

Considerations and discussion around an optimized link budget for 400GBASE-DR4

- towards TX OMA reduction and PAM4 PMDs alignment -

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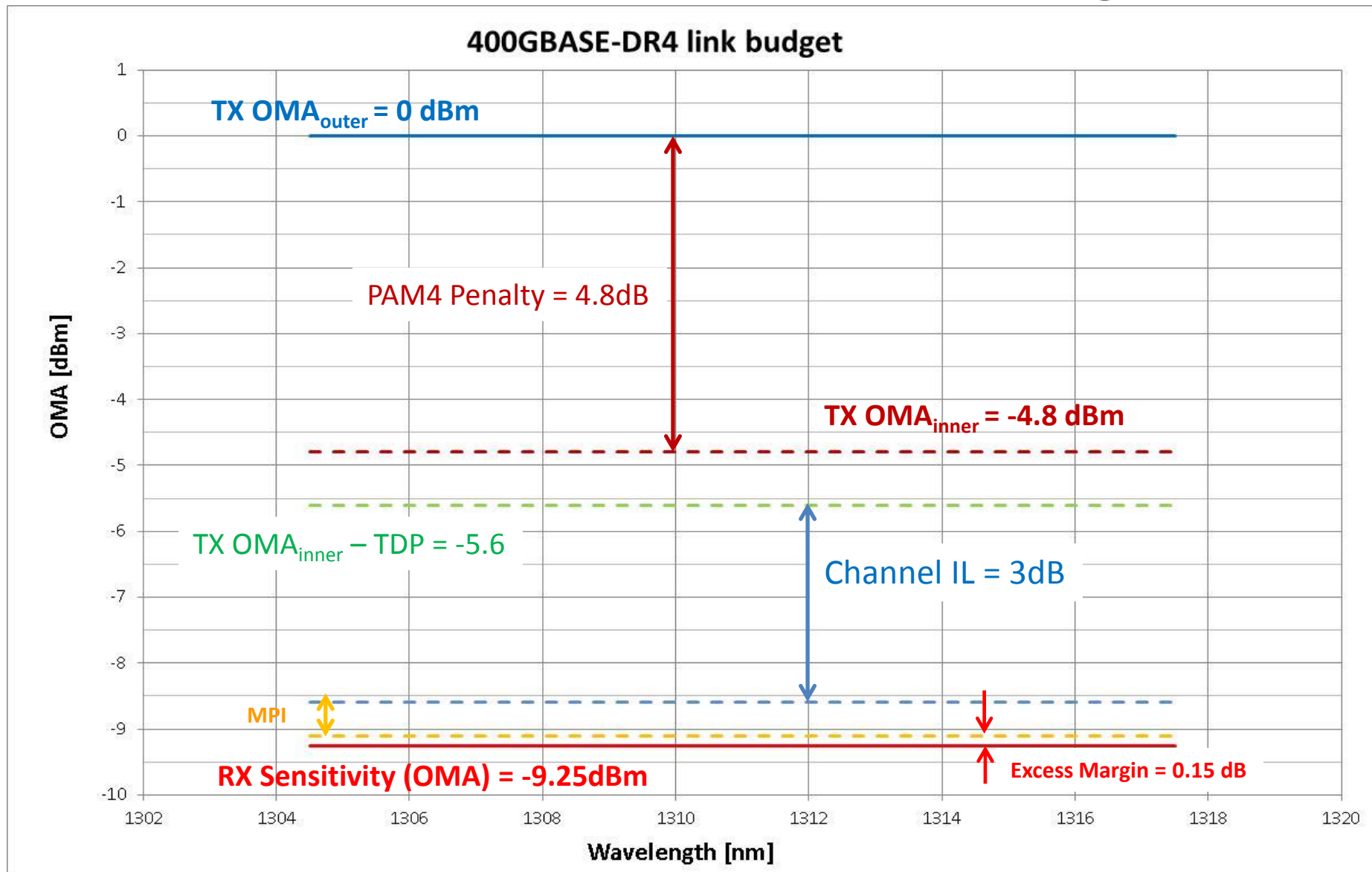
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Background

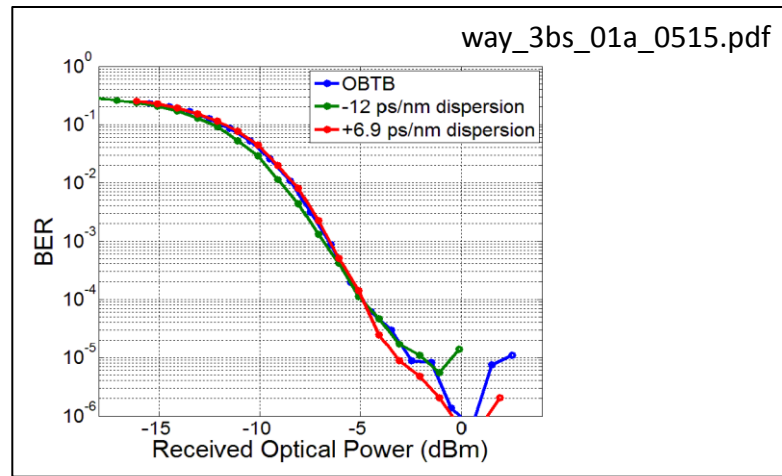
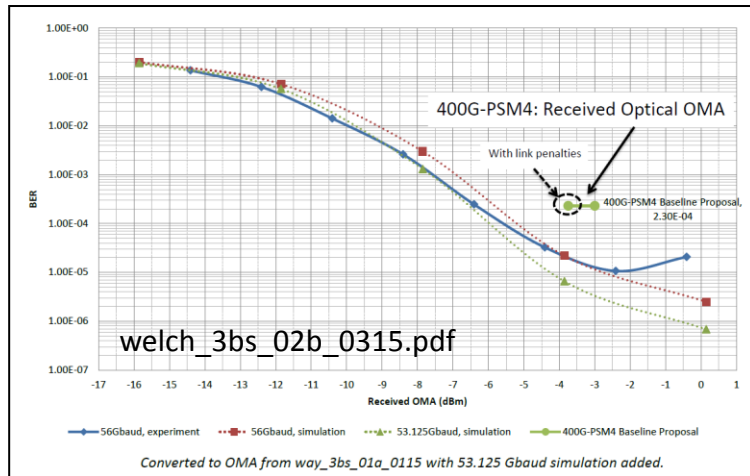
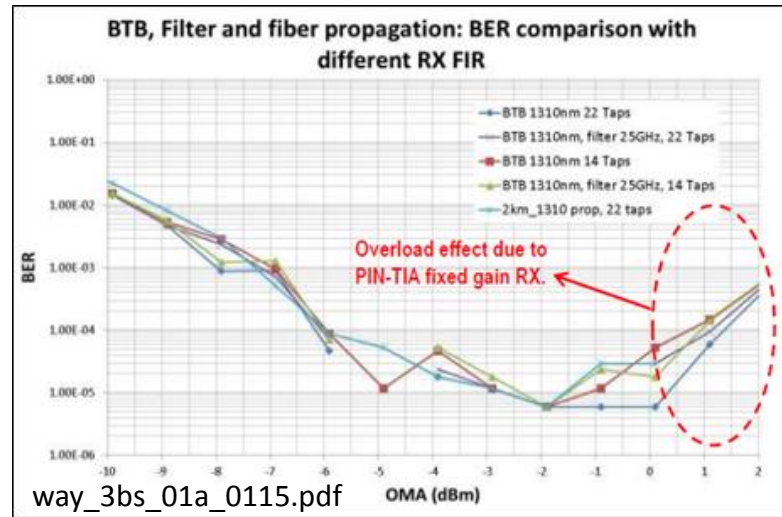
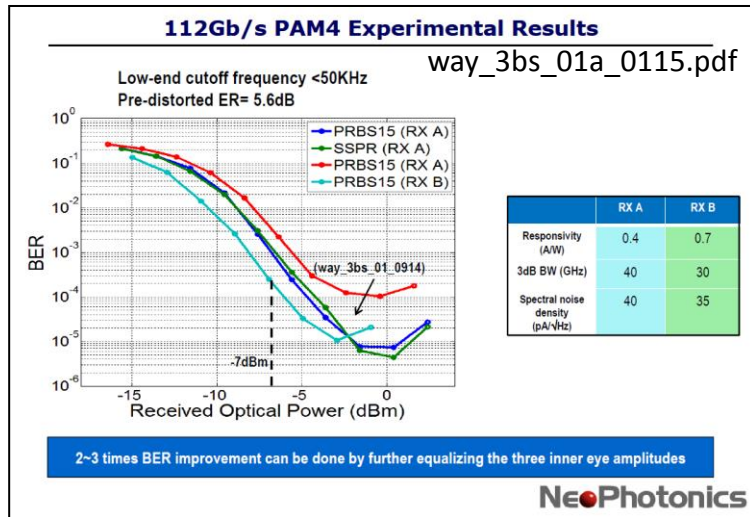
- Pluggable optics power consumption requirements for data center applications are usually the most stringent ones because port density.
- Low power 400G pluggable modules (<3.5W) can enable >12Tb/s throughput on 1RU.
- Laser power will be still a high percentage (estimated 25-28%) of the overall module's power consumption.
- This contribution suggests a change into 400GBASE-DR4 specification towards an overall module's power consumption reduction.
- Also show how to align 400GBASE-DR4 receiver sensitivity results, link and TX characteristics to other PAM4/802.3bs standard PMDs.

400GBASE-DR4: 802.3bs draft 1.0 link budget.



Current 400GBASE-DR4 link budget includes a margin of 0.15dB ($[TX\ OMA_{inner} - TDP] - CH\ IL - RX\ Sens$) which takes into account MPI penalty (0.5dB) into.

56GBaud RX sensitivity – measurements.



Up to -11.25dBm OMA_{inner} (at 56GBaud) measured sensitivities from different experiments and TX technologies.
> 2dB margin w/respect -9.1dBm OMA sensitivity.

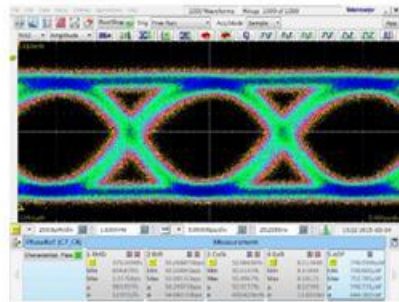
(Note: RX sens = -8.8dBm OMA at TP3 was considered into [lewis_3bs_01a_0515](#), for 400GBASE-FR4 proposal, which included a demux stage of 2dB).

53GBaud RX sensitivity – future improvements?

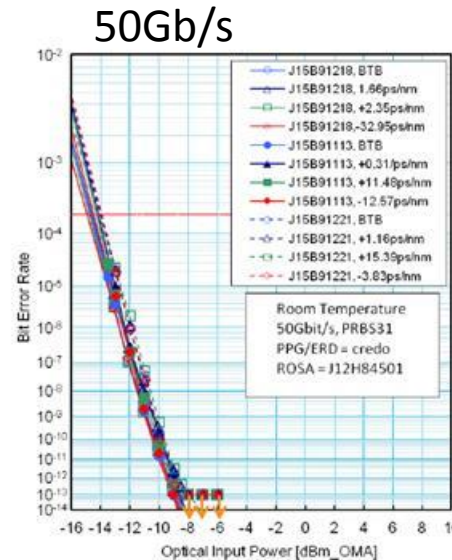
Expected that Equalizers/TIA/detectors technology will keep improving BW/responsivities. Currently there >6.5dB delta between the best 26GBaud results ([-18dBm](#)) and 56GBaud results, which seems not realistic when 56GBaud (53GBaud) technology will become mature.

Measurement Result

- Credo CDR shows good performances for stable transmission
 - Equalization seemed to work effectively
- No error floor confirmed BER of down to $1e-13$
 - PRBS31, No-FEC
- OMA sensitivity of <-14dBm was obtained
 - TIA: Equivalent input noise current= $20 \text{ pA}/\sqrt{\text{Hz}}$



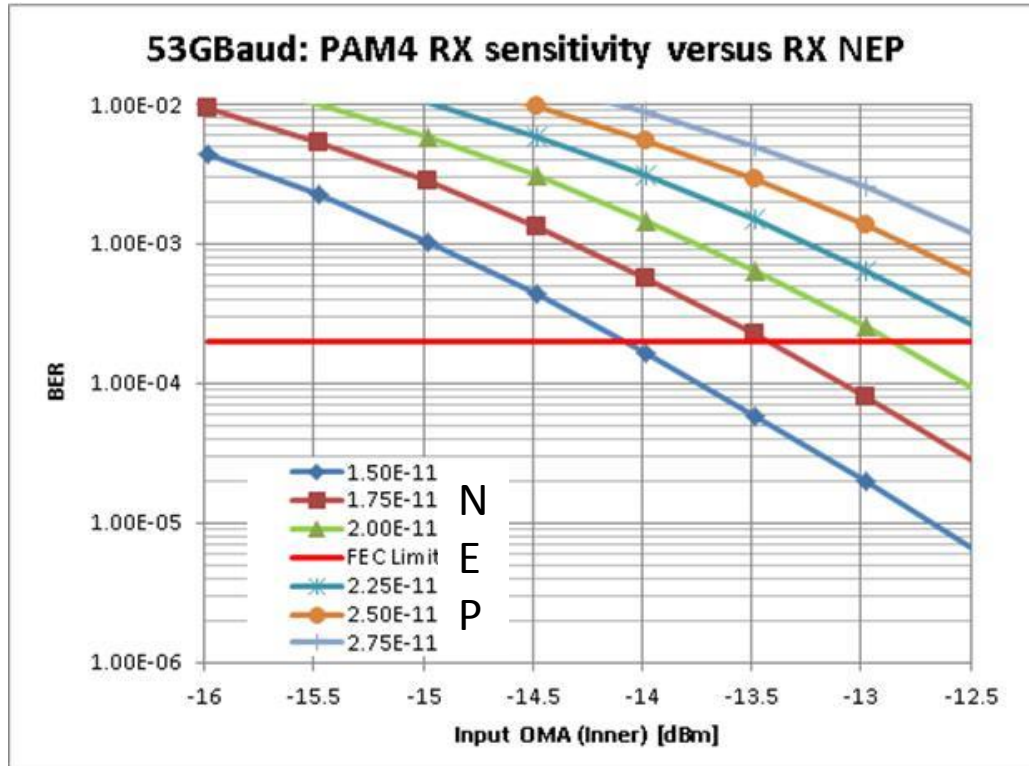
Optical Waveform



Assuming some horizontal eye closure penalty on [01] and [23] eyes, we think -12 to -12.5dBm OMA sensitivity would be possible around 53.2GBaud rate too.

53Gbaud RX sensitivity – simulations.

Currently there's >6.5dB offset between best 26GBaud results ([-18dBm](#)) and 56GBaud results, which seems not realistic when 56GBaud (53Gbaud) technology will become mature.



Simulations input conditions of:

Laser RIN = -142 dB/Hz

TX BW = 35 GHz

RX BW = 35 GHz

Responsivity = 0.7 A/W

Residual ISI penalty <0.5dB

Overall (TIA, AGC, ADC) RX NEP (Noise Equivalent Power) swept between 15 to 27.5 pa/vHz. 20 to 22.5 pa/vHz is considered feasible at 53GBaud → RX sensitivity target of around -12.5dBm OMA. (Note: this value is 1.25dB better than current experiments, but still 5.5 dB worse than what already experimentally achieved at 26Gbaud).

Proposal

In order to enable lower power consumption towards 400GBASE-DR4 modules, we propose then to:

- Take out any residual margin from current 400GBASE-DR4 budget (0.15dB)
- Incorporate MPI penalty into max TDP of 2.5dB (0.5dB)
- Consider the same PAM4 implementation penalty as for 400GBASE-FR8/LR8 (delta of 0.2dB).
- Reduce TX OMA by 1.5dB;
- Improve RX sensitivity by 1.05dB;

This translates in the following changes into transmit and receive characteristics:

- Table 122-6:
 - TX OMA_{outer} : from 0 to -1.5dBmConsequently TX OMA_{inner} will be reduced, but we indeed propose to:
 - remove TX OMA_{inner} from table 122-6 and replace with OMA_{outer} – TDP = -2.3 dBm.
 - Incorporate MPI penalty into max TDP penalty of 2.5dB.
- Table 122-7:
 - RX sensitivity (OMA_{inner}) : from -9.25 to -10.3dBm
- Table 122-8:
 - Add : Allocation for modulation penalties = 5dB.

These changes would still allow to keep a safe optical margin (around 1dB) over current experimental results (looking at simulations > 2dB margins are expected).

Above changes align to the way other PAM4 PMD TX/RX characteristics, links budgets and margins ([400GBASE-FR8 and LR8](#)) were defined into 123-7, 123-8 and 123-9.

Proposed changes to 400GBASE-DR4 characteristics (1).

Table 122-6—400GBASE-DR4 transmit characteristics

| Description | Value | Unit |
|--|-----------------------------|----------------|
| Signaling rate, each lane (range) | 53.125 ± 100 ppm | GBd |
| Modulation format | PAM4 | — |
| Lane wavelength (range) | 1304.5 to 1317.5 | nm |
| Side-mode suppression ratio (SMSR), (min) | 30 | dB |
| Average launch power, each lane (max) | 4 | dBm |
| Average launch power, each lane ^a (min) | -2.1 -3.6 | dBm |
| Outer Optical Modulation Amplitude (OMA _{outer}), each lane (max) | 4.2 | dBm |
| Outer Optical Modulation Amplitude (OMA _{outer}), each lane (min) ^b | 0 -1.5 | dBm |
| Inner Optical Modulation Amplitude (OMA_{inner}), each lane (min)^b | -4.8 | dBm |
| Launch power in OMA_{inner} minus TDP, each lane (min) | -3.0 -2.3 | dBm |
| Transmitter and dispersion penalty (TDP), each lane (max) | 2.5 | dB |
| Average launch power of OFF transmitter, each lane (max) | -30 | dBm |
| Extinction ratio, each lane (min) | 5 | dB |
| RIN _{OMA} (max) | -142 | dB/Hz |
| Optical return loss tolerance (max) | TBD | dB |
| Transmitter reflectance ^c (max) | -20 | dB |
| Transmitter eye mask definition | TBD | |

Relax these too?

OMA_{outer} proposed relaxation

Remove OMA_{inner} parameter

Launch power in OMA_{outer} minus TDP, each lane (min)

MPI included into max TDP

^aAverage launch power, each lane (min) is informative and not the principal indicator of signal strength. A transmitter with launch power below this value cannot be compliant; however, a value above this does not ensure compliance.

^bEven if the TDP < 0.8 dB, the OMA_{outer} (min) and OMA_{inner} (min) must exceed these values.

^cTransmitter reflectance is defined looking into the transmitter.

This align with 400GBASE-FR8/LR8 TX/RX characteristics of Table 123-7. Proposed changes to transmitter characteristics are in red.

Proposed changes to 400GBASE-DR4 characteristics.

Table 122-7—400GBASE-DR4 receive characteristics

| Description | Value | Unit |
|---|--------------------|------|
| Signaling rate, each lane (range) | 53.125 ± 100 ppm | GBd |
| Modulation format | PAM4 | — |
| Lane wavelengths (range) | 1304.5 to 1317.5 | nm |
| Damage threshold ^a (min) | 6.5 | dBm |
| Average receive power, each lane (max) | 4 | dBm |
| Average receive power, each lane ^b (min) | -5.1 -6.15 | dBm |
| Receive power, each lane (OMA _{outer}) (max) | 4.2 | dBm |
| Receiver reflectance (max) | -26 | dB |
| Receiver sensitivity (OMA _{inner}), each lane ^c (max) | -9.25 -10.3 | dBm |
| Receiver 3 dB electrical upper cutoff frequency, each lane (max) | TBD | GHz |
| Stressed receiver sensitivity (OMA _{inner}), each lane ^d (max) | TBD | dBm |
| Conditions of stressed receiver sensitivity test: | | |
| Condition 1 ^e | TBD | |
| Condition 2 ^e | TBD | |

Relax these too?

Should provide some benefit too (less distortions).

Receiver sensitivity (OMA_{inner}) proposed change

Proposed changes to receive and link budget characteristics are in red.

^aThe receiver shall be able to tolerate, without damage, continuous exposure to an optical input signal having this average power level. The receiver does not have to operate correctly at this input power.
^bAverage receive power, each lane (min) is informative and not the principal indicator of signal strength. A received power below this value cannot be compliant; however, a value above this does not ensure compliance.
^cReceiver sensitivity (OMA_{inner}), each lane (max) is informative.
^dMeasured with conformance test signal at TP3 (see 122.8.10) for the BER specified in 122.1.1.
^eCondition 1 and condition 2 are test conditions for measuring stressed receiver sensitivity. They are not characteristics of the receiver.

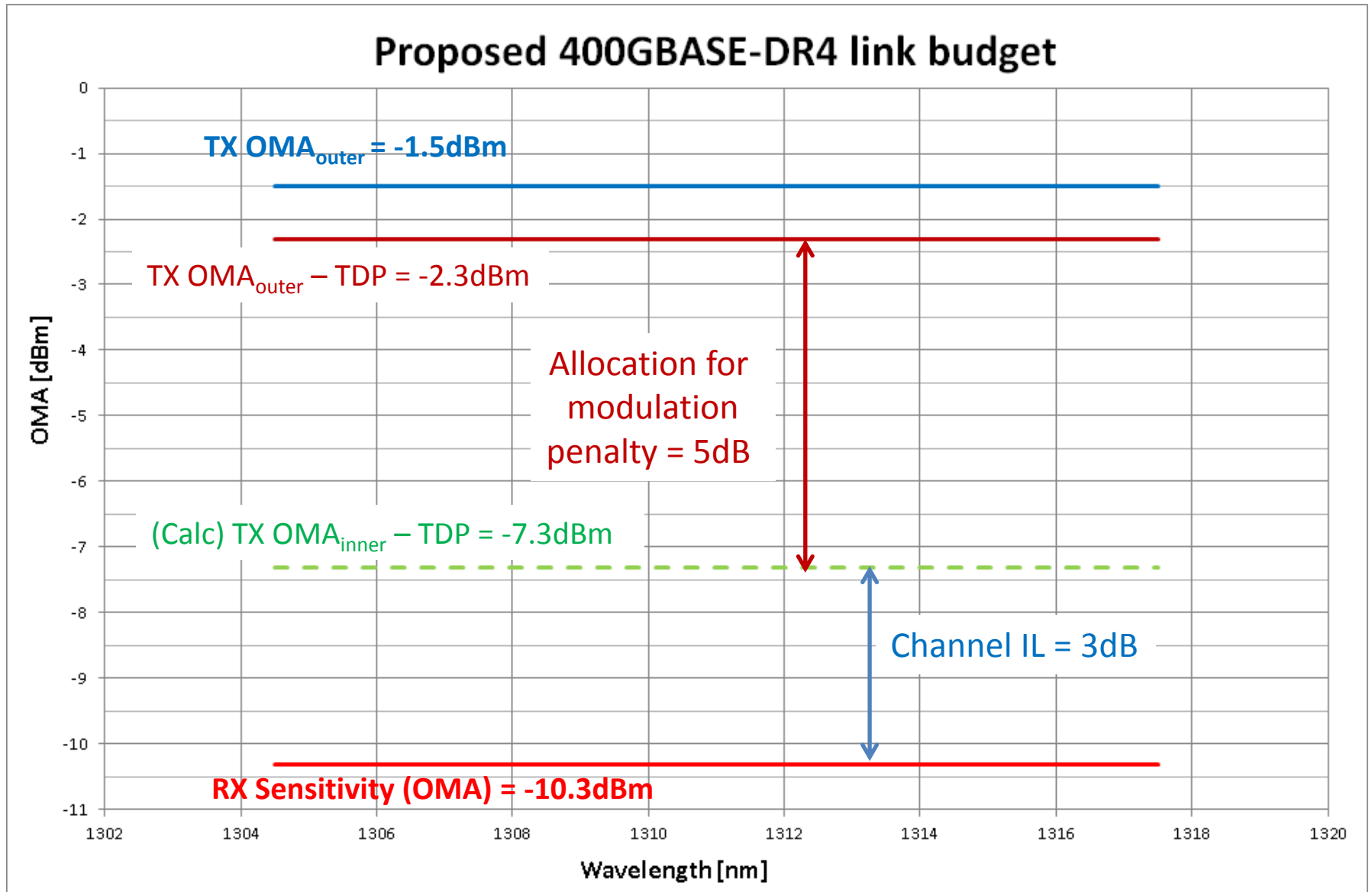
Table 122-8—400GBASE-DR4 illustrative link power budget

| Parameter | Value | Unit |
|---|--------------|------|
| Power budget (for max TDP) | TBD | dB |
| Operating distance | 500 | m |
| Channel insertion loss ^a | 3 | dB |
| Maximum discrete reflectance | -35 | dB |
| Allocation for penalties ^b (for max TDP) | 3 2.5 | dB |
| Additional insertion loss allowed | 0 | dB |

Include MPI penalty into allocation into max TDP penalties

Add a row: Allocation for modulation penalties of 5dB

Proposed 400GBASE-DR4 link budget.



Conclusion

- An opportunity to shift the 400GBASE-DR4 link budget RX sensitivity and TX OMA is given.
 - **This assumes expected 400GBASE-DR4 receiver to behave better than current experimental results, so target more margins.**
 - **This actually seems more than reasonable to us by looking at current sensitivity delta w/respect others PAM4/802.3bs standard PMDs receivers.**
- The improvement in TX yield and module's power consumption (laser current reduced by $\approx 30\%$) will benefit future developments of 400GBASE-DR4 in small form factor.
- We also think should be worthwhile to align the 400GBASE-DR4 TX and link characteristics of tables 122-6 and 122-8 to the 400GBASE-FR8/LR8 ones (tables 123-7 and 123-9).

THANK YOU

Back-up slides

Discussion

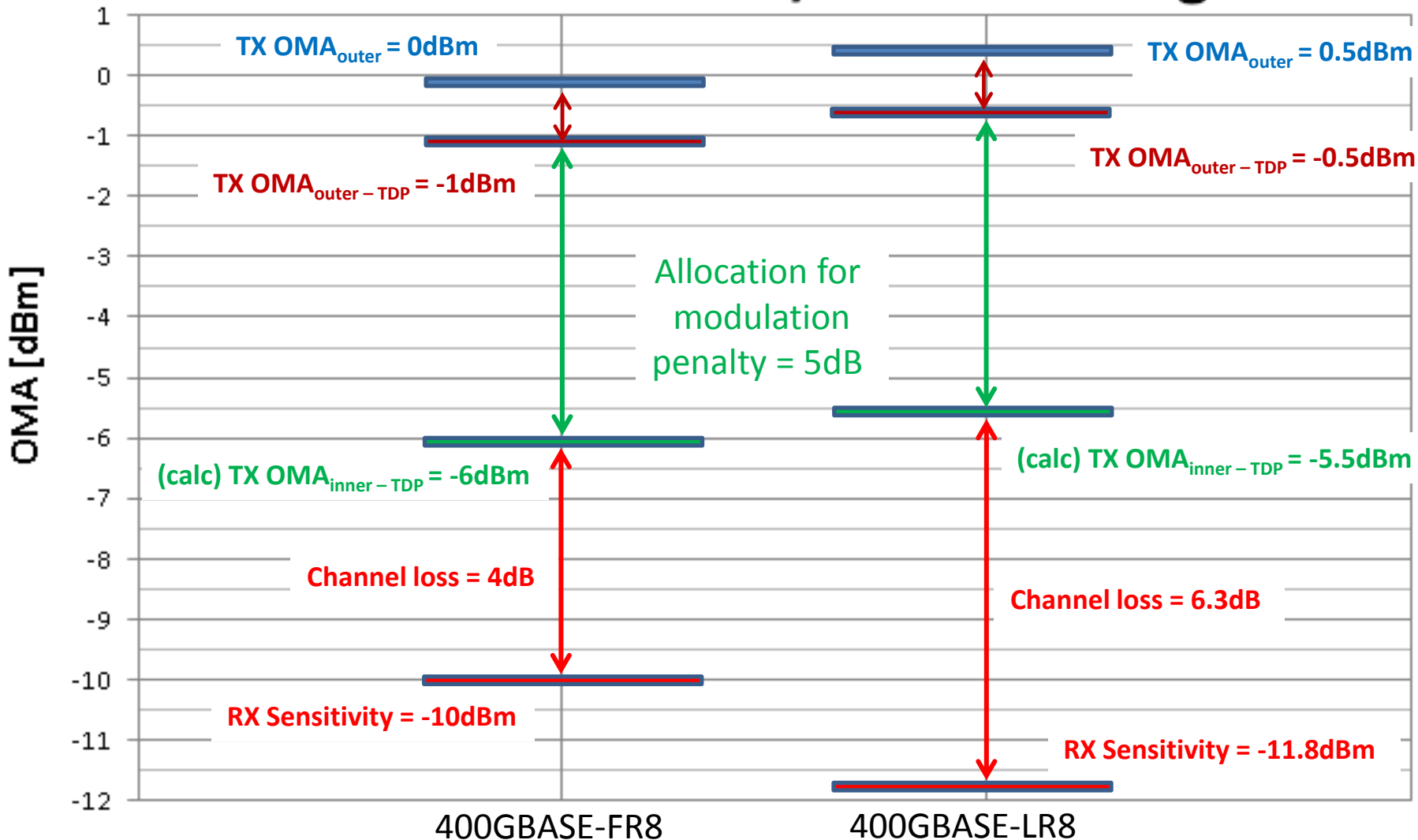
- During the March 2015 P802.3bs TF meeting 50G PAM-4 RX Sens. (inner eye OMA) data was presented
 - Finisar RX Sens. = $\sim -13.5\text{dBm}$ (BER = $2e-4$)
http://www.ieee802.org/3/bs/public/15_03/cole_3bs_02_0315.pdf#page=24
 - Huawei RX Sens. = $\sim -18\text{dBm}$ (BER = $2e-4$)
http://www.ieee802.org/3/bs/public/15_03/stassar_3bs_01a_0315.pdf#page=5

- Since the meeting, below deltas were identified:

| Parameter | Finisar | Huawei |
|-----------------|----------------------------|--------------------------|
| Noise Current | 16.5pA/ $\sqrt{\text{HZ}}$ | 15pA/ $\sqrt{\text{HZ}}$ |
| PD responsivity | 0.5A/W | 0.85A/W |
| Pattern | SSPR | PRBS15 |
| GBaud | 28 | 25.8 |

- With 0.8A/W PD responsivity, Finisar has since measured RX Sens. = $\sim -17\text{dBm}$ (BER = $2e-4$)

400GBASE-LR8/FR8 link budget



Draft 1.0 - 400GBASE-FR8/LR8 characteristics

Table 123-7—400GBASE-FR8 and 400GBASE-LR8 transmit characteristics

| Description | 400GBASE-FR8 | 400GBASE-LR8 | Unit |
|--|--|--------------|-------|
| Signaling rate, each lane (range) | 26.5625 ± 100 ppm | | GBd |
| Modulation format | PAM4 | | — |
| Lane wavelengths (range) | 1272.55 to 1274.54 1276.89 to 1278.89 1281.25 to 1283.27 1285.65 to 1287.68 1294.53 to 1296.59 1299.02 to 1301.09 1303.54 to 1305.63 1308.09 to 1310.19 | | nm |
| Side-mode suppression ratio (SMSR), (min) | 30 | | dB |
| Total average launch power (max) | 13.2 | | dBm |
| Average launch power, each lane (max) | 4.2 | | dBm |
| Average launch power, each lane ^a (min) | -3 | -2.5 | dBm |
| Outer Optical Modulation Amplitude (OMA _{outer}), each lane (max) | 5.5 | 5.7 | dBm |
| Outer Optical Modulation Amplitude (OMA _{outer}), each lane (min) ^b | 0 | 0.5 | dBm |
| Difference in launch power between any two lanes (OMA) (max) | TBD | TBD | dB |
| Launch power in OMA _{outer} minus TDP, each lane (min) | -1 | -0.5 | dBm |
| Transmitter and dispersion penalty (TDP), each lane (max) | 2 | 2.2 | dB |
| Average launch power of OFF transmitter, each lane (max) | -30 | | dBm |
| Extinction ratio (min) | 4.5 | | dB |
| RIN _{cc} OMA (max) | TBD | | dB/Hz |
| Optical return loss tolerance (max) | TBD | | dB |
| Transmitter reflectance ^c (max) | TBD | | dB |
| Transmitter eye mask definition | TBD | | |

^aAverage launch power, each lane (min) is informative and not the principal indicator of signal strength. A transmitter with launch power below this value cannot be compliant; however, a value above this does not ensure compliance.

^bEven if the TDP < 1 dB, the OMA_{outer} (min) must exceed this value.

^cTransmitter reflectance is defined looking into the transmitter.

Table 123-8—400GBASE-FR8 and 400GBASE-LR8 receive characteristics

| Description | 400GBASE-FR8 | 400GBASE-LR8 | Unit |
|---|--|--------------|------|
| Signaling rate, each lane (range) | 26.5625 ± 100 ppm | | GBd |
| Modulation format | PAM4 | | — |
| Lane wavelengths (range) | 1272.55 to 1274.54 1276.89 to 1278.89 1281.25 to 1283.27 1285.65 to 1287.68 1294.53 to 1296.59 1299.02 to 1301.09 1303.54 to 1305.63 1308.09 to 1310.19 | | nm |
| Damage threshold ^a | 5.2 | | dBm |
| Average receive power, each lane (max) | 4.2 | | dBm |
| Average receive power, each lane ^b (min) | -7 | -8.8 | dBm |
| Receive power, each lane (OMA _{outer}) (max) | 5.5 | 5.7 | dBm |
| Difference in receive power between any two lanes (OMA _{inner}) (max) | TBD | TBD | dB |
| Receiver reflectance (max) | TBD | | dB |
| Receiver sensitivity (OMA _{inner}), each lane ^c (max) | -10 | -11.8 | dBm |
| Receiver 3 dB electrical upper cutoff frequency, each lane (max) | 21 | | GHz |
| Stressed receiver sensitivity (OMA _{inner}), each lane ^d (max) | TBD | TBD | dBm |
| Conditions of stressed receiver sensitivity test | | | |
| Condition 1 ^e | TBD | TBD | |
| Condition 2 ^e | TBD | TBD | |

Table 123-9—400GBASE-FR8 and 400GBASE-LR8 illustrative link power budgets

| Parameter | 400GBASE-FR8 | 400GBASE-LR8 | Unit |
|---|----------------|--------------|------|
| Power budget (for maximum TDP) | 11 | 13.5 | dB |
| Operating distance | 2 | 10 | km |
| Channel insertion loss | 4 ^f | 6.3 | dB |
| Maximum discrete reflectance | TBD | TBD | dB |
| Allocation for penalties ^b (for maximum TDP) | 2 | 2.2 | dB |
| Allocation for modulation penalties ^b | 5 | 5 | dB |
| Additional insertion loss allowed | 0 | 0 | dB |

^aThe channel insertion loss is calculated using TBD plus an allocation for connection and splice loss given in 123.11.2.1.

^bLink penalties are used for link budget calculations. They are not requirements and are not meant to be tested.

Optical Margin

| Description (Inner Eye) | 400GBASE-FR8 | 400GBASE-LR8 | Unit |
|---|--------------|--------------|------|
| Receiver Sensitivity (OMA), each lane, pre-DeMux (max) | -10.0 | -11.8 | dBm |
| DeMux Loss | 3.0 | 3.0 | dB |
| Cross-talk penalty | 0.3 | 0.3 | dB |
| Receiver Sensitivity (OMA), each lane, post-DeMux (max) | -13.3 | -15.1 | dBm |
| Receiver Sensitivity (OMA) single lane (typical measured) | -17 | -17 | dBm |
| Optical Margin | 3.7 | 1.9 | dB |