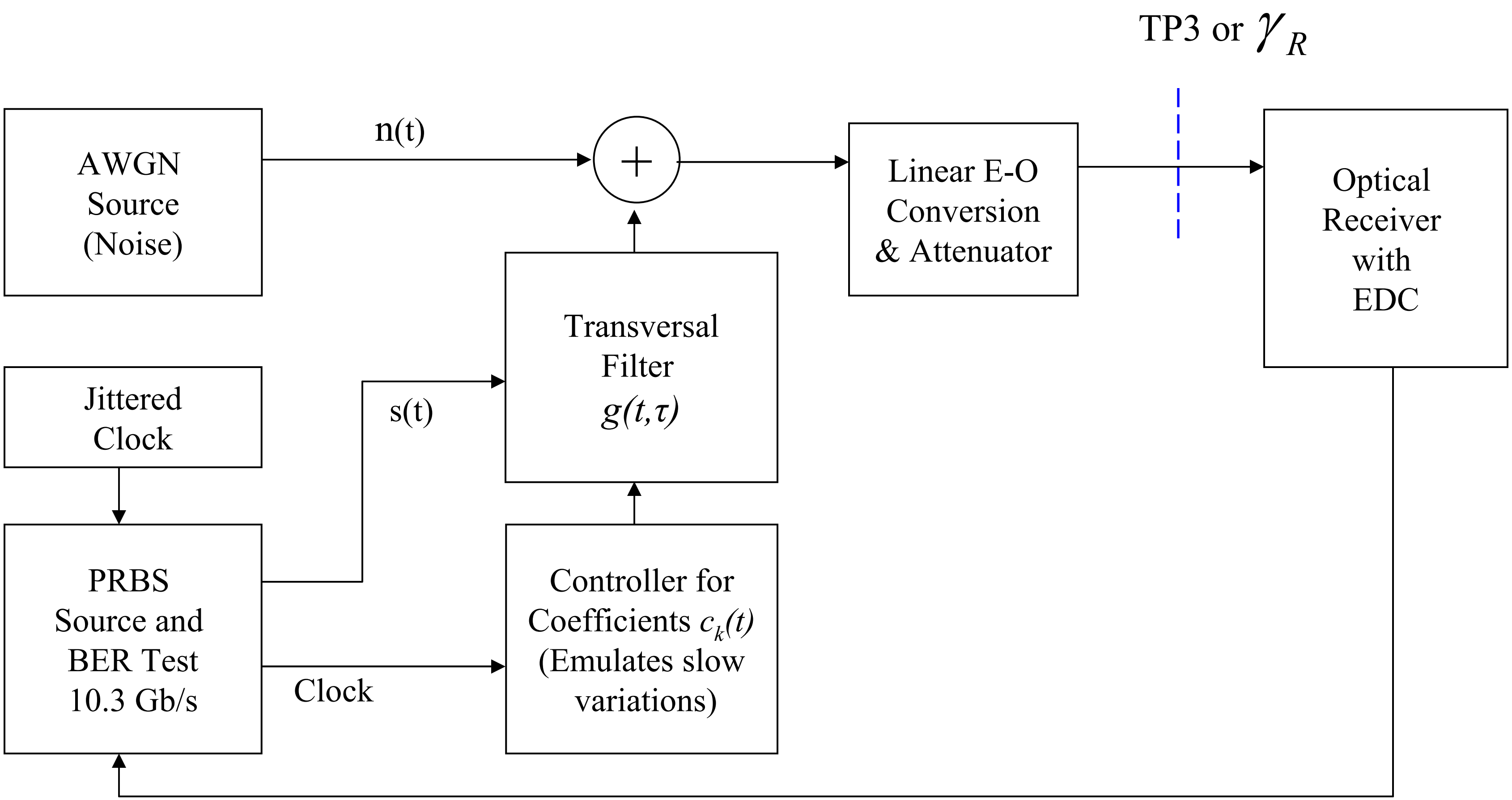


Impulse response of FIR is $g(t,\tau)=\sum_{1}^{L} c_k(t)\,\delta(\tau-\tau_k)$

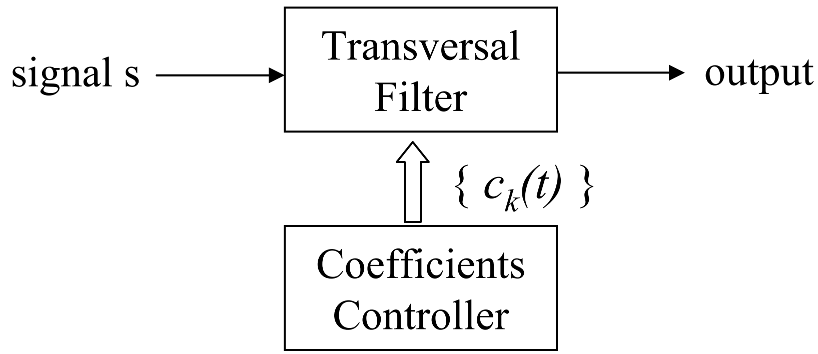
choose L, c_k, τ_k *for* $g(t,\tau) \cong h(t,\tau)$ *(defined on Page 7)*

Output of FIR $=\sum_{k=1}^{L} c_k(t)\,s(t-\tau_k)$

Test – Conceptual Block Diagram



How to Emulate Noise up to ~100 MHz



Suppose we wish to emulate the addition of a random signal n(t) to the test signal s(t) passing through the transversal filter. *Assume that the spectrum of n(t) is much smaller than spectrum of s(t).*

We want $output = n(t) + \sum_{k=1}^{L} a_k(t)\, s(t-\tau_k)$

Select $c_k(t) = a_k + b_k(t)$ Where a_k is constant, representing a fixed impulse response, and $b_k(t)$ is a random number, varying at a rate much smaller than s(t).

$$output = \sum_{k=1}^{L} b_k(t)\, s(t-\tau_k) + \sum_{k=1}^{L} a_k\, s(t-\tau_k)$$

Select $b_k(t) = \dfrac{n(t)}{L \cdot s(t-\tau_k)}$ $\Rightarrow output = n(t) + \sum_{k=1}^{L} a_k(t)\, s(t-\tau_k)$

Advantage of this approach:

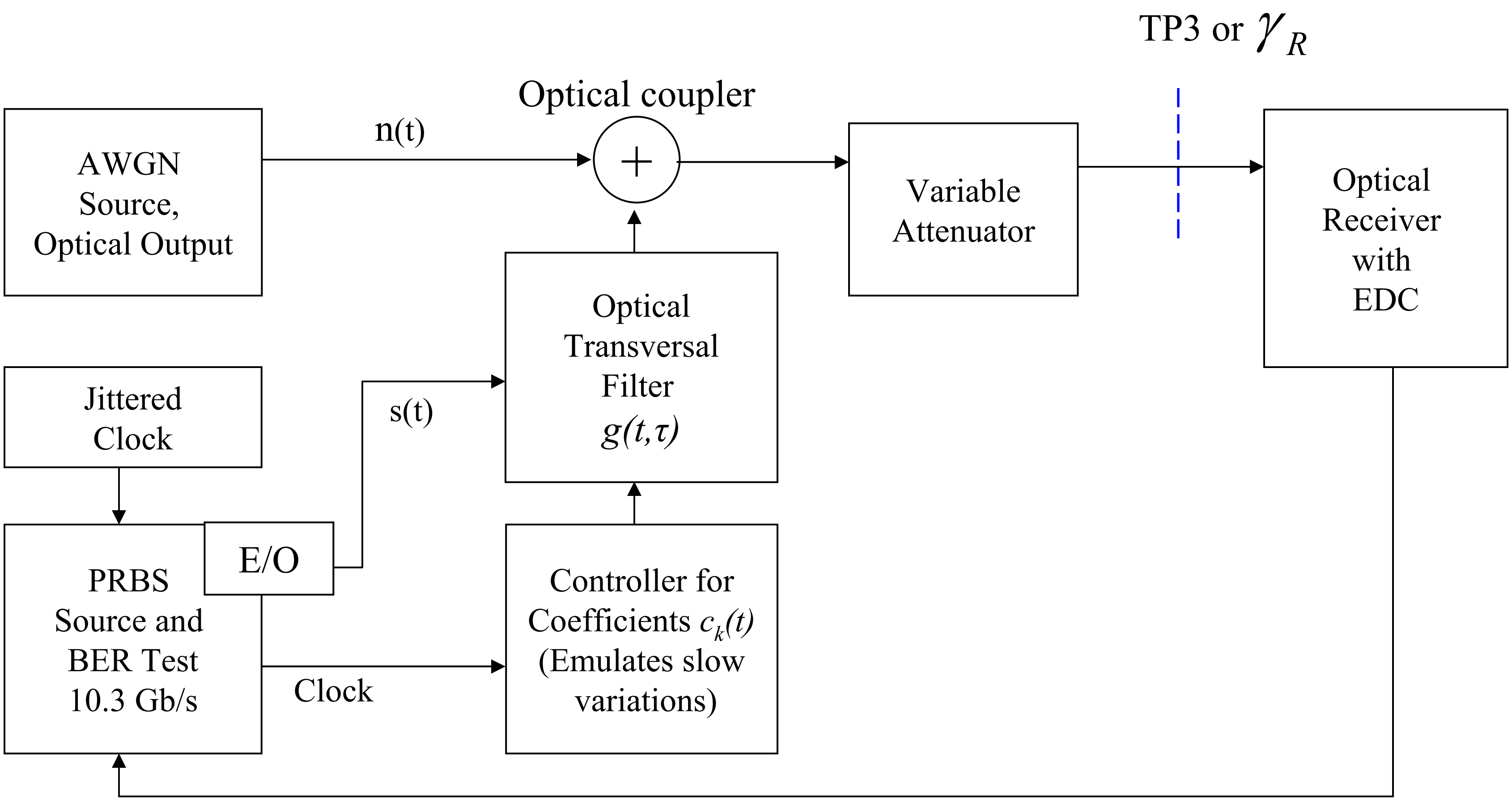
Makes possible a programmable, digital implementation of "noise".

In practice, one can take constant average value of s(t) in place of $s(t-\tau_k)$ to adjust $b_k(t)$, if the spectrum of s(t) is much higher than that of n(t).

Test – Implementation Challenges

- AWGN sources for 10 Gb/s links are difficult to calibrate. A practical implementation may have to settle for adjusted values of stressed OMA (per 802.3ae), but such a compromise will fail to spot EDC implementations that are sensitive to certain types of noise spectra.
- Linearity and noise of E-O converter are difficult to control.
- For a close to ideal reproduction of representative worst-case DMD fiber cases, we may need multiple delay elements with nominal values in the range of 10 to 100 psec., and accuracy of better than 10% of that. A practical implementation may have to settle for fewer elements with larger delay values.

Alternative Concept: Use **Optical** Transversal Filter



Optical Transversal Filter

- Can be built using a variety of technologies, including monolithic fabrication of silicon waveguides and MEMS.
- Can implement multipliers using variable attenuation, an adder using a coupler, and delay blocks using waveguides.
- Multiplier and delay elements can be made programmable using various technologies.
- A test instrument need not meet the cost, power and size constraints of a transversal filter that may be a part of EDC inside the optical receiver. But its operation needs to be accurate and reproducible.

Noise

- For simplicity, we modeled noise as additive, added after passing through fiber impulse response. But when quantifying it, we must consider each source case by case. Some types of noise pass through fiber (RIN), while others may be generated within (Modal Noise?).
- In stressed sensitivity test, we adjusted stressed eye OMA to account for noise. We chose to do it that way because AWGN sources are difficult to calibrate. And we could afford to do it that way because we had a conservative link model to help estimate SNR at the receiver.
- For EDC-enhanced links, the eye can be completely closed. EDC implementations can be sensitive to noise, and some may enhance noise at selective frequencies.
- So the EDC Compliance Test preferably should:
  - Use noise emulators instead of an adjusted signal, and
  - Be based on awareness of potential spectral sensitivity of some EDC implementations.

RIN

- Spectrum peaks at Relaxation Oscillation frequency. High frequency component of RIN may get exaggerated by EDC. We need to flag this possibility for further study.
- RO may have a deterministic component, which can possibly be tracked by EDC (depending on frequency).
- Will be filtered by the channel.
- RIN is affected by modulation and reflections. The AWGN noise emulator should take that into account.
- Can cause a BER floor. Since many practical applications expect error rates better than 10^-15, we need to assure, if not mandate, that interaction of EDC and RIN does not lead to an unacceptable BER floor.

Mode Partition Noise

- Assuming FP lasers(?), and including transversal mode partition noise for VCSEL sources on multimode fiber.
- Need to find out frequency distribution of mode partitioning, to confirm its broadband nature.
- Filtered by the channel?
- Highly unlikely that EDC can track it, so we will likely test an EDC for robustness against it.
- AWGN emulator for MPN should be placed before the transversal filter in the compliance test.

Modal Noise

- A mode selective loss element (connector, etc.) can be anywhere in the link, causing modal noise. If Structured Cabling guidelines are followed, there can be typically 4 connections, including two in the middle of the link.
- Even though the forcing functions (temperature, vibration) are slow, the observables can exhibit high frequency variations. What is the spectrum of this behavior?
- Some participants in IEEE Equalization Ad Hoc used a fiber shaker to emulate those forcing functions. It was observed that the EDC coefficients showed slow variations.
- How strong is the correlation to longitudinal mode partitioning? In almost all cases, lasers will be directly modulated. Can we treat Modal Noise and MPN as a composite effect?
- Not clear if a correct emulation requires suitable AWGN output before or after transversal filter in the compliance test.

Interferometric Noise

- Caused by multiple reflections at optical interfaces creating a channel interferometer that converts the laser phase noise into intensity noise.
- Power Spectral Density is band-limited typically to tens of MHz.
- Since multimode channel will have a large number of spatial modes, the probability of coherent interference will be low.
- Ignore this noise?

Jitter Considerations

- It is critical to include jitter in the compliance test because EDC implementations can show wide-ranging sensitivity to it.
- Link jitter terms should consider dispersion and noise sources. Depending on implementation of the filter and noise source, their effects may already be included.
- Clock jitter tends to be band-limited. Should we include some DCD?
- It may even be necessary to test an EDC's ability to track wander (low frequency jitter).
- Fortunately, we can piggyback on much of the work done for stressed eye sensitivity test.

Concluding Remarks

- Despite the challenges, there is sufficient agreement that EDC solutions are expected to increase optical link spans sufficiently well to have a broad market potential. The question is not if, but how much.
- Already, there are indications that EDC for 10G optical transceivers will be deployed widely.
- Therefore, developing an EDC Compliance Test within a standards organization is a good idea.
- Development of such a test appears to be feasible, though there are practical difficulties.
- More study of test filter architecture, noise and spectral considerations is required. The work may involve extending and refining the existing link model for use in an environment characterized by very low SNR and very high ISI.

References

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