Transmitter distortion parameters: measurement results and method validation

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IEEE 802.3bv Task Force - September 2016

Agenda

- Introduction and motivation
- Tutorial on the transmitter distortion parameters
- Measurement results

Introduction and motivation

- This presentation has as objective to provide measurement results to validate the transmitter distortion parameters in the draft P802.3bv/D3.0 as requested by comment 118 against P802.3bv/D2.0
- In order to cover the above objective, it will be also provided a detailed explanation of the script of 115.6.4.8 specified to calculate the transmitter distortion parameters.
- Characterization of 4 different almost compliant PMD TX implementations are presented:
    - Each PMD TX implementation integrates a different LED chip design and a different driver design
    - Each PMD TX is packaged in the same optical MDI connector together with a PMD RX to be able to establish bidirectional Gigabit link with a golden link partner (unique for all the tests)
    - Each PMD implementation under test is connected to a different part of the same PCS/PMA KDPOF chip design
    - The 4 PMD implementations are able to establish a full-duplex Gigabit link with BER < 10^{-12} with good receiver sensitivity in the link partner
    - The 4 PMD are evaluated in the temperature range of -40 and 110 ºC
    - PMD implementation #4 was used in the past to develop the specification of the transmitter distortion parameters in P802.3bv/D3.0
    - Implementations #1, #2 and #3 are new.
- Characterization of 2 non-compliant PMD TX implementations is also provided
    - These implementations are non-compliant so they are not able to establish link with the partner
    - Though these implementation may meet the specification of ER, RIN, rise-time/fall-time, and other parameters, the transmitter distortion parameters are not met, so the link cannot be established.

Tutorial on the transmitter distortion parameters

Tutorial on the transmitter distortion parameters

- As specified in P802.3bv/D3.0, the transmitter distortion is determined by 4 parameters:
  - Second order harmonic distortion (HD_2)
  - Third order harmonic distortion (HD_3)
  - Fourth order harmonic distortion (HD_4)
  - Residual distortion (RD)
- The 4 parameters are calculated by a Matlab script from a capture of the over-sampled (i.e. oversample ratio > 10) PMD transmit signal at TP2.
- The PHY is configured to generate test mode 6 signal.
- Acquisition clock and PHY symbol clock are generated from a common reference to guarantee null frequency deviation between the transmitter and the clock used to sample the transmit waveform.

Steps to get transmitter distortion parameters

- The Matlab script computes distortion parameters in several steps:

  1. Baseline compensation (any DC bias is eliminated from the captured samples)

```
xcap = xcap - mean(xcap);
```

  2. Signal is processed with a 2nd order Butterworth low-pass anti-alias filter with cut-off frequency one half of the symbol rate

```
[hb, ha] = butter(2, 1/ov, 'low');
xcap = filter(hb, ha, xcap);
```

  3. Synchronization for sample alignment based on cross-correlation of the oversampled signal

```
tm6_ov = reshape(repmat(tm6, ov, 1), 1, []);
xc = filter(tm6_ov(end:-1:1), 1, [xcap zeros(1, length(tm6_ov))]);
[mv mi] = max(abs(xc));
dly = mi - length(tm6_ov);
xcap = xcap(1+dly:end);
xcap = xcap(1:length(tm6_ov));
```

  4. Symbol rate clock phase recovery based on a modified Mueller-Müller criterion (K. H. Mueller et al., *“Timing recovery in digital synchronous data receivers”*, IEEE Trans on Comm., May 1976) and decimation (alpha = 0.7 vs. 0.5 because the fact of transmitter responses show larger post-cursor than pre-cursor)

```
alpha = 0.7;
min_ted = Inf;
for i = 0:ov-1,
  xcap_dec = xcap(1+i:ov:end);
  len0 = min([length(xcap_dec) length(tm6)]);
  ted = mean((1 - alpha)*xcap_dec(2:len0).*tm6(1:len0-1) - alpha*xcap_dec(1:len0-1).*tm6(2:len0));
  if abs(ted) < min_ted, min_ted = abs(ted); dly = i; end
end
xcap_dec = xcap(1+dly:ov:end);
```

Steps to get transmitter distortion parameters

5. Signal amplitude normalization

```
xcap_dec = xcap_dec/max(abs(xcap_dec));
```

6. MMSE (Minimum Mean Square Error) estimation of Volterra's symbol-rate time-domain response of the transmitter under test

```
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).';
```

Steps to get transmitter distortion parameters

7. Separate the Volterra's kernels per Volterra's linear filter (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)];

ofst = 0;
for i = 1:15,
  h{i} = hw(ofst+1:ofst+lw(i));
  ofst = ofst + lw(i);
end
```

8. Distortion parameters calculation based on the Volterra's identification. The factors 1/3, 1/5, 1/7, 1/9, etc. are the term 0 of the autocorrelations of the input signals to each Volterra's linear filter, taking into account that test mode 6 signal takes values from a uniform distribution between -1 and 1 and is an almost white stochastic process. We take into account the energy of each random signal feeding each Volterra's linear filter, and based on that, we calculate the ratios HD_2, HD_3 and HD_4.

```
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})));
```

Steps to get transmitter distortion parameters

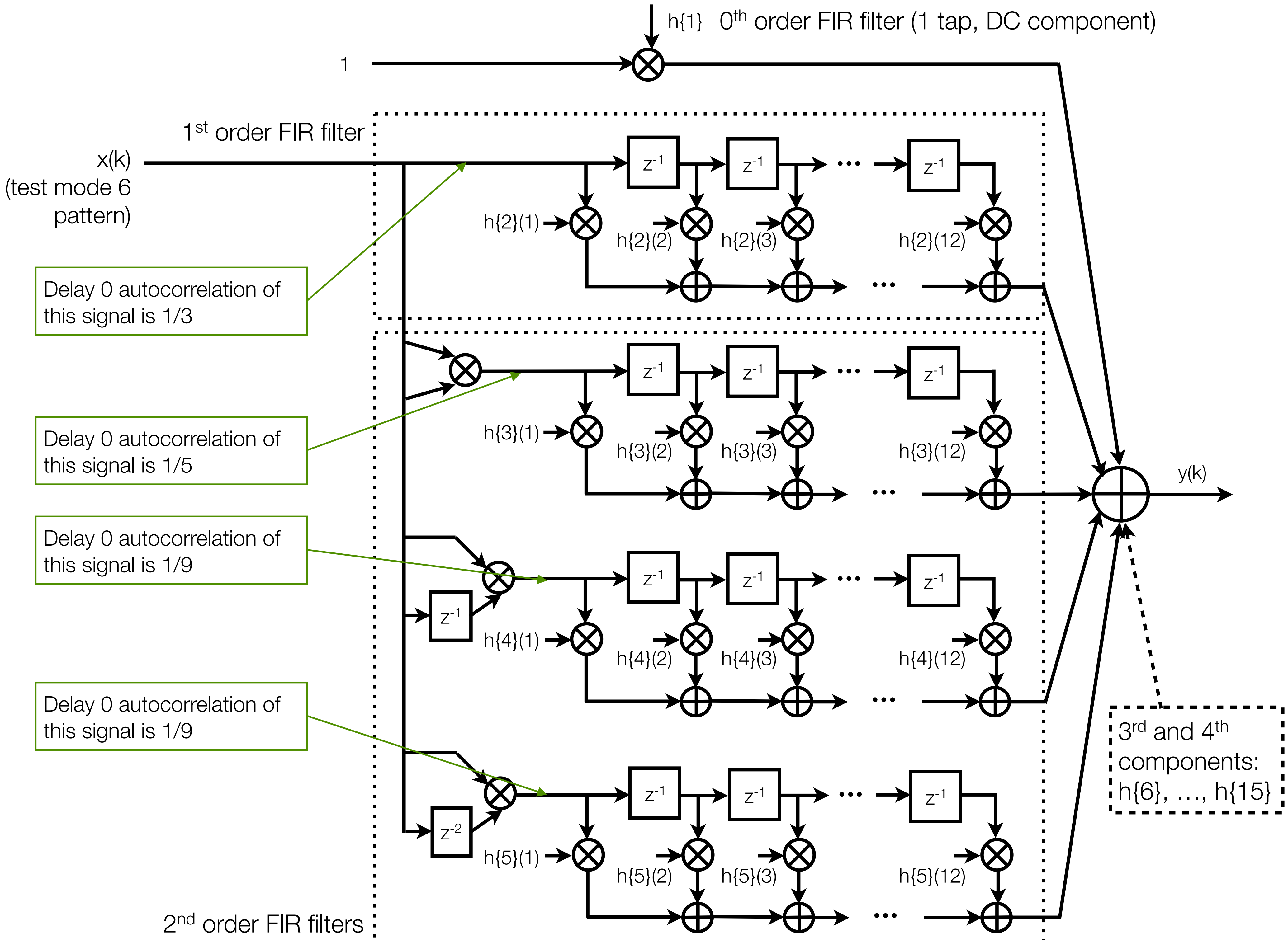
9. The test mode 6 signal is filtered through the estimated Volterra's system that represents the non-linear identification of the DUT response

```
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));
```

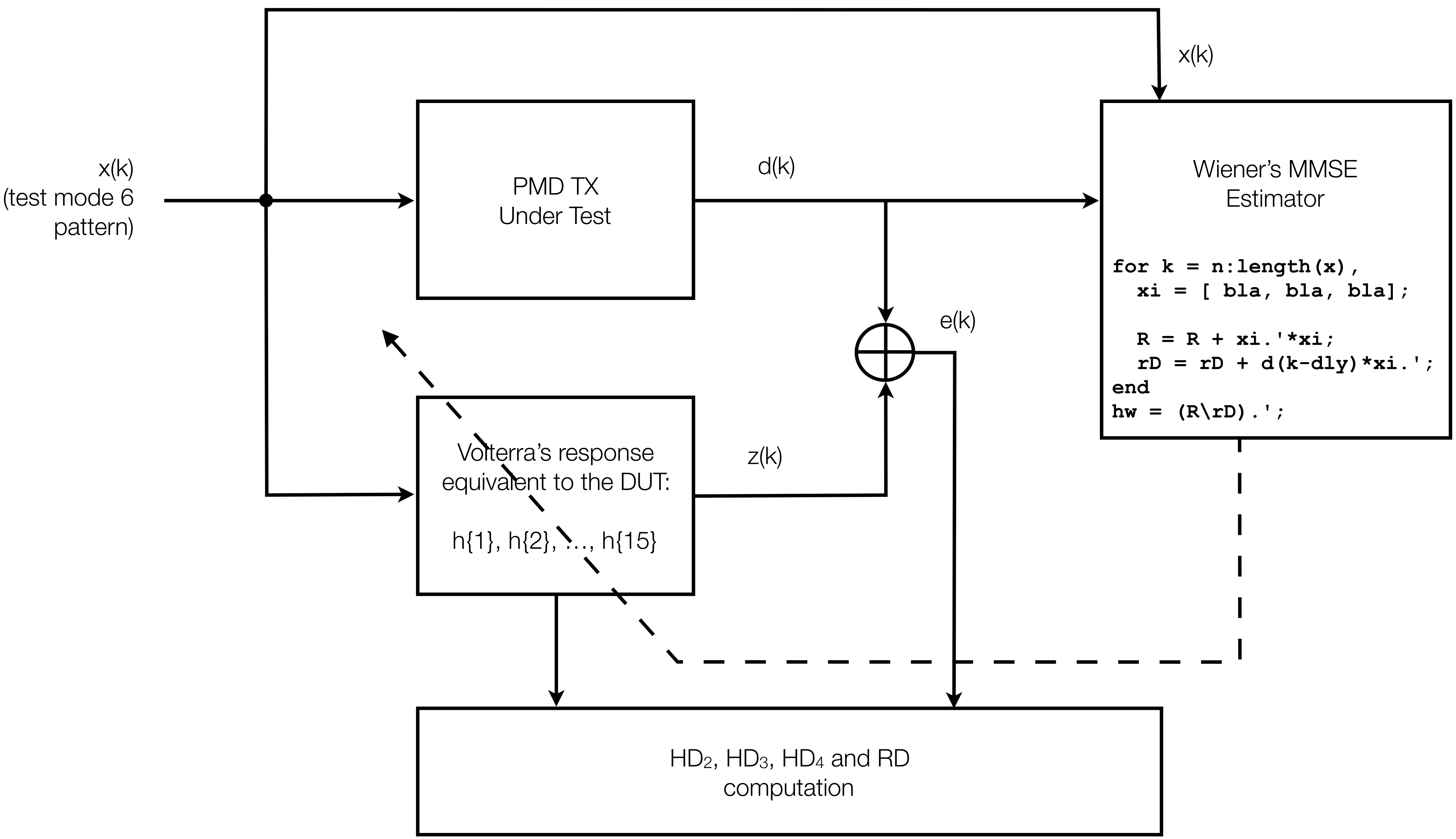
10. The resulting signal from step 9 is aligned and compared with the captured signal in TP2, and the error sequence between both is calculated. The residual distortion (RD) is computed as the relation between the energy of the first order Volterra's linear filter and the energy of the error sequence. The error sequence collects:
    - Distortion components not captured by the constrained Volterra's identification
    - Noise component already captured by the RIN measurement
    - Noise component due to quantization of the DAC

```
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);
RD = -10*log10(1/3*axc(h{2})/var(e));
```

Volterra's response equivalent to PMD TX



MMSE estimation of Volterra’s response

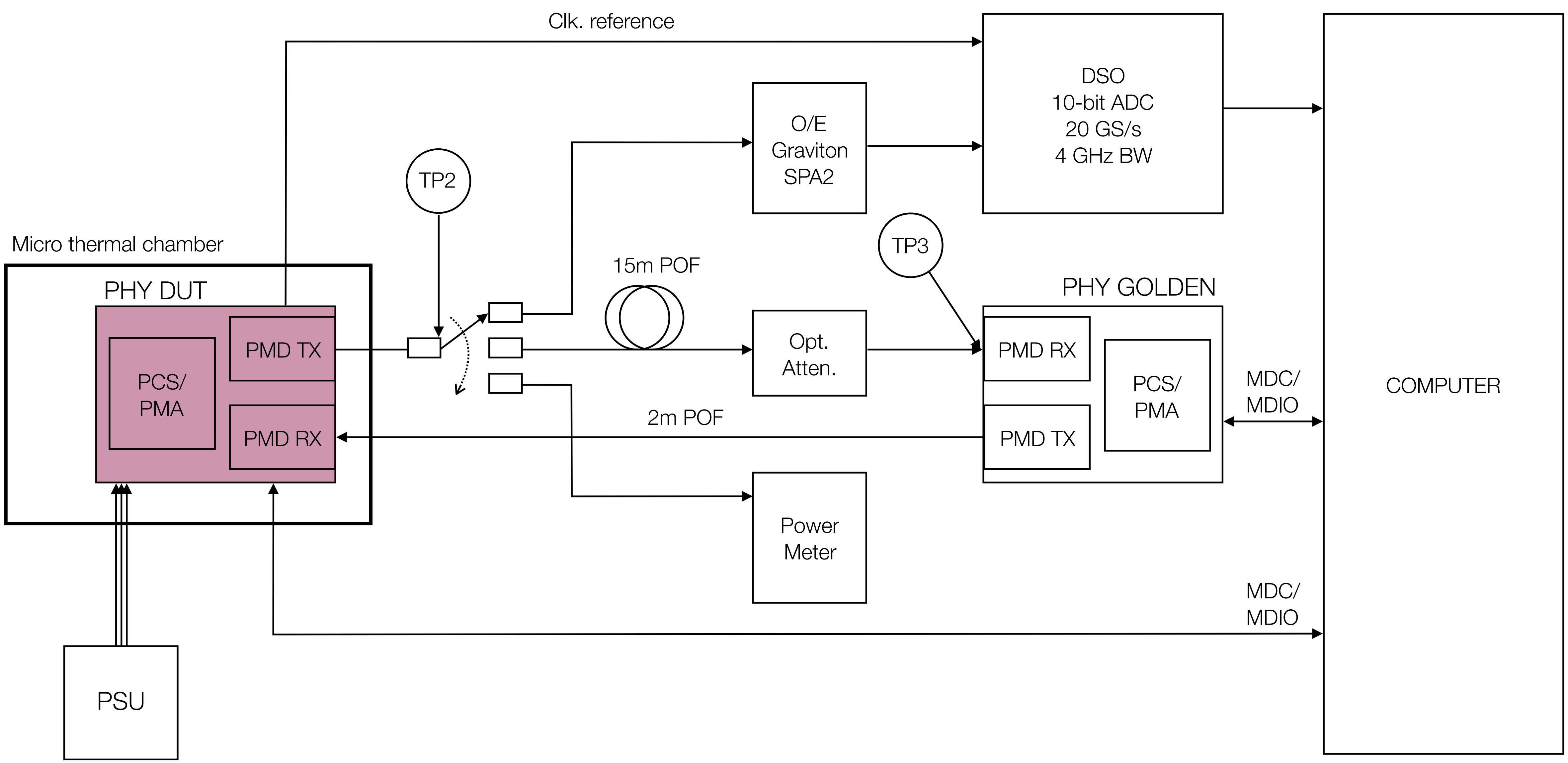


Notes on Volterra's estimation

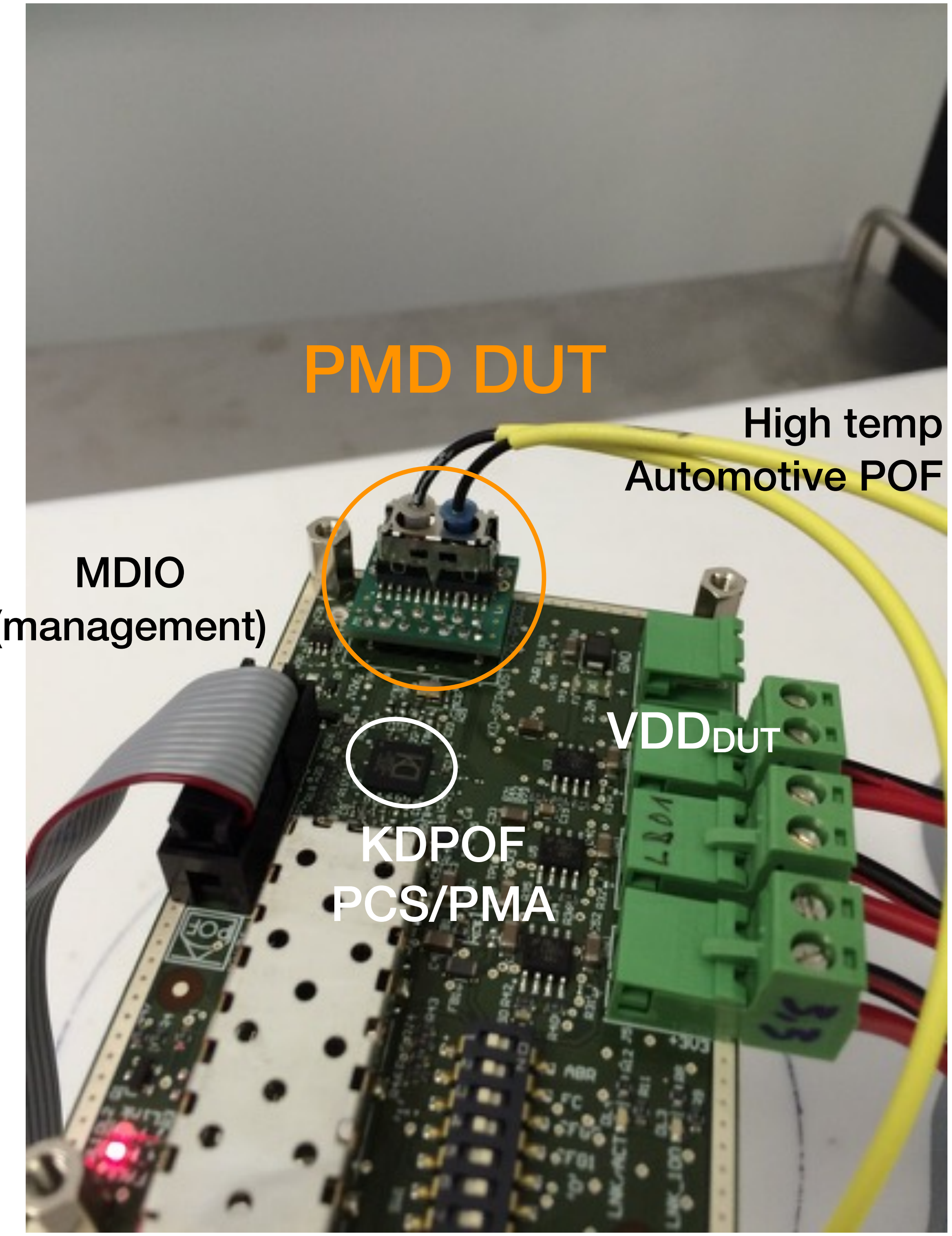
- Volterra's system that is MMSE estimated is a Volterra's truncated series, which topology has been selected based on experience with AlGaInP LED based transmitters (typical light source used in existing POF products):
  - The length of impulse response is limited based on the restrictions imposed to rise-time and fall-time
  - The delay-group is also limited based on experience
  - The maximum delay between products of signal with itself is limited based on measurement results
- Limitations on the filter length and delays between products are also imposed considering a reasonable complexity of the receiver DSP.
- It is important to note that the script specified to calculate the transmitter distortion parameters is, in essence, very similar to subclauses 97.5.3.2, 96.5.4.2 and 40.6.1.2.4. The differences are:
  - The script of 115.6.4.8 carries out a constrained non-linear Volterra's estimation, versus linear estimation of the other subclauses.
  - Limits are defined for the non-linearities assuming that the receiver implements a finite complexity channel linearization; linearization is necessary because the nature of the light emitters (AlGaInP LEDs that are foreseen as feasible implementation).

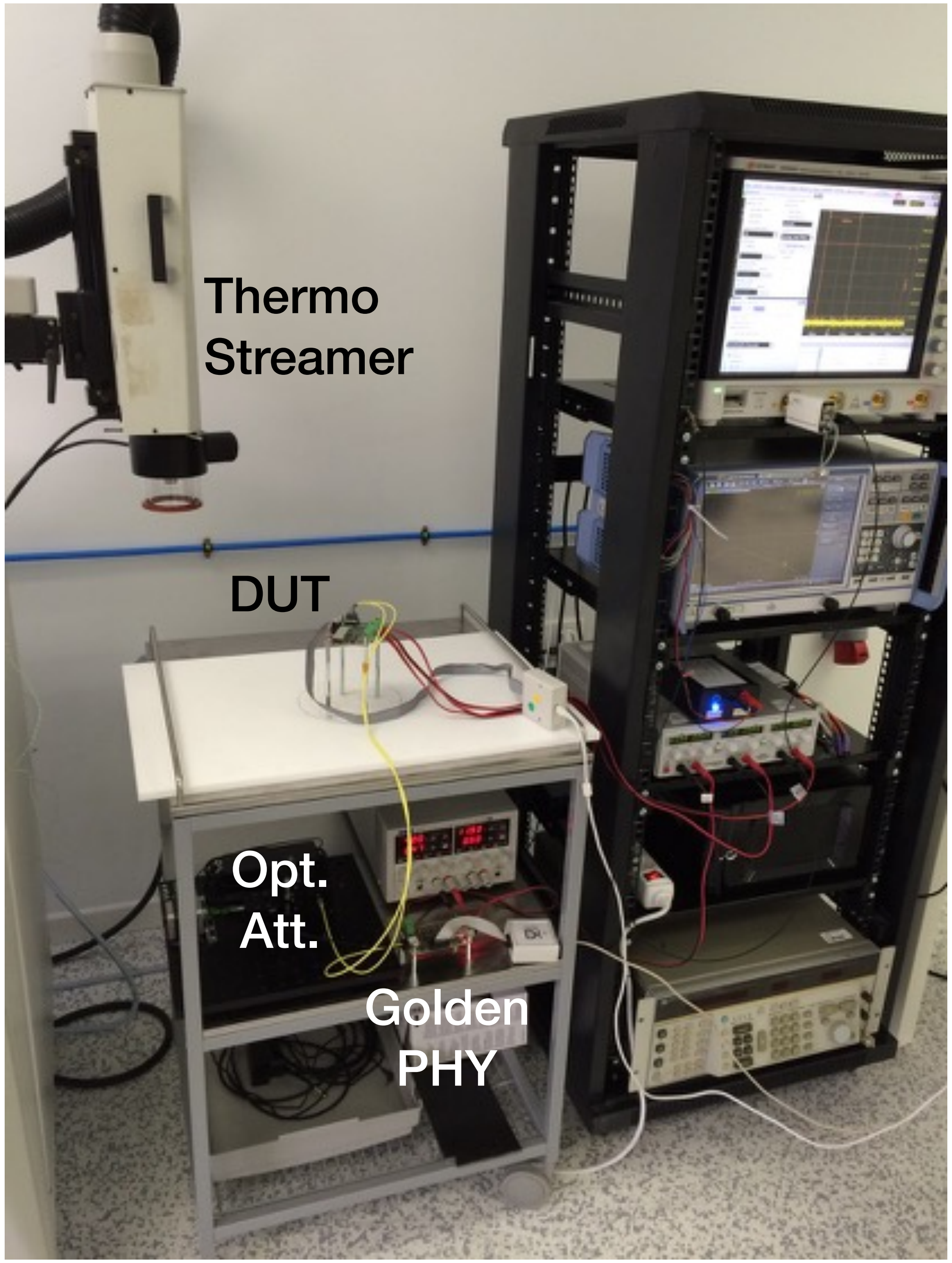
Measurement results

Characterization setup

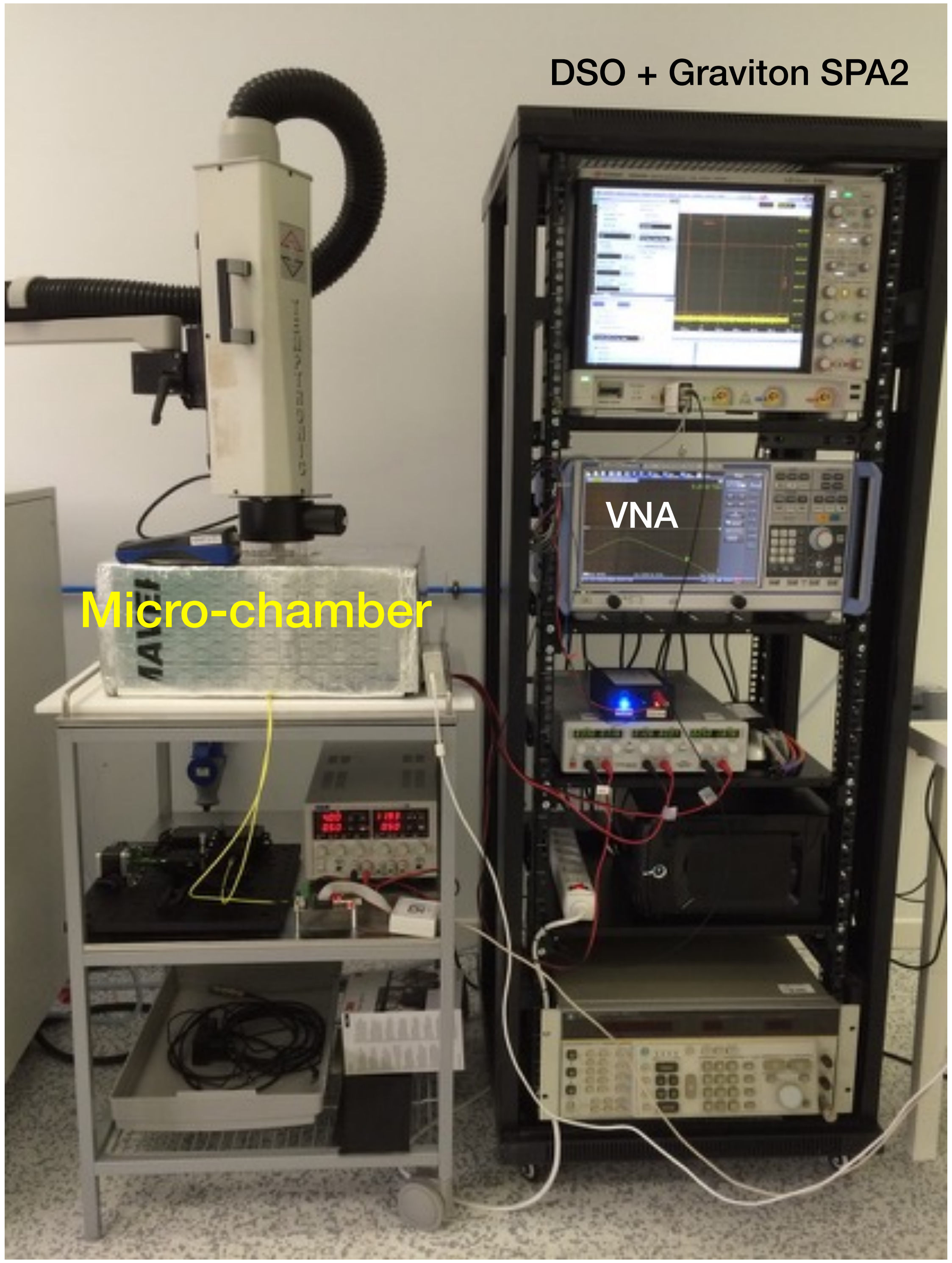


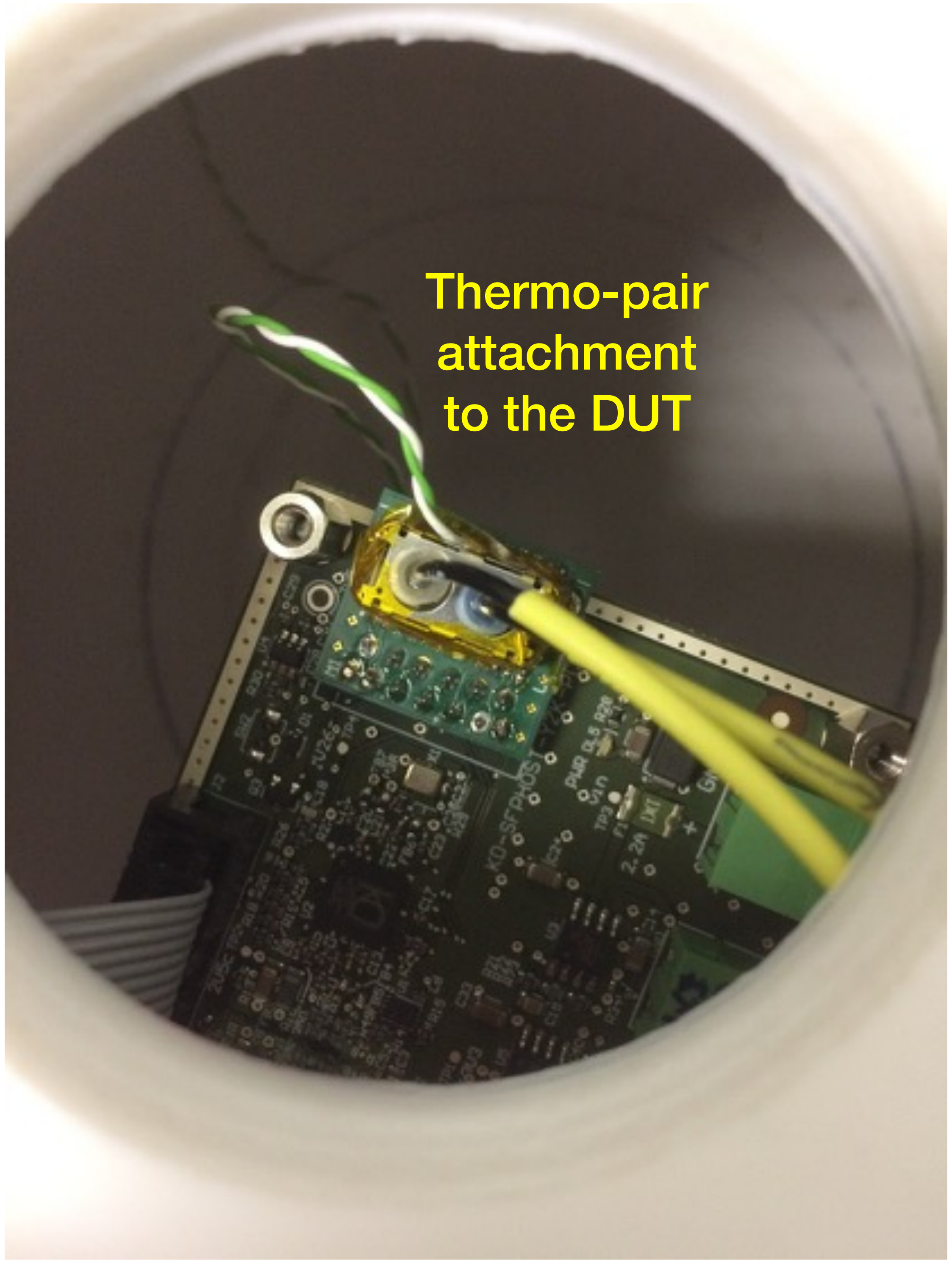
Characterization setup



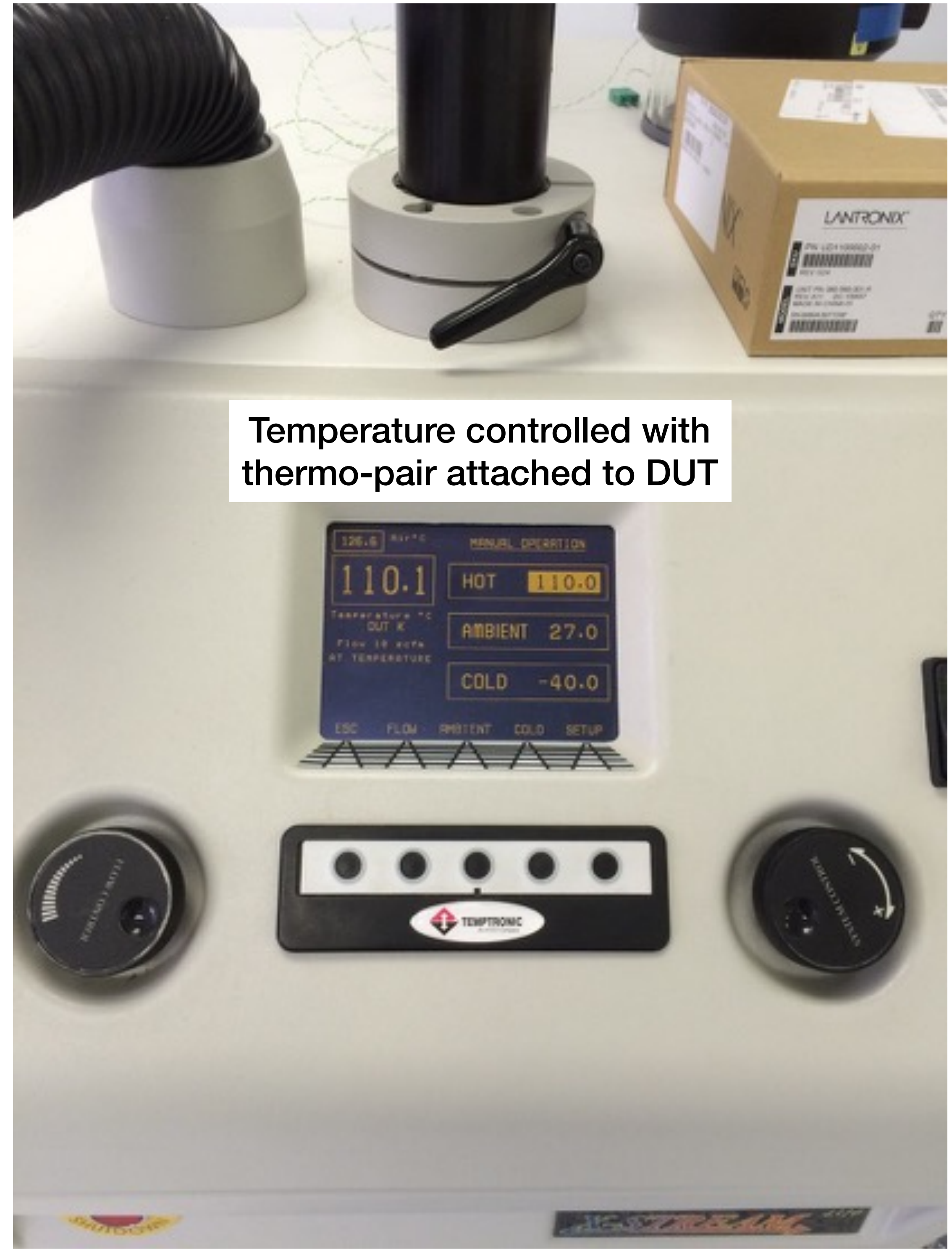


Characterization setup





Characterization setup



Temperature controlled with thermo-pair attached to DUT

Measurement results

- 4 different PMD TX almost compliant implementations:
  - Each PMD TX implementation integrates a different LED chip design and a different driver design
  - Each PMD TX is packaged in the same optical MDI connector together with a PMD RX to be able to establish bidirectional Gigabit link with a golden link partner (unique for all the tests)
  - Each PMD implementation under test is connected to a different part of the same PCS/PMA KDPOF chip design

- Results for implementations #1 and #2:

PMD TX Implementation	#1			#2		
Temperature (ºC)	27,00	110,00	-40,00	27,00	110,00	-40,00
AOP_{TP2} (dBm)	-1,97	-5,01	-2,69	-3,30	-11,20	-0,50
Delta AOP (dB)	0,00	-3,04	-0,72	0,00	-7,90	2,80
ER (dB)	10,96	10,75	12,47	10,70	10,41	11,53
Rise-time (10%-90%)	3,26	2,67	2,43	1,33	0,96	1,76
Rise-time (20%-80%)	2,00	1,65	1,57	0,83	0,55	0,96
Fall-time (10%-90%)	4,14	2,91	2,39	1,50	1,03	1,86
Fall-time (20%-80%)	2,11	1,62	1,24	0,91	0,70	1,08
HD2 (dBc)	-21,20	-20,40	-24,00	-20,10	-20,40	-22,00
HD3 (dBc)	-25,50	-25,20	-24,30	-24,40	-23,40	-24,10
HD4 (dBc)	-37,50	-36,00	-37,60	-34,80	-34,70	-35,00
RD < -40 dBc	1,00	1,00	1,00	1,00	1,00	1,00
TP3 sensitivity (dBm)	-17,47	-18,25	-18,04	-18,37	-19,73	-18,21
TP3 sensitivity delta (dB)	0,00	-0,78	-0,57	0,00	-1,36	0,16

Green: pass.
Red: fail.

Measurement results

- Results for implementations #3 and #4:

PMD TX Implementation	#3			#4		
Temperature (ºC)	27,00	110,00	-40,00	27,00	110,00	-40,00
AOP_{TP2} (dBm)	-3,10	-6,32	-3,88	-3,24	-8,66	-1,65
Delta AOP (dB)	0,00	-3,22	-0,78	0,00	-5,42	1,59
ER (dB)	12,05	10,27	13,50	9,68	11,41	8,10
Rise-time (10%-90%)	2,11	1,19	2,70	1,85	1,60	1,88
Rise-time (20%-80%)	1,25	0,79	1,70	1,26	1,10	1,30
Fall-time (10%-90%)	2,09	1,39	2,18	2,20	2,00	2,18
Fall-time (20%-80%)	1,21	0,91	1,35	1,47	1,35	1,49
HD2 (dBc)	-22,00	-20,50	-22,80	-24,20	-21,30	-26,70
HD3 (dBc)	-23,70	-23,20	-23,00	-28,70	-27,20	-27,90
HD4 (dBc)	-37,40	-34,30	-36,30	-38,40	-34,80	-38,40
RD < -40 dBc	1,00	1,00	1,00	1,00	1,00	1,00
TP3 sensitivity (dBm)	-18,49	-18,29	-18,62	-18,13	-19,08	-18,09
TP3 sensitivity delta (dB)	0,00	0,20	-0,13	0,00	-0,95	0,04

Green: pass.
Red: fail.

Measurement results — conclusions on #1 to #4

- None of the 4 implementations are fully compliant, but it is expected an iteration of the designs would be compliant
- However, all of them are very close to P802.3bv/D3.0 spec and are functional, i.e. Gigabit link @BER < 10^{-12}, in automotive temperature range with good sensitivity in the golden receiver
- Implementation #2, although it shows the best sensitivity because is the fastest one, it also shows a large variation of AOP_{TP2} with temperature and probably the implementation should be limited to Class Regular (see Table 115-19)
- We can see that all the implementations produce very similar sensitivity in the receiver. The main deviations between them are because the differences of speed (rise/fall times) and ER:
    - Eg 1: #1 at 27 ºC has >4 ns fall-time, that explains the impact on sensitivity
    - Eg 2: #3 and #4 at 27ºC have very similar speed, but the TP3 sensitivity can be explained by ER difference
- #1, #2, and #3 do not meet HD3 specification, however the equalizer is able to compensate it without relevant TP3 sensitivity differences respect to #4 that meets HD3 spec
- #2, #3, and #4 does not meet HD4 at 110ºC. The HD4 parameter was selected to be far enough of the SNR needed in the detector for sensitivity (25 dB), avoiding the necessity of HD4 compensation in the receiver. Also no correlation with TP3 sensitivity differences

Measurement results — discussion on #1 to #4

- ER and rise/fall-time deviations are expected to be solved in further iterations of the driver (topologies and tuning)
- The harmonic distortion (HD3, HD4) depends overall on the physics of the AlGaInP LED and RCLED. It is not feasible to be solved by driver iteration, and the 4 LED chips are in production, so iteration is not expected
- Discussion on refinement of HD3 and HD4 parameters:
  - The measurement results show that we may relax the specifications of HD3 and HD4 without impact on the sensitivity at TP3 … but the question is: how much?
  - It is important to note that it is not possible to fine tune independent parameters in the lab (as HD2, HD3 and HD4) and see the impact in the receiver without affecting others: different chips show differences in all the parameters. From the measurement results, the only conclusion is that no clear correlation exists between the HD3 and HD4 deviations and the TP3 sensitivity (max measured deviations are 3 dB for HD3, and 1.7 dB for HD4)
  - By simulation we know that we cannot permit any value of HDx, because the compensation of non-linearities is not perfect and always produce capacity loss (i.e. concept that is analogous to the noise enhancement produced by linear equalizers). See perezaranda_3bv_3_0316.pdf.
  - Proposal: do refinement of HD3 and HD4 specifications to allow more implementations.

Proposal for HD3 and HD4 refinement

- Proposal for refined parameter specifications based on test of multiple implementations:

	P802.3bv/D3.0	P802.3bv/D3.1
$HD2_{max}$ (dB)	-20	-20
$HD3_{max}$ (dB)	-26	-23
$HD4_{max}$ (dB)	-36	-34
RD_{max} (dB)	-40	-40

Measurement results of non-compliant implementations

- Implementation #5:
  - The PMA TX is connected to a PMD TX designed for OOK transmission through an impedance matching circuit. Also the current reference of the current steering DAC is configured for voltage matching.
  - It is important to note that measurement results of many parameters are compliant
  - No Gigabit link is possible
  - Results:

PMD TX Implementation	#5
Temperature (ºC)	27,00
AOP_{TP2} (dBm)	-1,45
Delta AOP (dB)	—
ER (dB)	14,70
Rise-time (10%-90%)	1,50
Rise-time (20%-80%)	—
Fall-time (10%-90%)	1,80
Fall-time (20%-80%)	—
HD2 (dBc)	4,50
HD3 (dBc)	-4,90
HD4 (dBc)	-1,40
RD (dBc)	-8,65
RIN (dB/Hz)	-137,30
TP3 sensitivity (dBm)	—
TP3 sensitivity delta (dB)	—

Measurement results of non-compliant implementations

- Implementation #6:
  - The least significant bits of DAC in PMA TX are fixed to 0 and unconnected from transmit power scaling block (see 115.3.1.2), so the ENOB of the DAC is drastically reduced. DAC full scale current is also adjusted for similar peak-to-peak input to driver.
  - The PMD TX implementation is a different part of design in #1
  - RIN is compliant and is not able to capture the quantization noise (as expected)
  - No Gigabit link is possible
  - Results:

PMD TX Implementation	#6	
DAC ENOB	3,00	4,00
Temperature (ºC)	27,00	27,00
AOP_{TP2} (dBm)	-2,00	-2,00
Delta AOP (dB)	—	—
ER (dB)	10,70	10,80
Rise-time (10%-90%)	3,30	3,30
Rise-time (20%-80%)	—	—
Fall-time (10%-90%)	4,20	4,20
Fall-time (20%-80%)	—	—
HD2 (dBc)	-17,10	-19,70
HD3 (dBc)	-17,30	-22,20
HD4 (dBc)	-15,10	-21,70
RD (dBc)	-19,30	-25,00
RIN (dB/Hz)	-135,40	-135,40
TP3 sensitivity (dBm)	—	—
TP3 sensitivity delta (dB)	—	—

Measurement results — conclusions on #5 to #6

- Some parameters (e.g. ER, rise-time, AOP) of #5 meet the specifications, but because the linearity is not good, the Gigabit link cannot be established:
  - This is a very worst case scenario, because the PMD TX is only able to transmit 2 levels of light.
  - The measurement result of the transmitter distortion parameters detect this condition.
- Implementation #6 uses exactly the same PMD TX design of #1 that was able to establish the Gigabit link with good sensitivity. However, because the DAC performance of PMA TX not good enough, the link cannot be established (i.e. good precision of DAC is important for THP operation).
  - We can see the impact on the transmitter distortion parameters and how the condition is detected.

- As can be seen, results of HD_x and RD that meet the specification, guarantee that the transmitter is linear enough to implement THP and to allow the receiver to compensate the continuous non-linearities produced by transmitter opto-electronics with low impact in sensitivity.
- On the other hand, when specifications are not met, the link cannot be established.