Optimize equalization for FFE, CTLE, DFE, and crosstalk

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Combining equalization at both the transmitter and receiver in a high-speed serial-data channel lets designs reach more than 28 Gbits/s. Equalization will continue to play a key role as we switch from baseband, two-level NRZ (non-return to zero) to PAM4 (four-level pulse-amplitude modulation) at lane rates in excess of 50 Gbits/s.

The ideal equalization scheme inverts a channel's frequency response. Such inversion, which can be implemented at the transmitter, receiver, or both, can remove ISI (intersymbol interference). That leaves just random noise, jitter, DCD (duty-cycle distortion), crosstalk, and electromagnetic interference behind.

Figure 1 shows the frequency response, $S_{DD12}$, and pulse response of a pretty good channel. The number of UIs (unit intervals) over which the pulse response extends indicates the number of symbols that interfere with each other. The longer the channel and the greater the signal bandwidth, the smaller the UI, the larger the number of interfering symbols, and the greater ISI impairment.

![Figure 1. The frequency and pulse response of a high speed serial channel drops as frequency increases.](image)

An ideal equalizer would invert the channel response and convert the pulse response back into a square pulse.

Three types of equalization are used in high speed serial designs.

*Tx FFE* (transmitter feed-forward equalization) modifies the amplitudes of symbols surrounding
transitions while keeping the transmitted power constant. In principle, Tx FFE should be able to invert ISI if the number of symbols modified, that is, the number of “taps,” extends over the entire length of the pulse response. In reality, Tx FFE seems to peter out after about three taps. Three taps of Tx FFE amounts to a blunt instrument: increase the ratio of high frequency to low frequency signal components to counter the channel's low-pass nature. That blunt instrument doesn't help fix the ugly nuances of channel frequency response.

**CTLE** (continuous time linear equalization) is a linear filter applied at the receiver that attenuates low-frequency signal components, amplifies components around the **Nyquist frequency**, and filters off higher frequencies, as shown in Figure 2. CTLE gain can be adjusted to optimize the ratio of low frequency attenuation to high frequency amplification. Of course, it runs out of steam when the attenuation pushes the low frequency signal components down into the noise and, like 2-3 tap Tx FFE, CTLE only addresses the gross low-pass filtering effect of the channel.

![CTLE filtering options](image)

**Figure 2.** CTLE filtering options.

Because both Tx FFE and CTLE address the problem by inverting the channel's low pass nature, they're somewhat redundant. Designs at very high rates, especially those using PAM4 signaling, rarely include both.

**DFE** (decision feedback equalization) is implemented at the receiver (Figure 3). Implicitly nonlinear, DFE feeds a sum of logic or symbol decisions back to the symbol decoder (a.k.a., the slicer). We've talked about the magic of DFE before and how it meshes with **Reed-Solomon FEC** (forward error correction). Where Tx FFE peters out around three taps, the ISI-inverting capabilities of DFE usually plateaus around six taps.
DFE (decision feedback equalization) uses a decision circuit as part of its feedback loop.

CTLE technology doesn't change for PAM4 signaling. Tx FFE doesn't change in principle, though with four different symbol levels, it changes in practice. But with four distinct "decisions" to feed back to the decision circuit, DFE differs for PAM4. I think we'll see some clever DFE designs in the next couple of years as we come to understand the nuances of PAM4 signaling.

An optimally equalized serial differential signal complements the high-frequency amplifying/low-frequency attenuating nature of either Tx FFE or CTLE (or both) with the number of DFE taps. But, the optimization problem can't be addressed without considering crosstalk.

Jolts of crosstalk radiate from nearby channels during symbol transitions, the higher frequency content, the greater the crosstalk; both Tx FFE and CTLE amplify crosstalk, whereas DFE is crosstalk-neutral. In PAM4 systems, with 12 different transitions, crosstalk comes in different doses. For example, the extreme 00→11 transition hits harder than the 01→10 transition between adjacent symbols.

The trick is to balance cost and power against CTLE/Tx FFE and the number of DFE taps in a way that reduces ISI without amplifying crosstalk. Doing so will let you meet your BER (bit-error ratio) requirements.

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