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Baseline Wander, its Time Domain and Statistical Analysis

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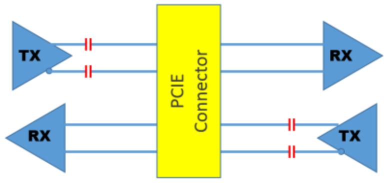
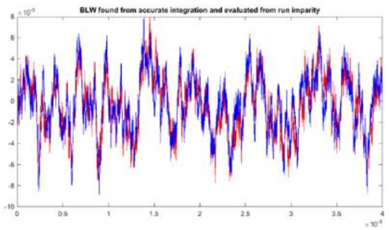
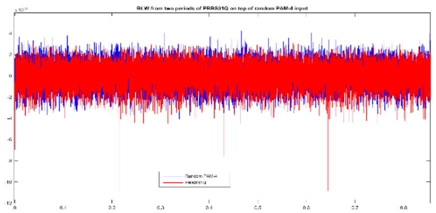
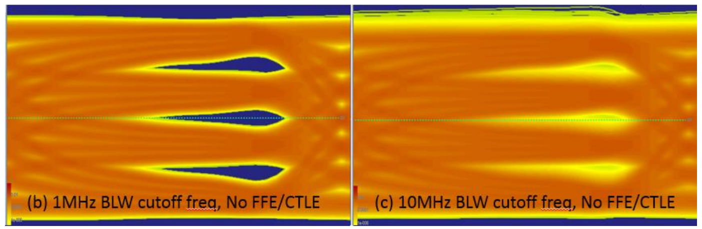
What is Baseline Wander and Why it’s Important

- AC-coupled channels are widely used: in interconnect logic with different switching thresholds, to provide removable interface, to connect pieces without DC connection between chassis, etc. PCIE with DC blocking caps is just one example…
- However, AC-coupling causes the effect called DC Wander or Baseline Wander (BLW), which manifests itself as a slowly changing additive noise
- Two necessary conditions for BLW to occur: (a) the channel’s transfer function doesn’t pass low-frequency signal (including DC); (b) input pattern does have energy in low-frequency part of the spectrum. If so, the rejected part of the signal (with opposite sign) creates low frequency noise.
- BLW is especially harmful for multi-level signaling (PAM-4) because of smaller level separation







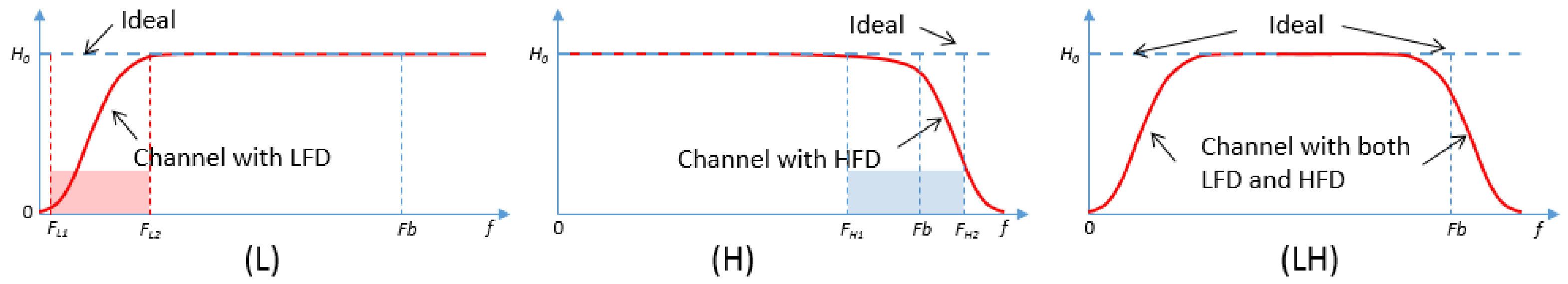


What is Baseline Wander and Why it’s Important

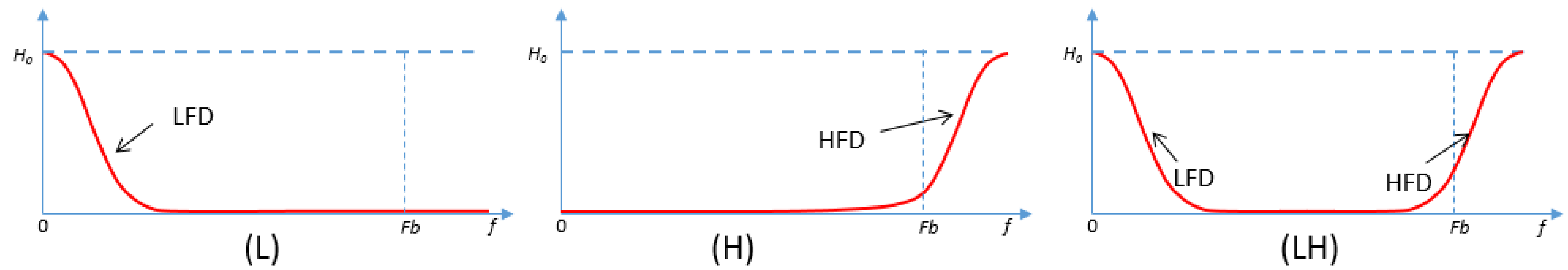
- Most of the link simulation approaches don't include BLW analysis (StatEye, IBIS AMI), or COM/JCOM/PCIE compliance analyses. For example, the channel is often characterized by S-parameters measured starting from 20-50MHz. If so, BLW effects are completely ignored.
- Possibly, because DC-balanced encoding (8b10b) and larger voltage margins made BLW less significant. But we cannot ignore it now, with non-DC-balanced input pattern
- Although BLW phenomenon is known for decades, its efficient analysis methods are not well established. Publications on BLW analysis are scarce.
    - N. Sommer, L. Lusky, M. Miller, “*Analysis of the probability distribution of the baseline wander effect for baseband PAM transmission with application to gigabit Ethernet*”, Proc. of the 2004 11th IEEE International Conference on Electronics, Circuits and Systems, ICECS 2004 – **Considers statistical analysis of BLW**
    - N. Na, D. Dreps, J. Hejase, “DC wander effect of DC blocking capacitors on PCI Gen3 signal integrity”, 2013 IEEE 63rd Electronic Components and Technology Conference – **Analyzes physical source of BLW, ways of its mitigation**
    - P. Anslow, “Baseline wander with FEC”, IEEE P802.3bs Task Force, 2017 – **Finds stress patterns that causes considerable BLW noise, for testing purpose**
- Here we’ll consider:
    - Physical meaning of BLW
    - Its quantitative analysis, both in time domain and statistical domains
    - See what it takes to make BLW a part of link simulation / channel compliance evaluation

Bandwidth Limitations at Low and High Frequency (LFD, HFD)

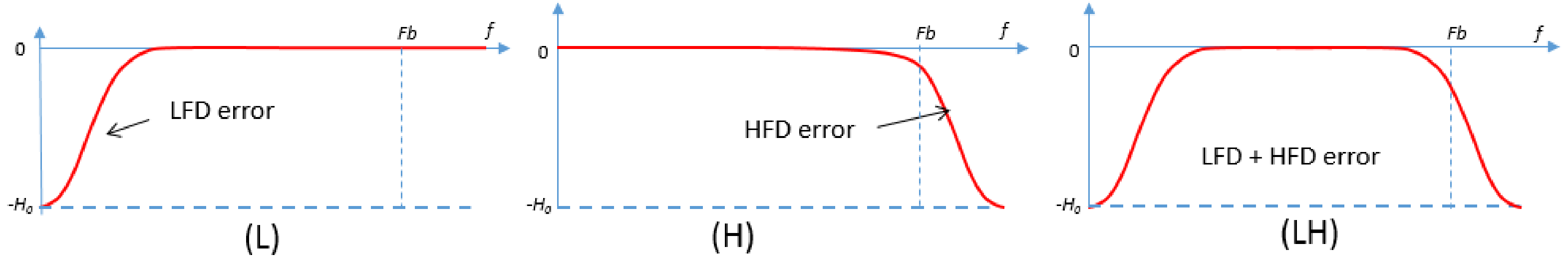
- High-frequency deficiency of the channel (LFD) causes ISI (inter-symbol interference). ISI is defined by the frequency range marked blue. (Below and above Baud frequency)
- Low frequency deficiency (LFD) causes BLW; its range is marked pink
- More distortions could be caused by reflections
- F_{H1} and F_{H2} define duration and resolution of the step/impulse response used in SERDES analysis
- F_{L1} and F_{L2} define duration and necessary resolution of the BLW response
- Typically, BLW response duration is 10K to 1M times longer than ISI response
- Even the time step required for BLW computation greatly exceeds symbol length
- ISI and BLW live in different time/frequency scales. This makes traditional simulation approaches ineffective



(a) Channel transfer functions



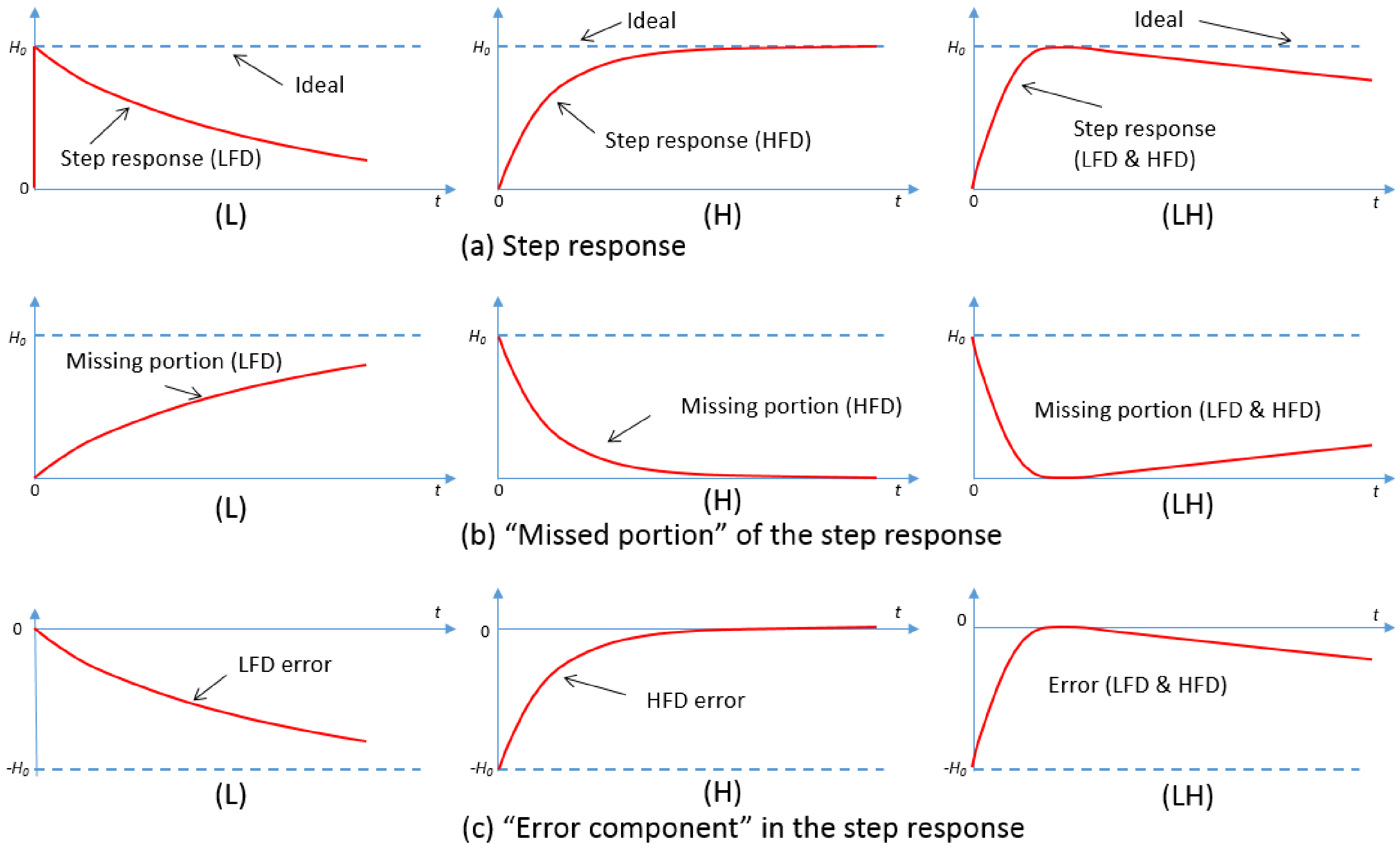
(b) Bandwidth missing



(c) Error transfer function (missing part of bandwidth with sign “-”)

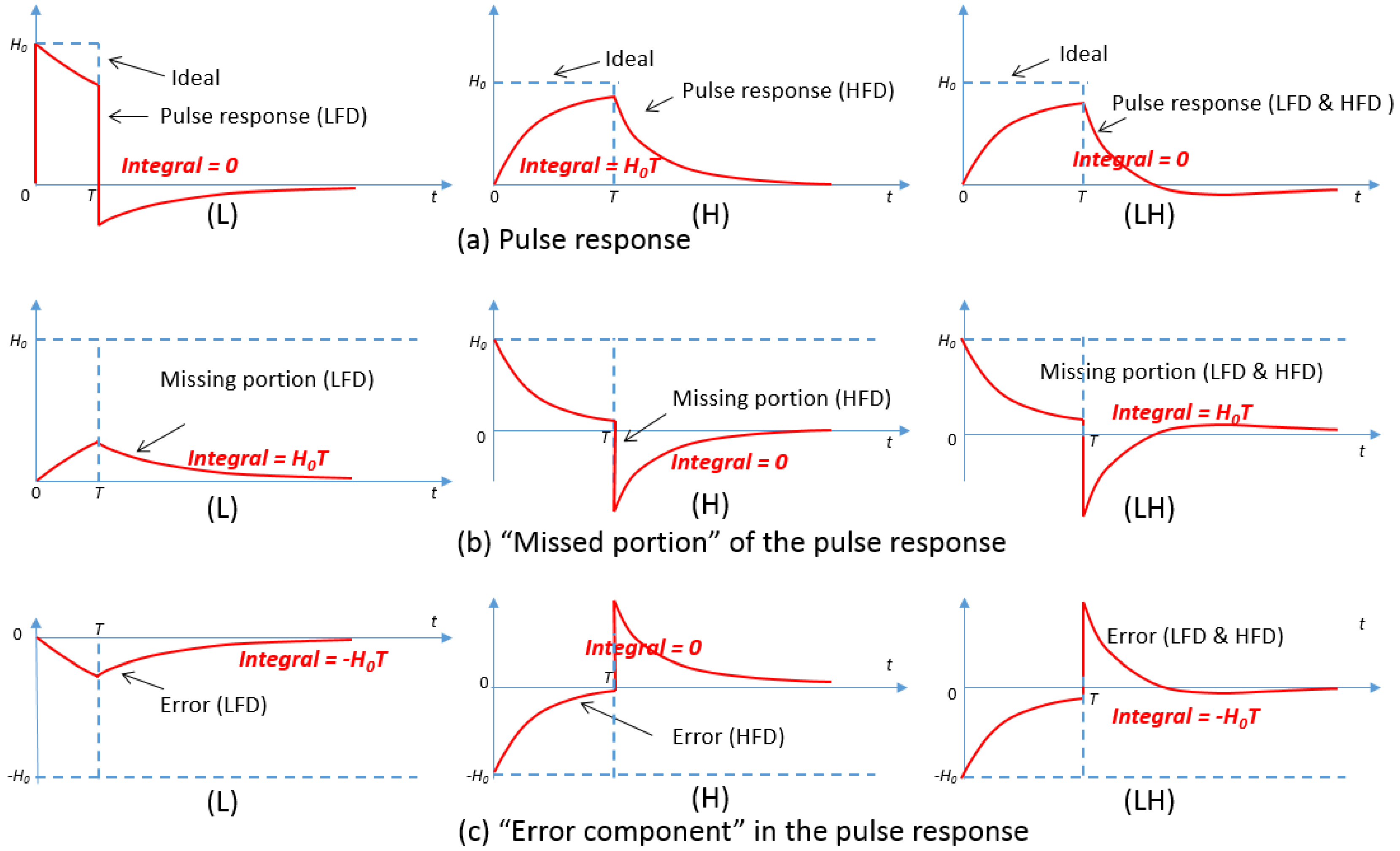
Step Responses in Channels with Bandwidth Limits

- For convenience of drawing, the time constants of low- and high-frequency processes were made much closer to each other than they are in reality
- If only low-frequency band limits exist, the step response makes an instant ramp then slowly decays to zero
- Typical channels with high-frequency deficiency only show the step response that gradually increases than stays at the constant level
- If both are present, we observe a fast rising ramp (per HFD time scale) then slow decay to zero level
- Note that the "error component" is a "missing portion" of the response taken with opposite sign



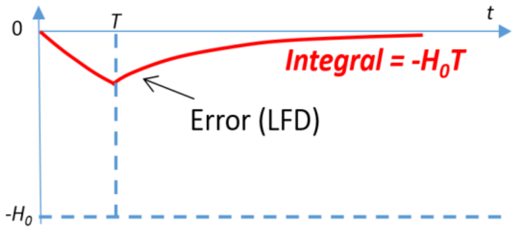
Pulse (symbol) Responses in Channels with LFD and HFD

- Pulse responses can be found by superimposing step responses
- A channel that doesn't modify DC/LF component of the input, preserves the ***integral*** of the pulse response (a, H)
- Channels that don't pass DC/LF component (a, L and LH) make integral of the pulse response zero.
- If both are present, we observe a fast rising ramp (per HFD time scale) then slow decay to zero level
- The opposite happens with error components. When DC/LF component is not in the pulse response, it becomes part of the error (with opposite sign)
- Integral of the error from a single pulse is constant for cases (c, L and LH).
- Duration of the error response depends on the LF cutoff frequency, but not its integral

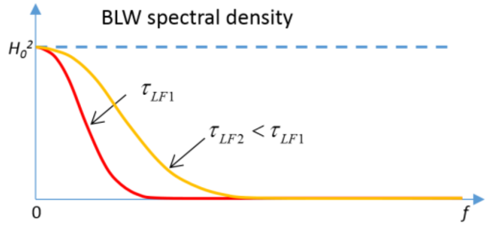


BLW Error Accumulation

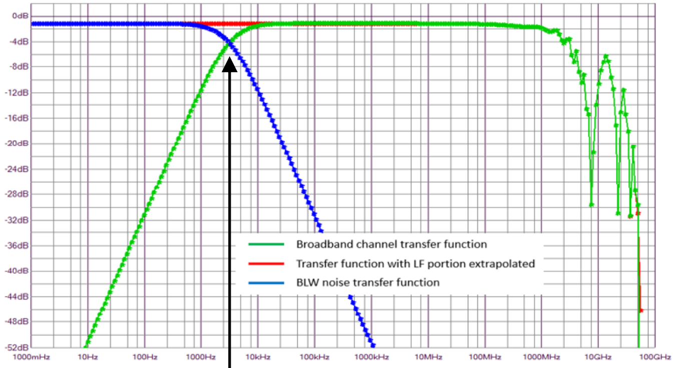
- As we have shown above, every symbol creates a prolonged error response that lasts from many thousands to millions of unit intervals
- Since the integral of this error is not zero, it has a tendency to accumulate. Accumulated error creates low frequency noise that we call BLW
- What happens if we increase the value of DC blocking capacitor? LF time constant will increase, the peak value of the error gets smaller, but its tail – longer, to preserve the value of the integral.
- As a result, BLW will accumulate from increasingly many symbols, its behavior becomes less predictable and less correlated with the input pattern
- Even though the energy of the single pulse error remains constant, with more symbols involved, it's less probable that the magnitudes of individual error components will add up in concert.
- As we can show, for uncorrelated pattern, standard deviation of BLW is in inverse proportion of the square root of the capacitor.

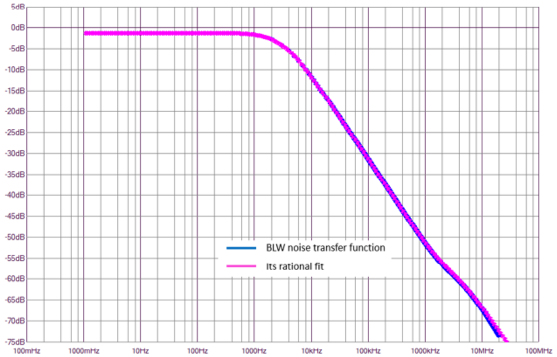


$$\sigma_{BLW} \sim \frac{1}{\sqrt{\tau_{LF}}} = \frac{1}{\sqrt{R_{eff} C_{dc}}}$$



Separating ISI and BLW Components





BLW cutoff frequency

Use this to find the waveform at Rx in a usual way

And this one to produce additive BLW noise

- Transfer function (TF) of a channel with AC coupling, $H_0(f)$
- Same TF with LF portion eliminated and the result extrapolated down below 50MHz (using rational fit), $H_{hf}(f)$
- Difference between them (BLW error transfer function), $H_{BLW}(f)$
- Rational fit of BLW transfer function

$$H_0(f) = H_{hf}(f) - H_{BLW}(f)$$

Time Domain Simulation of BLW (by Recursive Convolution)

With vector fit, we convert BLW transfer function into a sum of simple components (may contain real and complex poles):

$$H_{BLW}(s) = \sum_{m=1}^{M} \frac{1}{2}\left[\frac{A_m}{1+s/\Omega_m} + \frac{A_m^*}{1+s/\Omega_m^*}\right]$$

Then, at every time point BLW noise can be found as: $y(t_n) = \sum_{m=1}^{M} \mathrm{Re}\{K_m z_{m,n}\}$, where $z_{m,n} = E_m z_{m,n-1} + x(t_{n-1})$ are internal state variables, which should be updated with samples of the input pattern $x(t)$, and complex factors $K_m = A_m(1-e^{-\Omega_m T})$ and $E_m = e^{-\Omega_m T}$ are constant.

The time step *T* can be equal to symbol interval.

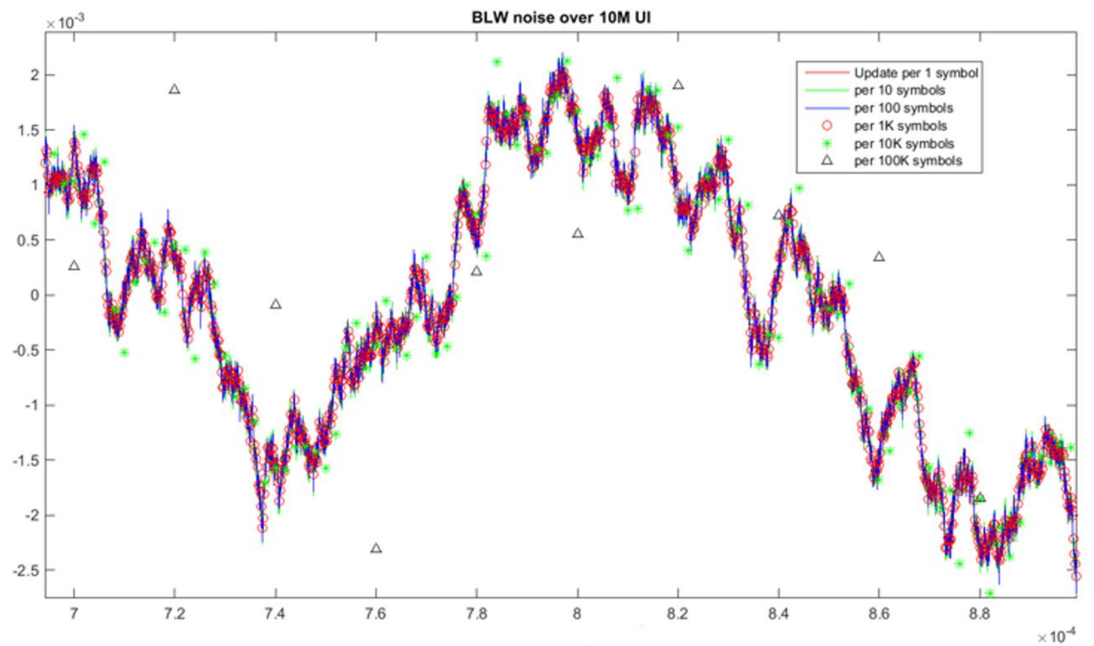
However, in many practical cases, we can choose a much larger step without loss of accuracy!

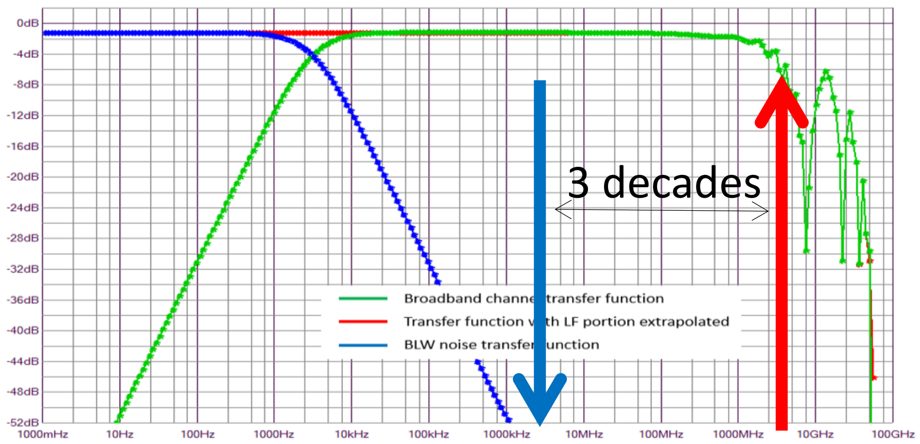
What is a Proper Time Step for BLW Noise Computation?

We computed BLW noise with different time steps for 5 Gbps NRZ signal:

- once per symbol (-----------)
- per 10 symbols (-----------)
- per 100 symbols (-----------)
- per 1K symbols (o o o o)
- per 10K symbols (* * * *)
- per 100K symbols (Δ Δ Δ Δ)

When time step exceeds 1UI, the input to BLW solver is replaced by average imparity of the aggregated symbols

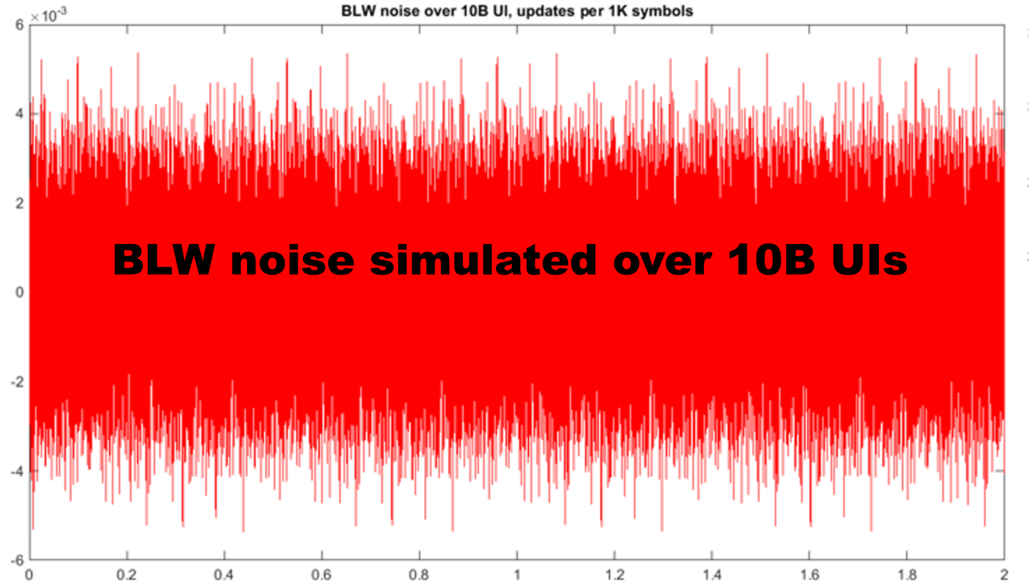


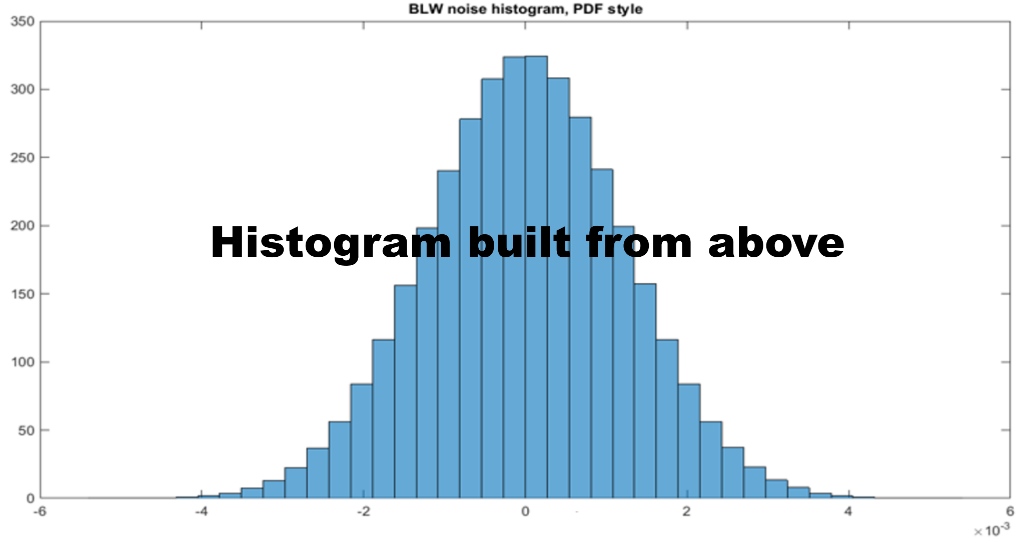


Only the last two demonstrated considerable inaccuracy. Why?
Because BLW noise drops by about 60dB at frequency that is 3 decades below Baud frequency, hence 10K UI step is OK, but not much more.

BLW Noise Simulation is Very Fast, but Not Enough

- Now, that we established a proper time granulation for BLW (1K symbols), we can simulate it very fast. 10B UI long simulation takes less than 2 min, about 1 sec per 100M UI.
- If so, can we estimate BLW noise down to probability 1e-12 by going over 1T UIs, which would take only 200 min?
- We can easily run simulation for that long, but the histogram will NOT let us go down to BER = 1e-12. This is because only uncorrelated samples matter for a histogram, but correlation length of BLW is by orders longer than symbol interval.
- In our case, time constant of BLW response is about 6 order of magnitude larger than Baud frequency. It means we need to increase simulation length of BLW in the same proportion. Not possible with time domain analysis!
- That's why statistical simulation of BLW is immensely important.





Statistical Analysis of BLW

Preparation

To find statistical properties of BLW we need to write its samples as linear combination of input symbols. Assuming that time step equals symbol length, and zero initial conditions, unwrap state variable formula into a sum:

$$z_{m,n} = E_m z_{m,n-1} + x(t_{n-1}) \Longrightarrow z_{m,N} = E_m^{N-1} x_1 + E_m^{N-2} x_2 + \ldots + x_N = \sum_{n=1}^{N} E_m^{N-n} x_n$$

Then, substitute the result into expression for BLW sample: $y_N = \mathrm{Re} \sum_{m=1}^{M} K_m \sum_{n=1}^{N} E_m^{N-n} x_n$

By changing the order of summation, we get: $y_N = \sum_{n=1}^{N} P_n x_n$, where $P_n = \sum_{m=1}^{M} \mathrm{Re}\{K_m E_m^{N-n}\}$

Note that weight factors P_n are constant and independent from the input pattern. They are fully defined by the fit of BLW transfer function. The number of summands N should be defined by the length of BLW response (up to millions of UI)

Case of Random Uncorrelated Input Pattern

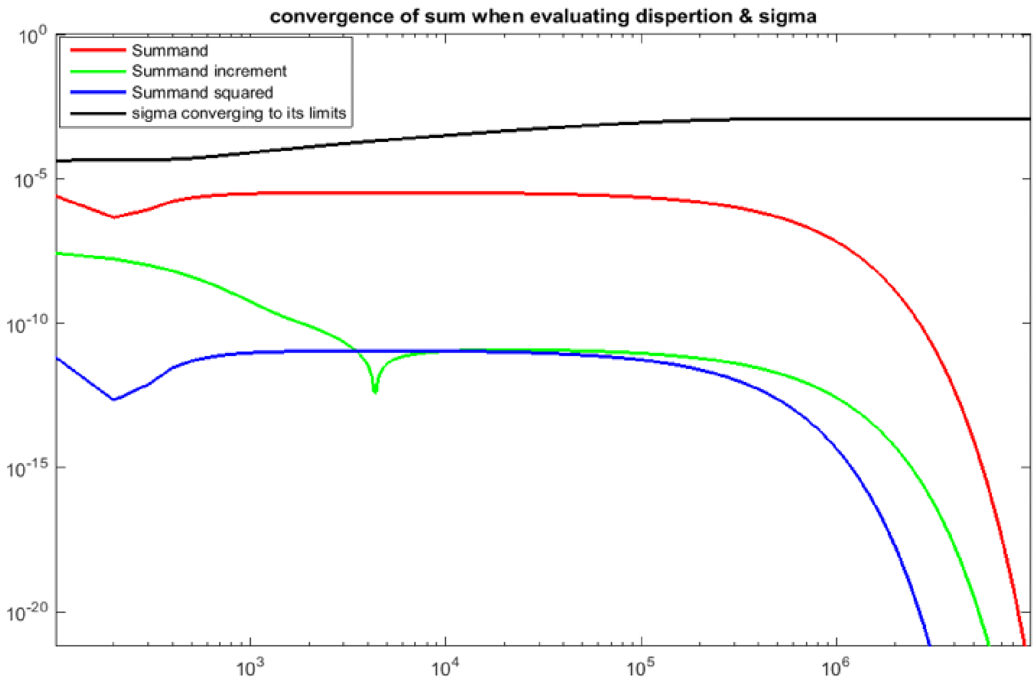
- We assume L-level modulation, meaning to zero, all states equally probable
- Symbol values are completely uncorrelated
- Since BLW transfer function is a low-pass filter with time constant exceeding symbol length by orders, and input pattern is uncorrelated, BLW noise must have practically Gaussian distribution
- BLW has zero mean, as does the input pattern. Therefore, distribution is fully defined by standard deviation of BLW

Square of standard deviation is the average of the product: $\sigma_y^2 = \left\langle \left(\sum_{n=1}^{N} P_n x_n \right) \left(\sum_{q=1}^{N} P_q x_q \right) \right\rangle$

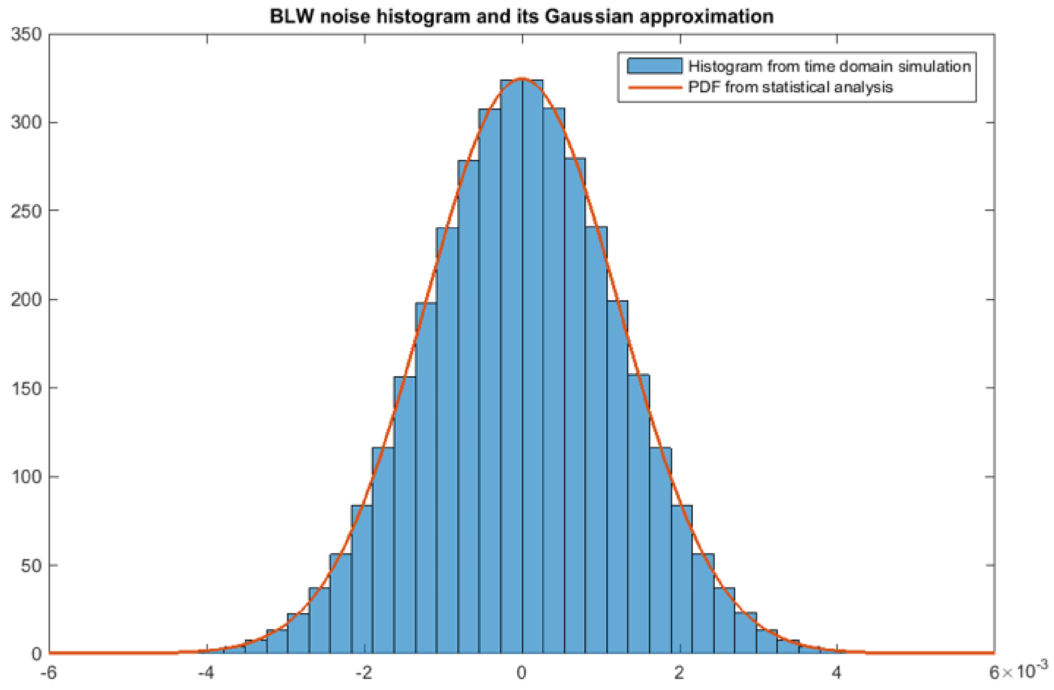
The product of sums can be written as a weighted sum of products of symbol values. However, the average $\langle x_n x_q \rangle$ is zero for all $n \neq q$, from where we get: $\sigma_y^2 = \sum_{n=1}^{N} P_n^2 \langle x_n^2 \rangle = \sigma_x^2 \sum_{n=1}^{N} P_n^2$, with $\sigma_x^2 = A_s^2 \dfrac{L+1}{3(L-1)}$.

The required number of summands *N* can be conservatively estimated from $e^{-N\Omega_{\min}T} < \varepsilon$, where $\Omega_{\min}$ is the slowest pole, *T* – symbol interval, and ε is a desired relative error. In our example, for ε =1e-10 this formula gives about 5.8M summands, although the value of sigma settles within double precision in 3.8M summands.

Case of Random Uncorrelated Input Pattern



Convergence of the sum representing dispersion and standard deviation of BLW



Comparison of BLW histogram found by 10B time-domain analysis and PDF predicted by statistical method

Random Correlated Input Pattern

- Again, assuming L-level modulation, zero mean value for any symbol, all states equally probable
- Now, the average $\langle x_n x_{n+k} \rangle$ is not zero even if *k*≠0, because of correlation between symbols. However, correlation is stationary, meaning that the average of the product depends on *k*, not on *n*.
- Averaging/Integration by BLW filter still works, BLW noise has Gaussian distribution, but its standard deviation depends on both BLW transfer function and the pattern correlation properties (or spectrum)

Let's denote correlation coefficients by $C_{x,k} = \langle x_n x_{n+k} \rangle$. In particular, $C_{x,0} = \sigma_x^2$. Then dispersion of BLW becomes:

$$\sigma_y^2 = \left\langle \left(\sum_{n=1}^{N} P_n x_n \right) \left(\sum_{q=1}^{N} P_q x_q \right) \right\rangle = \sum_{n=1}^{N} P_n^2 \langle x_n^2 \rangle + 2 \sum_{k=1}^{N} \sum_{n=1}^{N-k} P_n P_{n+k} \langle x_n x_{n+k} \rangle \approx$$

$$C_{x,0} \sum_{n=1}^{N} P_n^2 + 2 \sum_{k=1}^{K} C_{x,k} \left(\sum_{n=1}^{N} P_n P_{n+k} \right).$$

This is a sum of per-element products of the discrete correlation functions of both input pattern and pulse response of BLW. The first summand equals dispersion in case on uncorrelated pattern. The second – a term caused by correlation between symbols. The upper index *K* is a pattern correlation length; no need to proceed with summation beyond this limit. As before, limit *N* is defined by the slowest pole of the BLW transfer function.

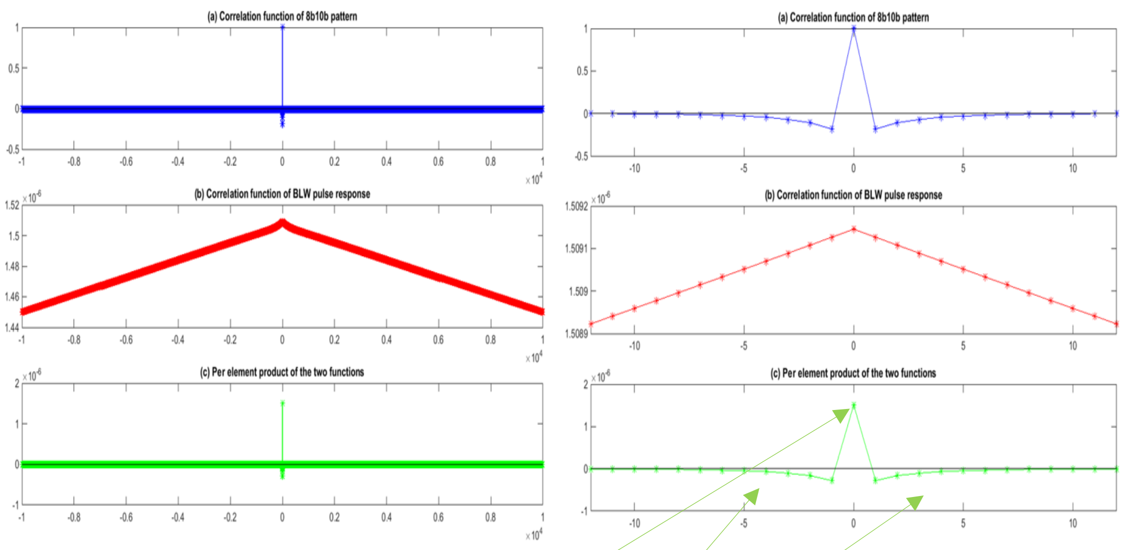
Random Correlated Input Pattern

Zoomed out | Zoomed in

Correlation function of 8b10b pattern

Correlation function of BLW pulse response

Per-element products of the two



$$\sigma_y^2 = C_{x,0} \sum_{n=1}^{N} P_n^2 + 2 \sum_{k=1}^{K} C_{x,k} \left(\sum_{n=1}^{N} P_n P_{n+k} \right)$$

- As an example, consider 8b10b pattern demonstrating strong correlation.
- All correlation coefficients of the pattern - except the central - are negative, and so are the per-element products.
- The first summand in the formula is a central peak of the resulted product. The second summand incorporates the values on both sides, that’s why factor 2 at the sum.
- The resultant sigma is way below the value we get for uncorrelated pattern. For a given example – 13.3μV versus 1.23mV.
- Statistical analysis is confirmed by time domain simulation with 8b10b input pattern

BLW Noise from Periodic Test Patterns

- Periodic patterns are opposite to random, but the method using state variables can be efficiently applied to them, too
- No need to run multi-million UI simulation to get into a cyclo-stationary mode. It can be found directly, by considering a geometrical progression, describing contribution from progressively distant periods, and finding the sum of this progression. (See paper for more details)
- If the period of the pattern is longer than BLW response duration, the summation can be truncated by the length of this response. In this case, no need for cyclo-stationary correction. (See paper for more details)
- Some periodic patterns are used as stress tests for BLW. For example PRBS31Q, whose period is formed by taking two periods of NRZ PRBS31 and converting them into PAM-4 by Gray coding (P. Anslow, “SSPRQ test pattern”, IEEE P802.3bs Task Force, 2016).
- This pattern is known to produce unusually large spikes of BLW noise magnitude, because at some points in time the symbols, although non-constant, tend to stay on either positive or negative side, thus creating a considerable running average imparity.

BLW Noise from Periodic Test Patterns (PRBS31Q)

- Example: the response of BLW filter on PRBS31Q (with period about 2.15B symbols) was found by the proposed method directly (red)
- Compared to random PAM-4 stimulus (blue) we observe peak value increase from 0.92mV to 10.9mV (Fig. 1)
- Histogram of the resulting noise appears asymmetrical (Fig. 2)
- SER has a certain vertical offset, too. Its sign is opposite to the peaks of BLW noise (Fig. 3)
- Vertical cross-section of the central eye zoomed out (Fig. 4)

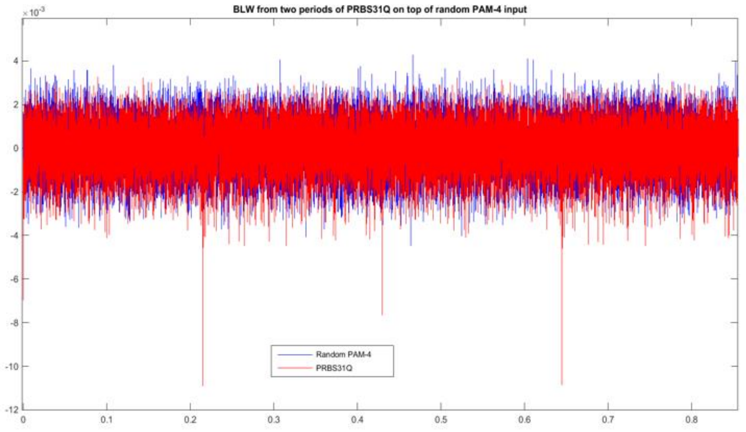


Figure 1

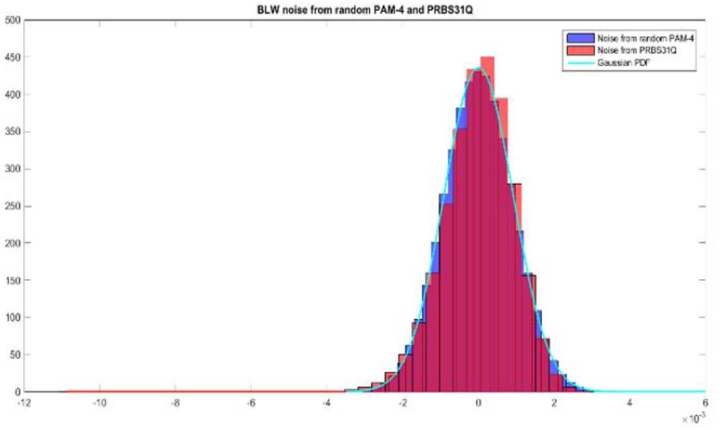


Figure 2

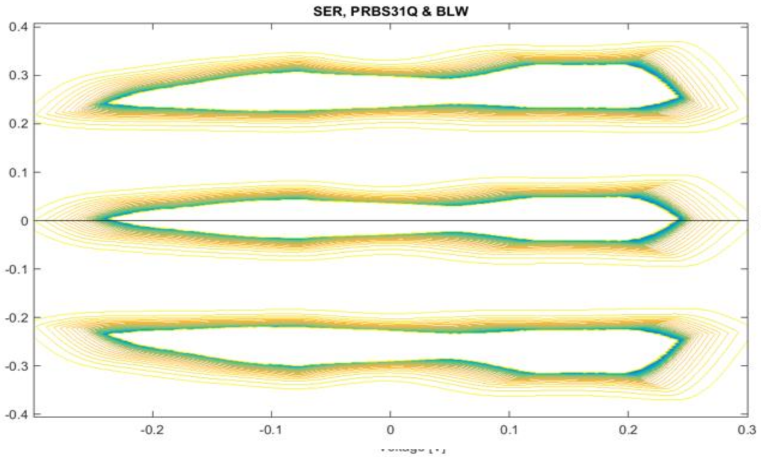


Figure 3

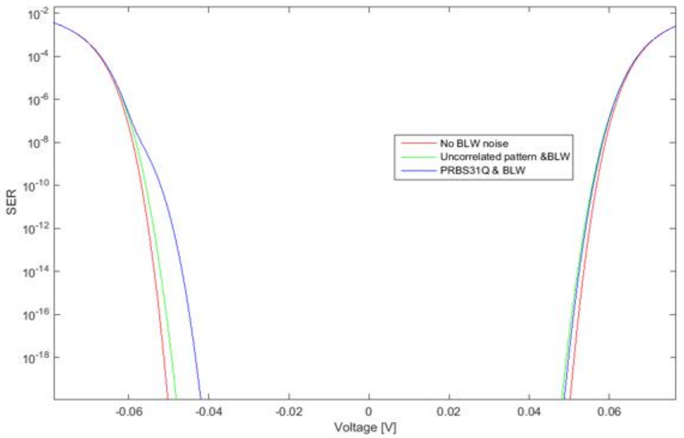
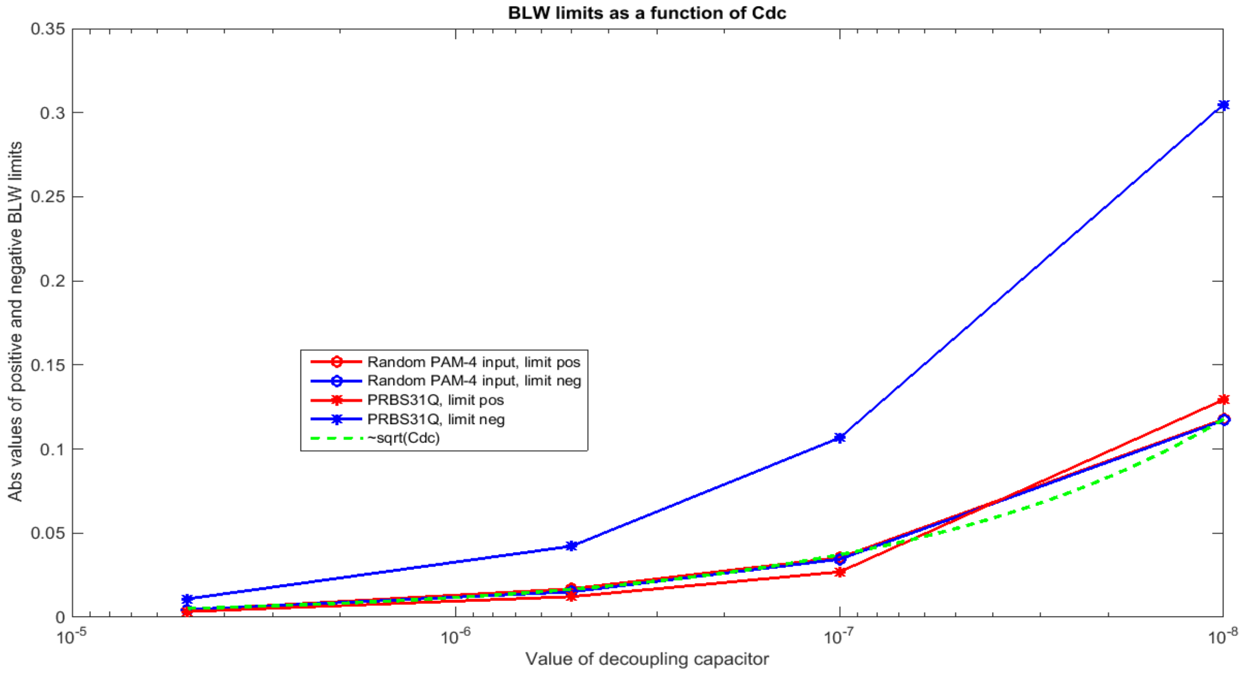


Figure 4

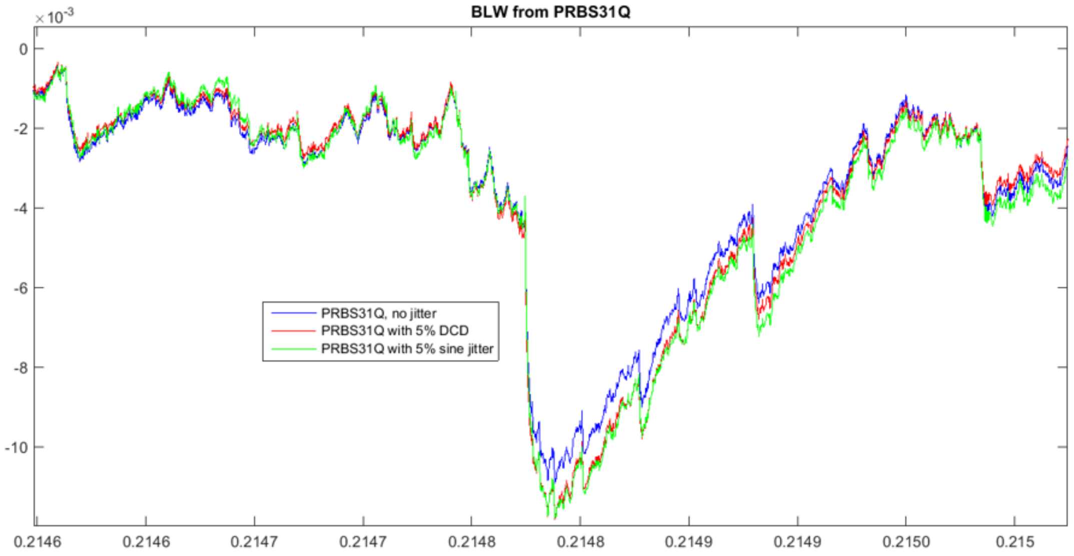
Factors Affecting BLW Noise: the Value of DC Blocking Capacitor

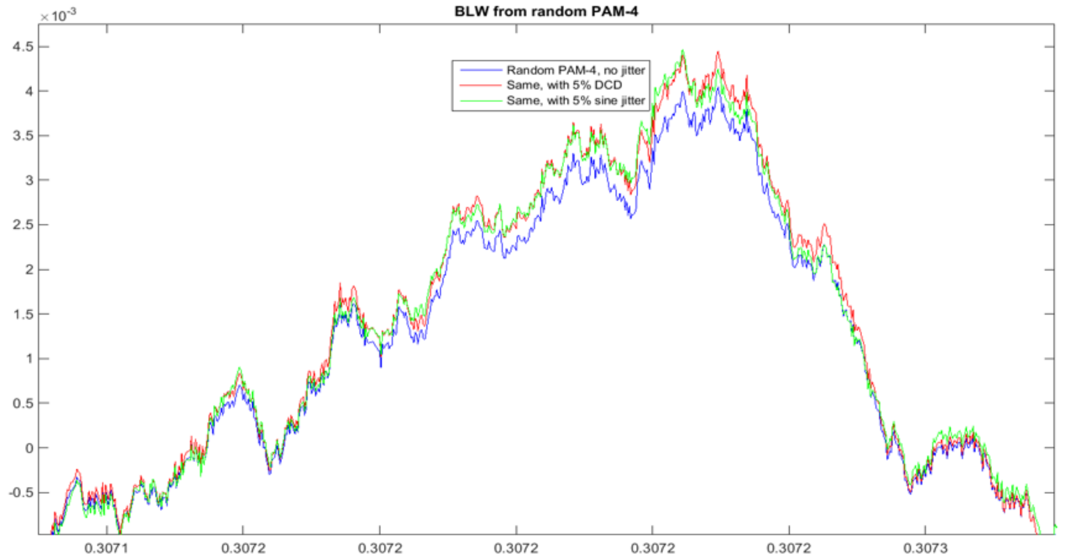
- General trend agrees with theoretical prediction: ~1/sqrt(C_{dc})
- However, the magnitudes vary, especially for BLW test patterns, both by polarity and compared to random uncorrelated input
- This can be explained by considerable difference in spectrum of the uncorrelated pattern and PRBS31Q. The latter has larger DC component, and magnitudes of its first harmonics
- Another cause: BLW response is not exactly exponential; its transfer function may have resonances (complex poles)



Factors Affecting BLW Noise: Tx Jitter

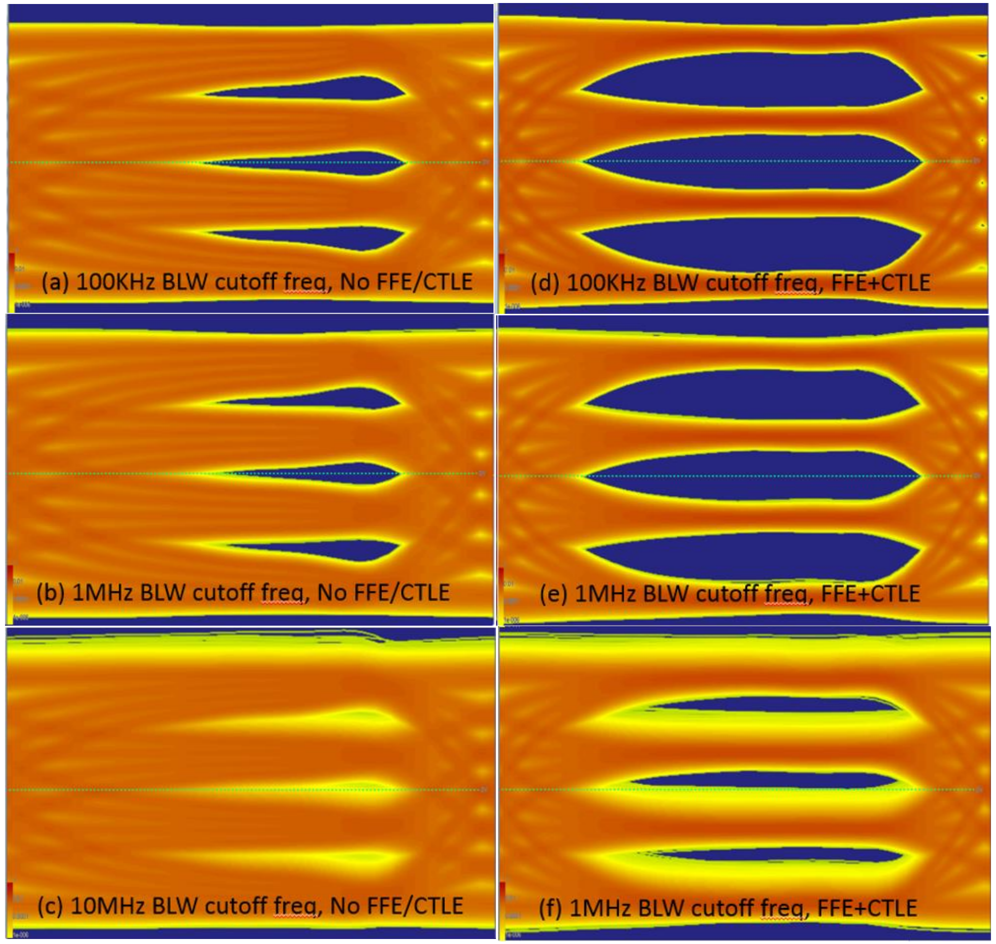
- Tx jitter modifies symbol lengths and hence, average running imparity that affects BLW
- In some special cases (e.g. meander pattern with DCD jitter) imparity changes drastically and may increase BLW by orders
- In less "regular" cases, the effect is moderate. DCD and sine jitter typically modify BLW by a few percent. Random jitter with comparable deviation provides similar or lesser effect
- However, in terms of final BER or SER measures, jitter is more destructive with respect to the signal waveform itself, regardless of BLW





Factors Affecting BLW Noise: Linear Equalization (FFE, CTLE)

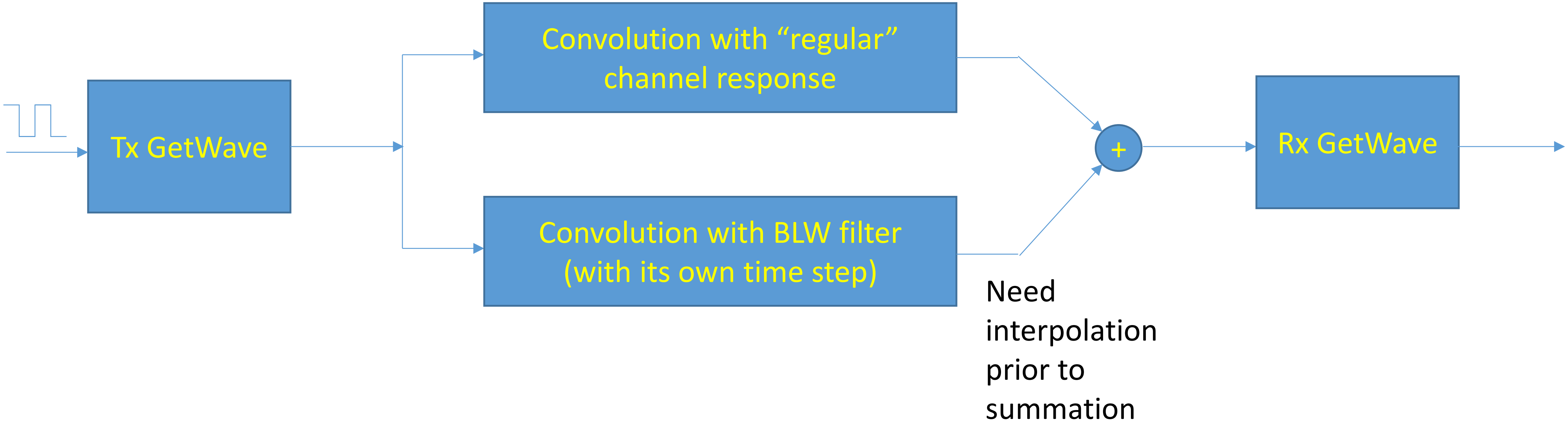
- Linear equalization, both FFE and CTLE, reduces signal amplification at low frequency. This makes signal level separation at Rx decision point smaller
- At the same time, amplification reduce at low frequency, changes BLW magnitude in the same proportion. Hence the “ratio of BLW noise to signal” doesn’t change much.
- However, equalization efficiently eliminates a portion of ISI-related noise, which makes it useful regardless of BLW
- BLW is “neutral” to the presence of DFE, because DFE length is too small for a slow developing BLW
- These conclusions are confirmed by experiments



No equalization FFE+CTLE

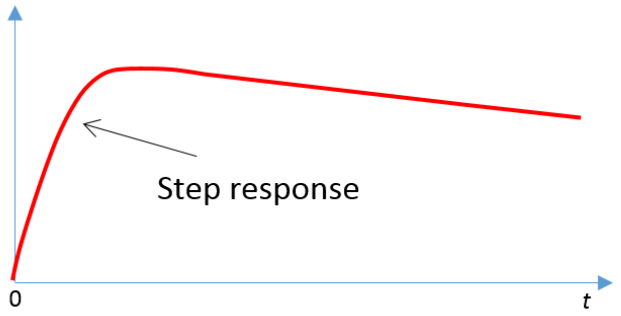
BLW and IBIS AMI, *Time Domain Flow*

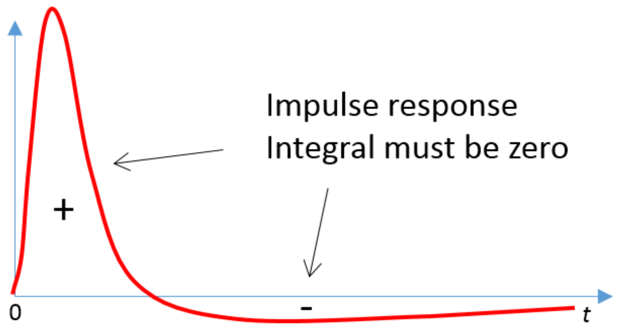
- Most efforts are required from EDA tools
- IBIS AMI models can be readily used

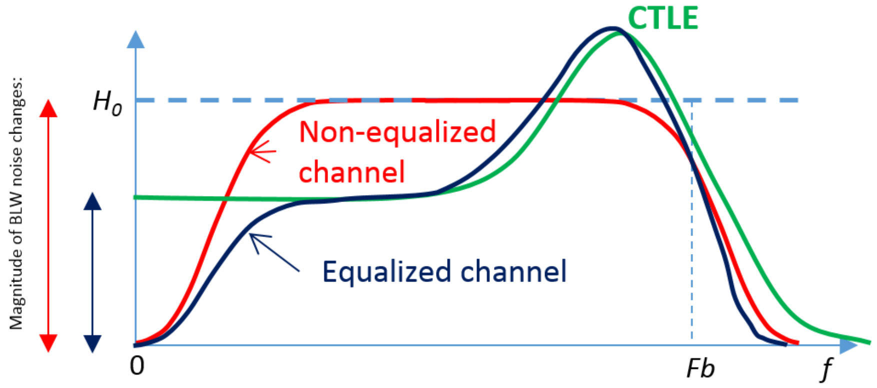


BLW and IBIS AMI, *Statistical Flow*

- Low frequency effects are not included in Tx and Rx impulse responses, because their duration doesn't exceed few hundred UIs, but we may need millions. Plus, the constraint must be held: integral over IR should be zero
- EDA tool can find ***non-equalized*** transfer function of BLW noise and ***non-equalized*** time response from e.g. S parameters
- However, linear equalizers in Tx and Rx (FFE, CTLE) do affect BLW transfer function (mostly, by scaling it)
- We need Tx and Rx AMI models ***to report their DC gain*** for given settings, so that BLW filter can be scaled accordingly
- Then, EDA tool can proceed with statistical analysis. All other related information, e.g. correlation properties of the input pattern, are irrelevant to AMI and can be considered by EDA tool as well
- This approach appears useful for time-domain analysis as well. Because EDA tool may allow combining TD results of AMI analysis with BLW distribution estimated statistically







Conclusions

- Baseline Wander is an important impairment; it should be considered in SERDES design process.
- With multi-level modulation, and tighter signal margins in state of the art designs, BLW can no longer be ignored.
- We proposed efficient methods of its time domain and statistical analysis, based on separating low-frequency error (BLW noise component) from ISI component
- Channel evaluation methods (COM/JCOM/USB/PCIe) can be upgraded to consider BLW noise
- A few simple modifications are required to IBIS AMI models to support statistical analysis (need to report DC gain).