Transmitter distortion: specification refinement based on real measurements

Rubén Pérez-Aranda
(rubenpda@kdpof.com)

Agenda

- Transmitter distortion refinement
- Measurements
- Effect of TX distortion on RX sensitivity

Transmitter distortion refinement

Transmitter distortion measurement in D2.0

- As specified in 802.3bv D2.0, the TX distortion is determined by 3 parameters:
  - Second order harmonic distortion (HD2)
  - Third order harmonic distortion (HD3)
  - Residual peak distortion (RPD)
- The 3 parameters are calculated by a Matlab script from a capture of the over-sampled PMD transmit signal. The PHY is configured to generate test mode 6 signal. Acquisition clock and PHY symbol clock are generated from a common reference. Basically, the Matlab script computes distortion parameters in several steps:
  - Baseline compensation (any DC bias is eliminated)
  - Signal is processed with a 2nd order Butterworth low-pass filter with cut-off frequency of one half of the symbol rate
  - Synchronization, time recovery and decimation of the signal: optimum sampling phase is obtained before decimation (like timing-recovery providing the clock phase to the ADC in a PHY implementation)
  - Signal amplitude normalization
  - Volterra's system identification (MMSE estimation) and distortion calculation based on that identification

Volterra's processing in D2.0

- Volterra's system that has to be estimated contains kernels of 0th, 1st, 2nd and 3rd order, and topology has been selected based on previous experience with AlGaInP LED based transmitters (typical light source used in existing POF products):
    - length of impulse response
    - delay group
    - maximum delay between products of signal with itself
- The ideal test-mode 6 signal is filtered by the identified Volterra's system and the resulting signal subtracted from the captured signal that was used for identification, obtaining an error signal that is used to calculate the RPD
- HD2 and HD3 calculations use relation between 1st order kernels and the 2nd and 3rd order kernels, respectively. HD2 and HD3 follow MMSE criterion
- RPD is calculated as a relation between the maximum absolute value of error signal and the energy of the 1st order estimated response. This parameter presents several <u>drawbacks</u> in real measurement:
    - RPD is <u>not a good estimate</u> like the MMSE, so the result oscillates.
    - RPD is the sum of many factors: not estimated kernels of order > 3, limited estimated impulse length, noise as RIN, noise as DAC quantization, noise of acquisition equipment, etc.

Proposed refinements for D2.1

- Include 4th order kernels and HD4 bound:
  - its contribution is really small in tested devices (see later), so it is not worth any compensation in the receiver
  - however, it can be comparable to some noise sources in the system. Because its correlation properties, HD4 can be distinguished from other uncorrelated noise sources (DAC, RIN, etc)
- Use a MMSE criterion for the residual distortion (RD)
  - more robust estimator
  - specification is relaxed (specially if dominant noise sources are gaussian)
- Review specification of maximum RD to be consistent with RIN specification and a margin for DAC quantization noise:

$$RD \geq 20\log_{10}\left(\frac{10^{RIN_{\max}/20}\sqrt{\frac{F_S}{2}}}{\frac{10^{ER_{\min}/10}-1}{10^{ER_{\min}/10}+1}\frac{1}{\sqrt{3}}} \right) + \Delta$$

RIN (dB/Hz)
ER (dB)
RD (dB)
Δ (dB), margin for DAC noise

Proposed refinements for D2.1

```
%--------------------------------------------------------------------------------
% Volterra's estimation and analysis
%--------------------------------------------------------------------------------
function [HD2 HD3 HD4 RPD] = volest(x, d, n, dly)

% Init
R  = 0;
rD = 0;

% Addition autocorrelation and cross-correlation
for k = n:length(x),
  % Volterra products
  xi = [1 ...
        x(k:-1:k-n+1) ...
        x(k:-1:k-n+1)  .*x(k:-1:k-n+1)   ...
        x(k:-1:k-n+1+1).*x(k-1:-1:k-n+1) ...
        x(k:-1:k-n+1+2).*x(k-2:-1:k-n+1) ...
        x(k:-1:k-n+1)  .*x(k:-1:k-n+1)    .*x(k:-1:k-n+1)   ...
        x(k:-1:k-n+1+1).*x(k:-1:k-n+1+1)  .*x(k-1:-1:k-n+1) ...
        x(k:-1:k-n+1+2).*x(k:-1:k-n+1+2)  .*x(k-2:-1:k-n+1) ...
        x(k:-1:k-n+1+1).*x(k-1:-1:k-n+1)  .*x(k-1:-1:k-n+1) ...
        x(k:-1:k-n+1+2).*x(k-1:-1:k-n+1+1).*x(k-2:-1:k-n+1) ...
        x(k:-1:k-n+1+2).*x(k-2:-1:k-n+1)  .*x(k-2:-1:k-n+1) ...
        x(k:-1:k-n+1)  .*x(k:-1:k-n+1)    .*x(k:-1:k-n+1)   .*x(k:-1:k-n+1) ...
        x(k:-1:k-n+1+1).*x(k:-1:k-n+1+1)  .*x(k:-1:k-n+1+1) .*x(k-1:-1:k-n+1) ...
        x(k:-1:k-n+1+1).*x(k:-1:k-n+1+1)  .*x(k-1:-1:k-n+1) .*x(k-1:-1:k-n+1) ...
        x(k:-1:k-n+1+1).*x(k-1:-1:k-n+1)  .*x(k-1:-1:k-n+1) .*x(k-1:-1:k-n+1)];

  % Autocorrelation matrix
  R = R + xi.'*xi;

  % Cross-correlation vector
  rD = rD + d(k-dly)*xi.';
end

% Wiener's MMSE solution
hw = (R\rD).';

% Separate the Volterra kernels per channel
lw = [1 ...
      n ...
      n (n-1) (n-2) ...
      n (n-1) (n-2) (n-1) (n-2) (n-2) ...
      n (n-1) (n-1) (n-1)];
```

Proposed refinements for D2.1

```
ofst = 0;
for i = 1:1115,
  h{i} = hw(ofst+1:ofst+lw(i));
  ofst = ofst + lw(i);
end

% Calculate harmonic distortion
HD2 = -10*log10(1/3*axc(h{2})/ ...
               (1/5*axc(h{3}) + 1/9*axc(h{4}) + 1/9*axc(h{5})));

HD3 = -10*log10(1/3*axc(h{2})/ ...
               (1/7*axc(h{6}) + 1/15*axc(h{7})  + 1/15*axc(h{8}) + ...
               1/15*axc(h{9}) + 1/27*axc(h{10}) + 1/15*axc(h{11})));

HD4 = -10*log10(1/3*axc(h{2})/ ...
               (1/9*axc(h{12}) + 1/21*axc(h{13})  + 1/25*axc(h{14}) + ...
               1/21*axc(h{15})));

% Calculate residual peak distortion
z = h{1} + ...
    filter(h{2},  1, x(3:end)) + ...
    filter(h{3},  1, x(3:end).*x(3:end))   + ...
    filter(h{4},  1, x(3:end).*x(2:end-1)) + ...
    filter(h{5},  1, x(3:end).*x(1:end-2)) + ...
    filter(h{6},  1, x(3:end).*x(3:end)  .*x(3:end))   + ...
    filter(h{7},  1, x(3:end).*x(3:end)  .*x(2:end-1)) + ...
    filter(h{8},  1, x(3:end).*x(3:end)  .*x(1:end-2)) + ...
    filter(h{9},  1, x(3:end).*x(2:end-1).*x(2:end-1)) + ...
    filter(h{10}, 1, x(3:end).*x(2:end-1).*x(1:end-2)) + ...
    filter(h{11}, 1, x(3:end).*x(1:end-2).*x(1:end-2)) + ...
    filter(h{12}, 1, x(3:end).*x(3:end)  .*x(3:end)  .*x(3:end))   + ...
    filter(h{13}, 1, x(3:end).*x(3:end)  .*x(3:end)  .*x(2:end-1)) + ...
    filter(h{14}, 1, x(3:end).*x(3:end)  .*x(2:end-1).*x(2:end-1)) + ...
    filter(h{15}, 1, x(3:end).*x(2:end-1).*x(2:end-1).*x(2:end-1));

z = z(1+dly-2+n:end);
d = d(1+n:end);
l = min([length(z) length(d)]);
e = z(1:l) - d(1:l);

RPD = 20*log10(max(abs(e))/abs(sum(h{2})));
RD = -10*log10(1/3*axc(h{2})/var(e));

end
```

Proposed refinements for D2.1

- This proposal is based on the measurement results reported in next slides

	802.3bv D2.0	802.3bv D2.1
$HD2_{max}$ (dB)	-21	-20
$HD3_{max}$ (dB)	-27	-26
$HD4_{max}$ (dB)	—	-36
RPD_{max} (dB)	-40	—
RD_{max} (dB)	—	-40

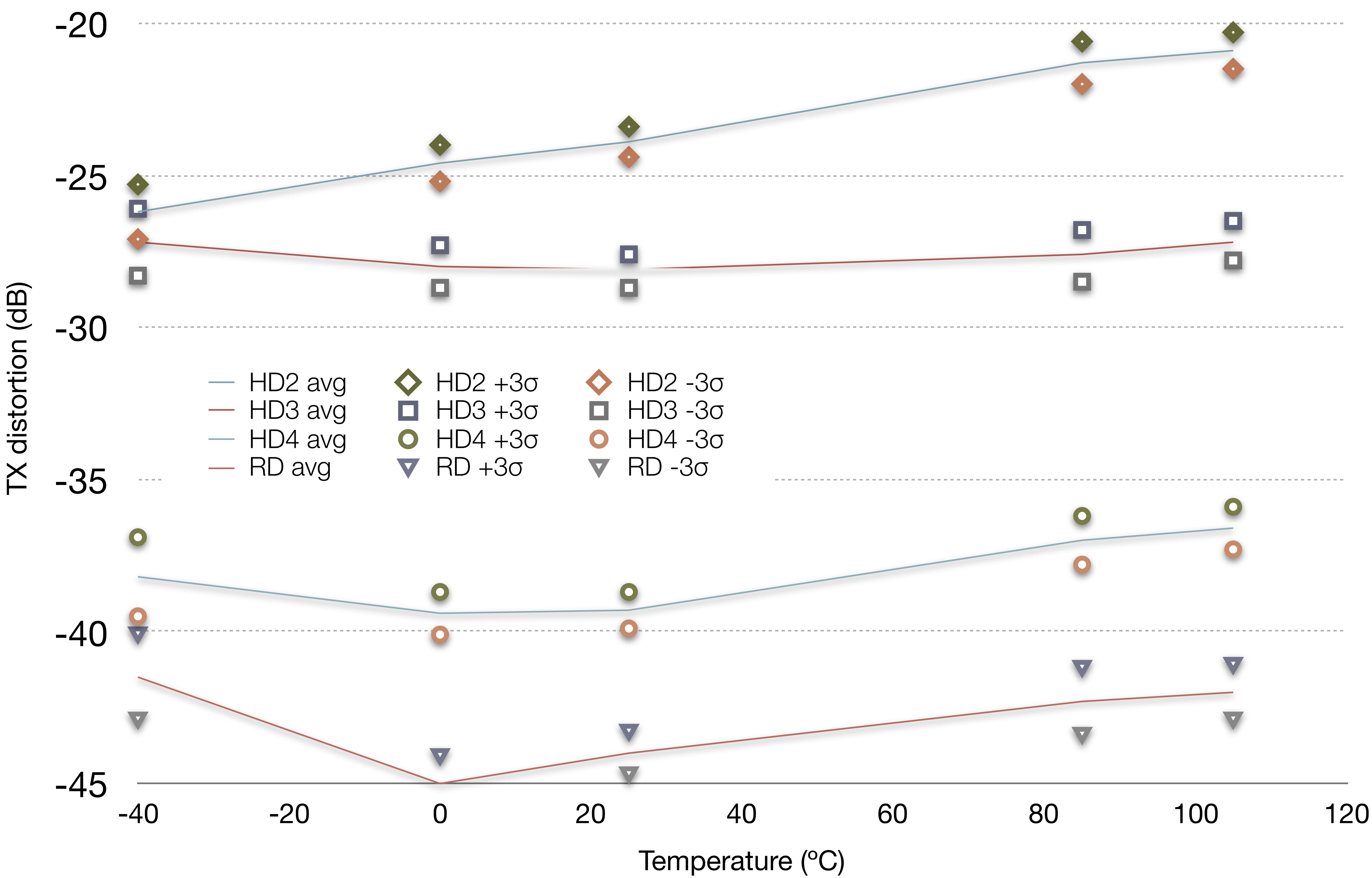
Measurements

Measurements: LEDs from 4 manufacturers

TX distortion per Matlab script of 802.3bv D2.0 (T_{amb} = 25 ºC)				
	LED part A (includes driver) average of many samples	LED part B	LED part C	LED part D
HD2 (dB)	-23,9	-24,1	-21,7	-23,1
HD3 (dB)	-28,1	-31,7	-34,6	-34,1
RPD (dB)[1]	-37,5	-37,1	-35,5	-39,0

[1] noisy estimate

Measurements: Part A in temperature (SS = 10)



Effect of TX distortion on RX sensitivity (Simulations)

Effect of TX distortion on RX sensitivity

- Rational of simulations:
  - We take a Volterra's model estimated in the laboratory for a real TX per script in D2.0
  - We scale the kernels of 2^{nd} and 3^{rd} order with different gains to analyze how the TX distortion affects to the RX sensitivity in simulation
  - The morphology of non-linearity is equal to a real LED, because we use kernels obtained in real setup
  - However, we are able to modify the magnitude of harmonic distortion by means of a constant that scale all the kernels of an order simultaneously, preserving morphology
- The simulation implements a complete 1000BASE-RHx physical layer (PCS/PMA/PMD) that includes compensation of non-linearities of 2^{nd} and 3^{rd} order
  - Real implementation of non-linear compensation: fixed-point arithmetics, finite length filters bounded complexity feasible for IC integration
  - 4^{th} order distortion is not compensated because being considered negligible, although it is up to the implementor
- Despite the non-linear distortion is compensated, it produces a capacity loss that cannot be recovered in any case
  - The root cause behind of that is the nature non-linear distortion: non-linear post and pre-cursor of channel impulse response are neither separable nor compensable in a DFE like structure

Effect of TX distortion on RX sensitivity

TX distortion per D2.0		Notes	Linear TX baseline		Real TX baseline	
HD2 (dB)	HD3 (dB)		Sens loss TP3 (dB), 15m POF	Sens loss TP3 (dB), 50m POF	Sens loss TP3 (dB), 15m POF	Sens loss TP3 (dB), 50m POF
-47,2	-43,3	Linear TX	0	0	-1,3	-1,8
-23,1	-27,5	Real TX	1,3	1,8	0	0
-20,2	-27,5	+HD2	1,7	—	0,4	—
-17,2	-27,5	++HD2	2,5	—	1,2	—
-20,2	-24,8	+HD2, +HD3	2,1	3,1	0,8	1,3
-17,2	-24,8	++ HD2, +HD3	3,0	—	1,7	—
-17,2	-21,9	++HD2, ++HD3	3,7	5,0	2,4	3,2

Effect of TX distortion on RX sensitivity

- The TX distortion penalizes the receiver sensitivity, because non-linearities produce unavoidable capacity loss (despite they are being compensated by the receiver)
- To be able to meet the specifications with worse transmitters, the O/E receiver should be able to perform with lower noise, which is not realistic:
  - size of photodiode: drift time, capacitance, responsitivity
  - technology process of TIA: max trans-conductance, GBW product, with bounded power supply
  - -40 to 105 ºC for RHC
- The specification has to limit the TX distortion from a holistic point of view:
  - POF channel, photodiode, TIA, DSP complexity, etc.
- The measurements carried out for different LED part numbers demonstrate that proposed limits are realistic and achievable
- The simulation results demonstrate the robustness of adaptive non-linear equalizers, able to compensate non-linear distortions in a very wide range
  - Bounds specified for TX distortion do not represent a *GO / NO GO* condition.
  - However, it is necessary for the transmitter to limit the distortion to be able to establish the Gigabit link with a compliant receiver under any environmental condition.

Questions?