Bit Error Rate and Signal Integrity of Cat-5 based DVI / HDMI Cables

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1. Introduction

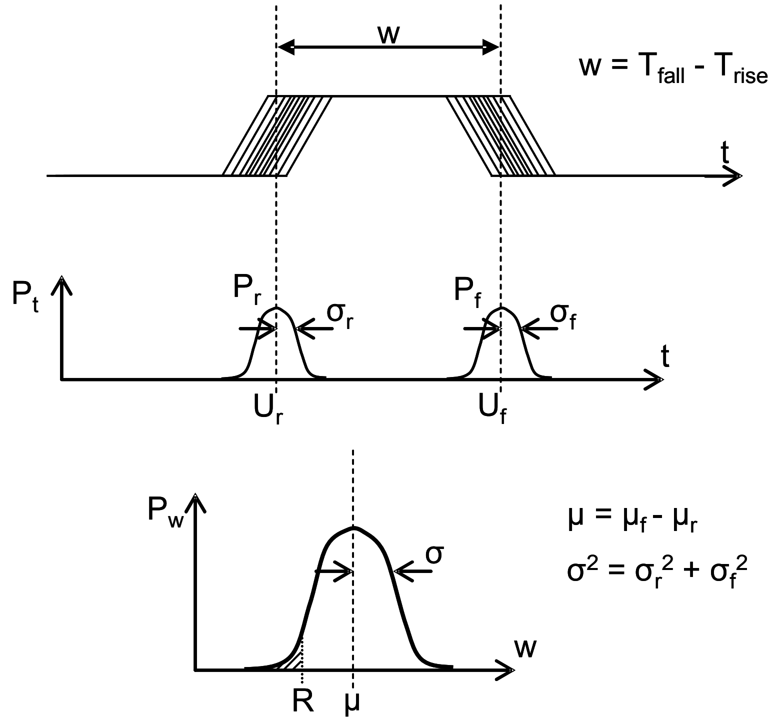
In a previous paper "Cat 5 Cable Modeling for DVI/HDMI Links" [2], we discussed modeling Cat-5 UTP cables in a verification environment that enabled co-simulation of transceiver circuits as well as link interconnect. ComLSI's 0.18um CMOS implementation of 2.5Gbps per wire-pair video data link employs Cat-5 (Cat-5e) UTP interconnect for wired, remote (25m and longer) video data communication. In this paper, we investigate link bit error rates and the relation to received signal quality over long UTP links, and study simple compensation techniques for the interconnect that enable HDMI transmissions over Cat-5e links.

DVI/HDMI links require a bit error rate better than 10^{-9}, or 1 bit error in a billion bits transmitted, as specified. For simplicity's sake, let us scale this number proportionately to assume that a single pixel error is tolerable when 1 billion pixels are transmitted. It is interesting to see what this means in practical terms. The HDTV standard 1080p specifies 1920x1080 lines at 60 full frames per second. This amounts to approximately 120 million pixels per second or 0.12 billion pixels. It takes about 8 seconds for 1 billion pixels to be transmitted at this image transmission rate, assuming only picture data is being transmitted. The standard of 1E-9 therefore calls for a single pixel error that remains on-screen for roughly 1/60th of a second in an 8-second duration. Now in order to truly notice a pixel error, it is known that a pixel error must either persist on the screen at the same spot, or must move to consecutive pixels on the image and reoccur at a significant repetition rate that allows the human eye to register its presence. The probability of either of these two events occurring, one may appreciate, is negligibly small, since bit errors created by the data transmission physical layer are not deterministic with respect to the image frames transmitted. One can imagine that a pixel error in each frame of the images transmitted, at random locations, may also not be noticeable, since each of these random, miniscule image errors would occur for about 1/60th of a second, and would be at random positions on the image. By these unverified arguments, one may appreciate that a pixel error rate of 1 in 2 million, or 0.5E-6 may also be tolerable from a visual quality perspective, indicating that the BER specification of 1E-9 is perhaps at least two orders of magnitude stricter than what may be necessary currently. An article on the HDTV online magazine [5] hints at this finding.

Additionally, established networking infrastructure employs Cat-5e cabling. Networks have moved from 10/100 to 1000T or Gigabit Ethernet, and there are developments underway to extend such copper-based cabling of as much as 100 meter length to 10GigE or 10 Gigabits per second of Ethernet connectivity. Indications are, therefore, that serial communications line driver and receiver circuits and systems technology has advanced to the point of being able to transmit data at 10Gbps, almost two orders of magnitude greater throughput than originally planned on Cat-5e.

These determinations lend confidence to the possibility of utilizing low-cost cabling (Cat-5e) for video data communication. HDMI 1.3 also calls for 10.2 Gbps data transmission, over much smaller lengths of cabling, therefore being a much lesser challenge than 10GigE over Cat-5e.

2. Bit error rate derivation



R = Receiver minimum pulse width rqmt.

$$BER \approx \int_{-\infty}^{R} P_w \, dw = \frac{1}{\sqrt{2\pi}\,\sigma} \int_{-\infty}^{R} e^{-\left(\frac{w-\mu}{\sqrt{2}\sigma}\right)^2} dw$$

$$= \frac{1}{\sqrt{\pi}} \int_{\frac{\mu - R}{\sqrt{2}\sigma}}^{R} e^{-y^2} dy$$

$$BER = \frac{1}{2}\left(1 - erf\left(\frac{\mu_f - \mu_r - R}{\sqrt{2\left(\sigma_r^2 + \sigma_f^2\right)}}\right)\right) = \frac{1}{2} erfc\left(\frac{\mu - R}{\sigma\sqrt{2}}\right)$$

$$BER = \frac{1}{2} erfc\left(\frac{\mu_f - \mu_r - R}{\sqrt{2\left(\sigma_r^2 + \sigma_f^2\right)}}\right)$$

Figure 1: BER relationship to EYE width, simple derivation from probability theory

The derivation above considers the variations in the positions of the edges of the received data pulse due to random and deterministic jitter as well as the limitation of a receiver system that requires a minimum data pulse width to be able to detect the data bit accurately. This, in effect, considers the horizontal width of the 'open' data EYE and relates it to receiver sensitivity. Figure 2 shows a graph of BER vs. receiver jitter tolerance in absolute time and bit cell width variation. It can be seen, for a 400ps data bit width (2.5Gbps), that with a receiver architecture capable of tolerating 0.5UI of jitter (one-half of the bit interval or 200ps consumed by jitter), the designer can budget for greater than 50ps of bit duration standard deviation or RMS jitter, with peak or total jitter being a significant multiple of this value.

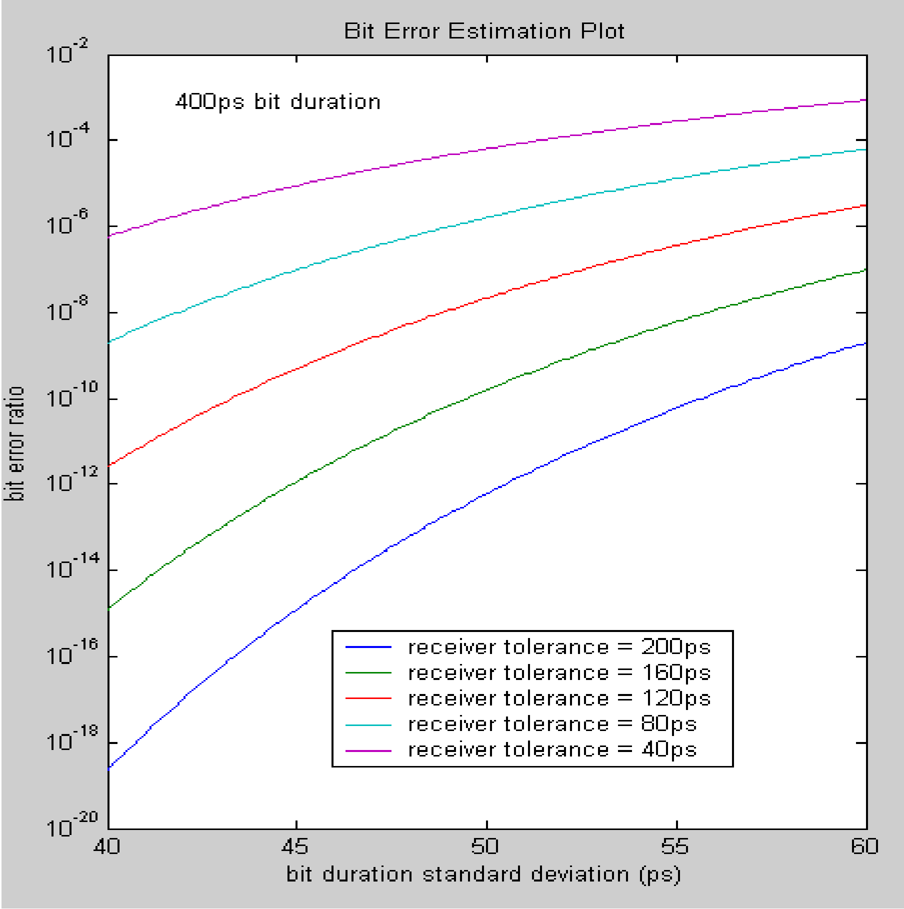


Figure 2: BER vs. Receiver Jitter Tolerance & Bit Cell Variation @ 2.5Gbps

A similar derivation holds good for amplitude variations of the differential inputs. The amplitude variation is indicated as a standard deviation number and relates to a minimum (or ideal) received signal amplitude. These derivations are combined to produce the BER surface of Figure 3, which is also plotted for a 2.5Gbps link.

A simplifying assumption made here is that much of the deterministic jitter (a term sometimes used to refer to pattern-dependent jitter or inter-symbol interference) can be eliminated through known circuit techniques such as transmit and receive equalization. In this paper, we will discuss a potentially unexploited aspect of the cable interconnect that can help minimize some of the deterministic jitter seen at high data rates.

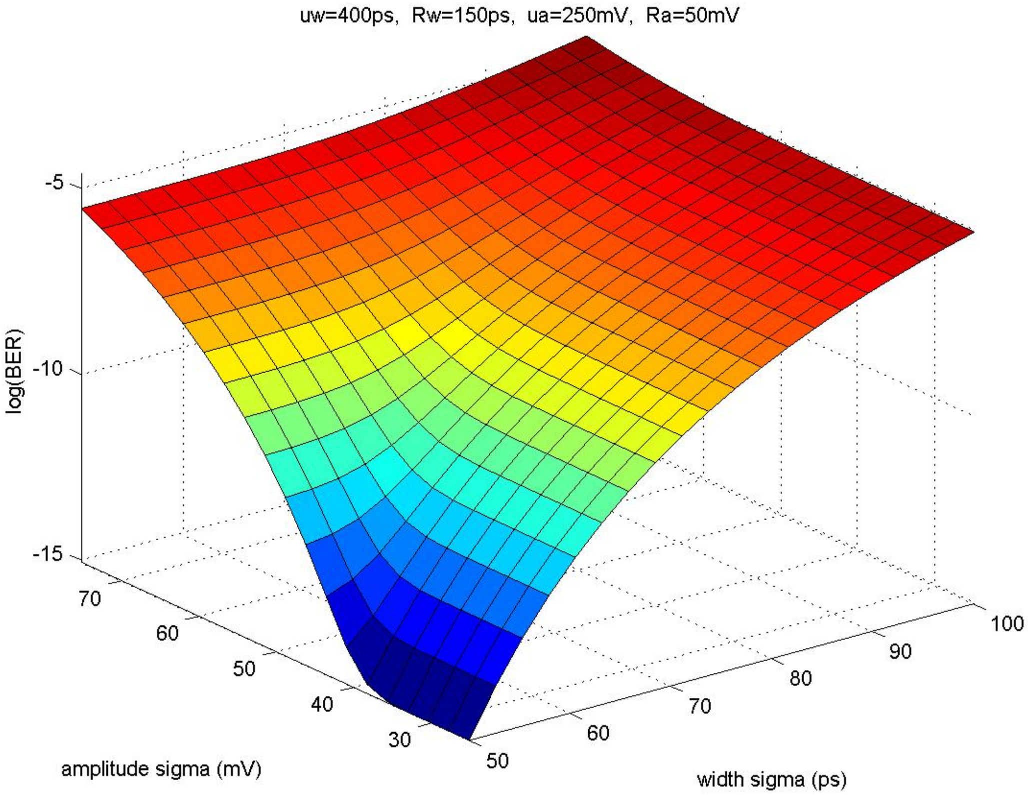


Figure 1: BER surface with eye-width and receiver amplitude thresholds

This simplified BER analysis indicates that meeting the DVI / HDMI specification of 10^{-9} may allow for substantial EYE closure in a 2.5Gbps link. Such EYE closure and jitter is anticipated in a long Cat-5e UTP cable, and that is the next aspect investigated.

3. Cat-5e non-idealities

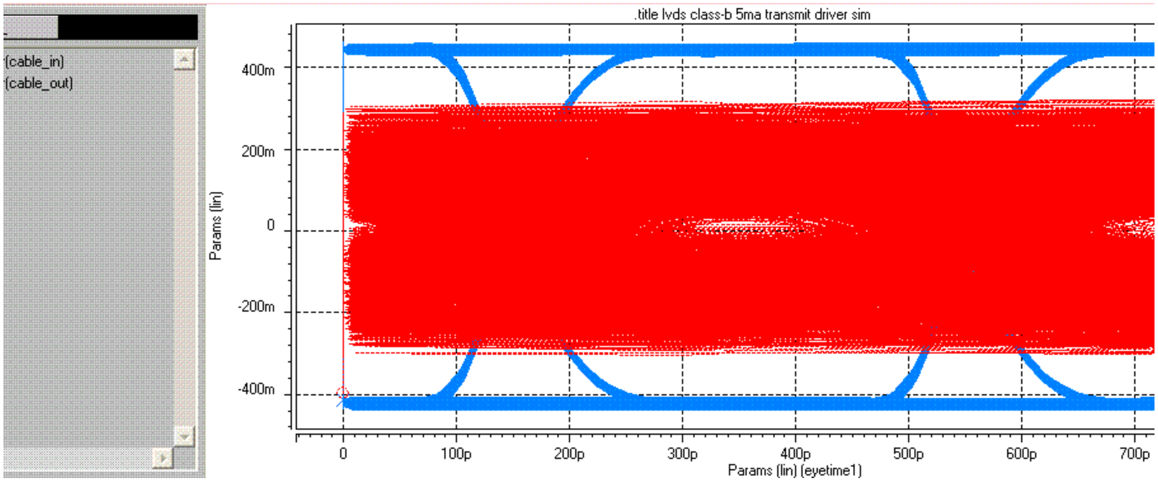


Figure 4: Cable-in and Cable-out EYE diagrams at 25m w/o equalization

Figure 4 above demonstrates the consequence of transmitting pseudo-random data (data streams with variable, multi-bit sequences of 1's and 0's) over a 25m Cat-5eUTP cable as modeled using the environment described in [2]. While signals at the transmitter end have as much as 900mV of differential EYE amplitude and 400pS of EYE width, these signals arrive at the end of the 25 meter length of Cat-5e cable with a 'closed' EYE, or in a form indistinguishable by a comparator circuit attempting to distinguish if the received data bit at any time point is a 1 or a 0.

While the causes for this can be numerous non-idealities in the link, a principal cause is the limited bandwidth of the cable (100MHz as specified) that attenuates the higher frequency spectral components of the data stream and another is energy loss within the cable, both in wire series resistances as well as in the dielectric. These energy losses increase with increasing frequency, attenuating spectral components in a non-linear manner. Additionally, longer cables lead to substantial signal artifacts due to dispersion of spectral components in time.

But there is good news as well. Various techniques are employed in the art to compensate for the nature of the interconnect link that impacts the integrity of differential signals transmitted through, of which 'spectral equalization' is perhaps the most important, and is discussed next.

4. Spectral equalization compensation

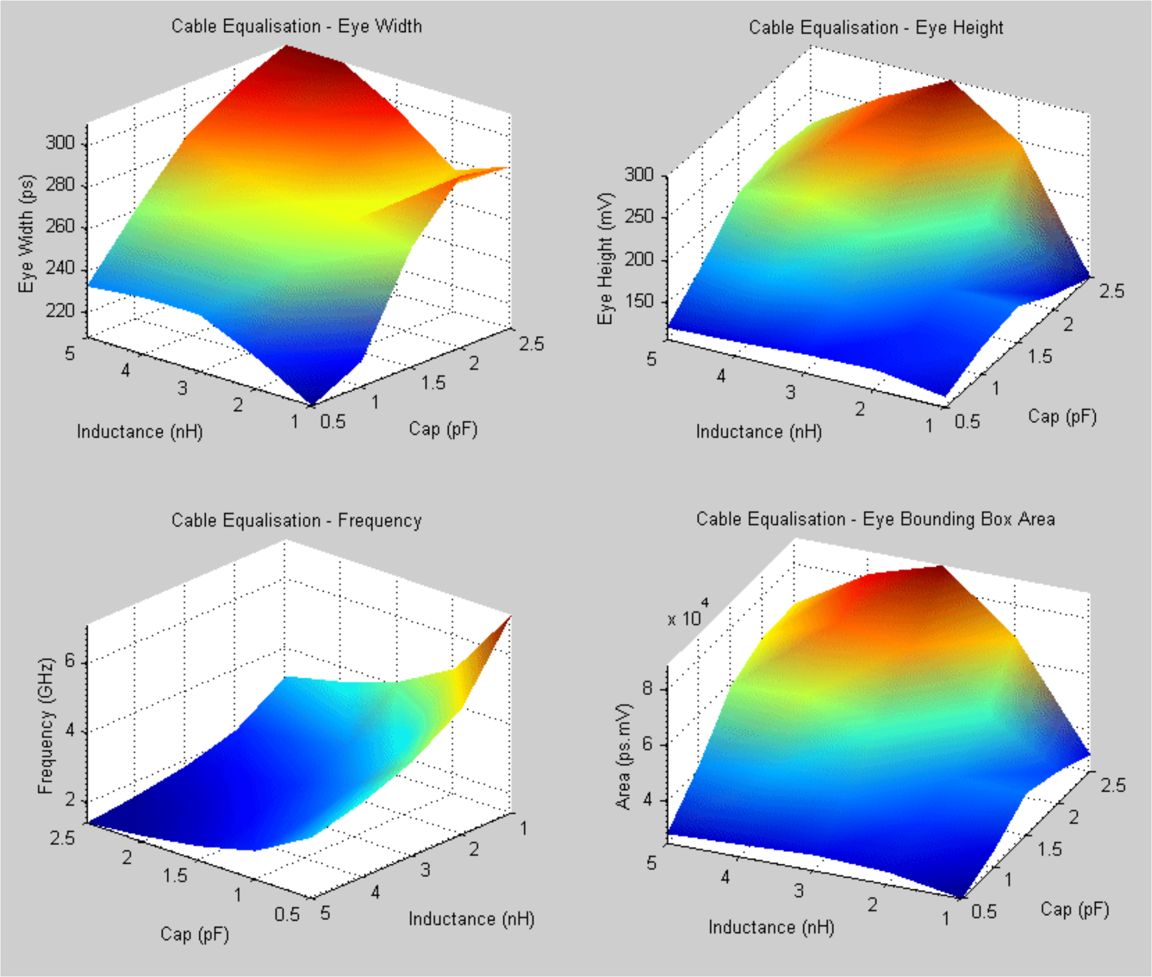


Figure 5: Optimization of a resonant equalization filter

Different spectral components of transmitted data streams are attenuated differently by non-ideal cables such as those conforming to Cat-5e specifications. Higher frequencies are attenuated much more both because of dielectric losses and because of skin-effect losses in the transmission wires. A technique often employed to correct for this effect is what is called passive equalization that employs filters providing a high-pass transfer function. Such filters attenuate the lower frequency spectral components while passing higher frequency components through, thereby compensating to an extent for the higher attenuation of the high frequency components in the cable. We study the benefit of employing a resonant filter tuned to assist in amplifying higher frequency components and thereby opening the data EYE at the receiver.

Careful design of a resonant equalization filter can assist in converting parasitic capacitance at the IO of a transceiver into useful elements. In results shown in figure 5, an optimization experiment is carried out to determine the most beneficial combination of inductors and capacitance to amplify the high-frequency components of the received signal waveform. For the configuration and data bit rate employed in the optimization, values of 3nH for inductance and 2pF for capacitance provided good results. The filter component values are small enough that they may be achieved through clever cable and connector design, thus integrating corrective techniques into the cable without incurring cost or performance limitations of discrete components. Attention to detail in the design of the interconnect link is therefore key!

It is important to note that the beneficial result seen in the optimization experiment is optimistic, and does not include implementation limitations that will reduce resonant filter gain.

The optimized filter is then included within the data transmission simulation of figure 4 to observe improvements in signal integrity. Figure 6 indicates potential benefit in the use of a resonant equalization filter. The data EYE, closed without equalization, is seen to be open to reasonable width and height in the output of the 25m Cat-5e data channel that employed this form of spectral response equalization. Other forms of equalization that are commonly employed to very good effect are what are called 'active equalization' techniques, and are implemented in transmit and receive circuits of the data transmission link. Active equalization techniques as implemented in the DVI / HDMI link over Cat-5e cable are discussed in a succeeding paper. HDMI 1.3 recommends active equalization at the receiver for backward compatibility of cables.

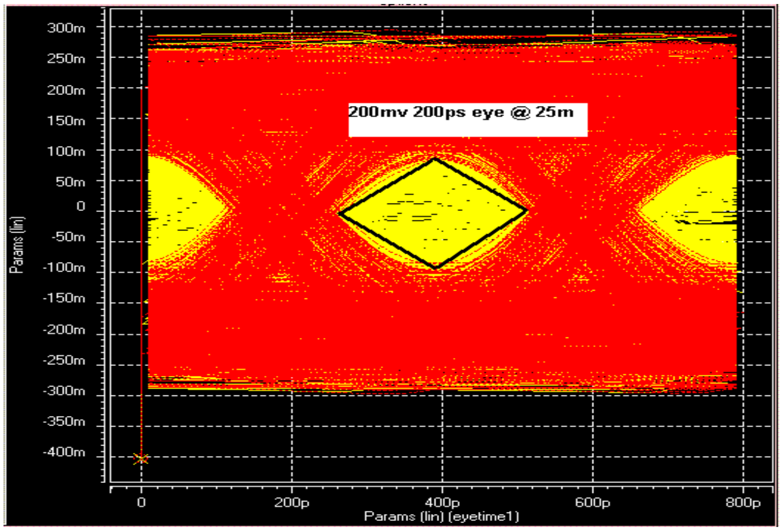


Figure 6: 25m 2.5Gbps data EYE opened through simple Cat-5e cable enhancements

Despite cable modeling and link performance verification as described in [2], and enhancements described here, aspects that are difficult to include without measurement-based models can play critical roles in the overall performance of the video communications link. Most important among these is intra-pair skew in the twisted pairs. References [3] and more specifically [4] provide substantial insight into this aspect of long communication links. Intra-pair skew is not correctable through circuit techniques and can greatly limit the maximum data rate of the channel. This aspect is therefore one to be controlled in cable manufacturing and interconnect assembly. As noted in the discussion in [5], it is often not the bigger cables that are better for intra-pair skew in part due to mechanical challenges in machines that tense and twist wire pairs. Cat-5e cables use thin 24-gauge wires that are easier to control in a manufacturing flow.

Bit error rate in serial transmission links is also impacted by the architecture employed for data recovery at the receiver, as discussed in [1]. For long cables, given the lowered signal-to-noise ratio and small data EYE that may be available at the receiver, jitter in receiver circuits and the choice of data recovery architecture must also be studied, and will be discussed in the next paper of this series.

5. Conclusions

A simplified relationship of bit error rate with respect to the amplitude noise and timing jitter standard deviations has been arrived at in the paper. Computations using this relationship indicate that the BER requirement for DVI / HDMI links of 10^{-9} may not pose too big a challenge for Cat-5e cable lengths of as much as 25 meters at binary data rates of up to 2.5Gbps.

Simple equalization techniques such as resonant filters that may be integrated into the cabling of a data transmission link can assist in improving signal integrity at high data rates. Advancements in transmitter and receiver circuits may address transmission cable inadequacies so as to permit low-cost cabling while providing high-quality, HD video data communications. Nevertheless, there are potential deficiencies in twisted wire pairs that may not be compensated for, and which must therefore be addressed through careful manufacturing and assembly control.

6. References

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