Reliability constrained link budget assessment for 25 and 10 Gb/s

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Introduction & objectives

- This contribution is based on the reliability criteria and reliability models presented in [1], which are consistent with the ones considered in [2]
- It is also based on the mission profile proposal of [3]
- The objectives of this contribution are:
    - Exploration of the maximum operation bias current at maximum temperature based on wear out reliability criteria
    - Link budget assessment based on max bias current
- As explained in [2], 5 FIT target of maverick failures have not been verified so far. The presented reliability analysis will only be based on the wear out / fatigue failures
- Only TRUMPF 850nm 25G VCSEL will be considered, because reliability data and oxide aperture of the tested devices are known
    - Smallest oxide aperture diameter corner will be considered for the reliability calculation
    - Smallest and largest aperture will be considered for link budget analysis

VCSEL wear out reliability models [1]

VCSEL wear out statistics — lognormal PDF

- VCSEL aging failures are collected in time according to a lognormal distribution
  - This is very different of the general consideration of exponential distribution used in complex CMOS integrated circuits (λ is constant)
- Because VCSEL lifetime statistics follow a lognormal distribution, λ is not constant
- Lognormal PDF is defined as:

$$f(t') = \frac{1}{\sigma'\sqrt{2\pi}} \exp\left(-\frac{1}{2}\left(\frac{t'-\mu'}{\sigma'}\right)^2\right)$$

where:

  - *t'* is the natural logarithm of the time to failure
  - *μ'* mean of the natural logarithms of the time to failure
  - *σ'* standard deviation of the natural logarithms of the time to failure
- Therefore, the unreliability function is:

$$F(t) = \Phi\left(\frac{\ln(t)-\mu'}{\sigma'}\right)$$

where *Φ* is the standard normal distribution (i.e. *N*(0,1))

VCSEL wear out reliability model

- Reliability model is as follows. The time to failure is reduced with temperature (T) according to Arrhenius's equation and with a negative power of the average current density (J):

$$TTF_{x\%} = C \cdot J^{-n} \cdot \exp\left(\frac{E_a \cdot e}{k_B \cdot T} \right)$$

where:

  - E_a is the activation energy of failure mechanism (eV)
  - e is the electron charge (SI units)
  - k_B is the Boltzmann's constant (SI units)
  - T is absolute temperature (Kelvin)
  - C is a constant
  - $TTF_{x\%}$ is the time to x% failures (e.g. in hours)

- Reliability model can be built on T_J (junction or active region temperature) or it can be built on T_S (substrate or heat-sink temperature, direct to measure)

VCSEL wear out reliability analysis results

VCSEL reliability analysis based on extracted model from [4]

Reliability parameters

Operation	Operation total time (h)	32000	Reliability model	Wear out Ea (eV) @ T_J	1.075
	Service life (years)	15		Wear out n @ T_J	6.084
	Min oxide aperture diam. (um)	6.5		Arrhenius C factor (hours) @ T_J	1.070547E-02
	I_{OP} (mA) max	4.4770		TTF x%	50
	J_{OP} (kA/cm^2)	13.50		Log-normal σ', ln (hours)	0.32
	V_F (V) w/c	2.0		Qe	1.6022E-19
	P_{opt} (mW) w/c	0		K_B	1.3806E-23
	P_{DIS} (mW)	8.9540		Qe/K_B	1.1605E+04
	R_{JS} (K/W) w/c	2500		ºC to Kelvin	273.15
	ΔT_{AS} (ºC)	20			

Calculation according to [1], slide 18. Model extracted from [4].

Reliability result

	Temperature profile					Failure rate						
	Percentage	Time per Temperature (h)	T_A (ºC)	T_S (ºC)	T_J (ºC)	TTF x% (hours)	TTF x% (years)	Equivalent time in max T (hours)	Log-normal mu', ln (hours)	Failure-rate wear out (FIT)	Failure-rate maverick (FIT)	Total ppm
T_0	6 %	1920	-40	-20	2.4	6.652E+10	7.594E+06	0.00	24.9208			
T_1	20 %	6400	23	43	65.4	1.454E+07	1.659E+03	4.84	16.4921			
T_2	65 %	20800	50	70	92.4	9.548E+05	1.090E+02	239.28	13.7692			
T_3	8 %	2560	100	120	142.4	1.570E+04	1.792E+00	1791.29	9.6612			
T_4	1 %	320	105	125	147.4	1.098E+04	1.254E+00	320.00	9.3042			
Cummulative	100 %	32000						2355.40	9.3042	5.0	5.0	319.21

Original mission profile

VCSEL reliability analysis based on extracted model from [4]

Reliability parameters

Operation	Operation total time (h)	12000	Reliability model	Wear out Ea (eV) @ T_J	1.075
	Service life (years)	15		Wear out n @ T_J	6.084
	Min oxide aperture diam. (um)	6.5		Arrhenius C factor (hours) @ T_J	1.070547E-02
	I_{OP} (mA) max	4.7960		TTF x%	50
	J_{OP} (kA/cm^2)	14.46		Log-normal σ', ln (hours)	0.32
	V_F (V) w/c	2.0		Qe	1.6022E-19
	P_{opt} (mW) w/c	0		K_B	1.3806E-23
	P_{DIS} (mW)	9.5920		Qe/K_B	1.1605E+04
	R_{JS} (K/W) w/c	2500		ºC to Kelvin	273.15
	ΔT_{AS} (ºC)	20			

Calculation according to [1], slide 18. Model extracted from [4].

Reliability result

	Temperature profile					Failure rate						
	Percentage	Time per Temperature (h)	T_A (ºC)	T_S (ºC)	T_J (ºC)	TTF x% (hours)	TTF x% (years)	Equivalent time in max T (hours)	Log-normal mu', ln (hours)	Failure-rate wear out (FIT)	Failure-rate maverick (FIT)	Total ppm
T_0	6 %	720	-40	-20	4.0	3.372E+10	3.849E+06	0.00	24.2413			
T_1	20 %	2400	23	43	67.0	8.045E+06	9.183E+02	1.93	15.9005			
T_2	65 %	7800	70	90	114.0	9.353E+04	1.068E+01	538.67	11.4461			
T_3	8 %	960	100	120	144.0	9.206E+03	1.051E+00	673.55	9.1276			
T_4	1 %	120	105	125	149.0	6.459E+03	7.374E-01	120.00	8.7733			
Cummulative	100 %	12000						1334.15	8.7733	5.0	5.0	119.54

New mission profile

VCSEL reliability analysis based on extracted model from [5]

Reliability parameters

Operation	Operation total time (h)	32000	Reliability model	Wear out Ea (eV) @ T_S	1.225
	Service life (years)	15		Wear out n @ T_S	6.588
	Min oxide aperture diam. (um)	6.5		Arrhenius C factor (hours) @ T_S	4.044972E-05
	I_{OP} (mA) max	4.5840		TTF x%	1
	J_{OP} (kA/cm^2)	13.82		Log-normal σ', ln (hours)	0.37
	V_F (V) w/c	2.0		Qe	1.6022E-19
	P_{opt} (mW) w/c	0		K_B	1.3806E-23
	P_{DIS} (mW)	9.1680		Qe/K_B	1.1605E+04
	R_{JS} (K/W) w/c	2500		ºC to Kelvin	273.15
	ΔT_{AS} (ºC)	20			

Calculation according to [1], slide 23. Model extracted from [5].

Reliability result

	Temperature profile					Failure rate						
	Percentage	Time per Temperature (h)	T_A (ºC)	T_S (ºC)	T_J (ºC)	TTF x% (hours)	TTF x% (years)	Equivalent time in max T (hours)	Log-normal mu', ln (hours)	Failure-rate wear out (FIT)	Failure-rate maverick (FIT)	Total ppm
T_0	6 %	1920	-40	-20	2.9	3.071E+12	3.506E+08	0.00	29.6139			
T_1	20 %	6400	23	43	65.9	4.229E+07	4.827E+03	0.61	18.4207			
T_2	65 %	20800	50	70	92.9	1.228E+06	1.402E+02	67.93	14.8818			
T_3	8 %	2560	100	120	142.9	6.317E+03	7.212E-01	1625.49	9.6118			
T_4	1 %	320	105	125	147.9	4.011E+03	4.579E-01	320.00	9.1576			
Cummulative	100 %	32000						2014.03	9.1576	5.0	5.0	320.05

Original mission profile

VCSEL reliability analysis based on extracted model from [5]

Reliability parameters

Operation			Reliability model		
	Operation total time (h)	12000		Wear out Ea (eV) @ T_S	1.225
	Service life (years)	15		Wear out n @ T_S	6.588
	Min oxide aperture diam. (um)	6.5		Arrhenius C factor (hours) @ T_S	4.044972E-05
	I_{OP} (mA) max	5.0775		TTF x%	1
	J_{OP} (kA/cm^2)	15.31		Log-normal σ', ln (hours)	0.37
	V_F (V) w/c	2.0		Qe	1.6022E-19
	P_{opt} (mW) w/c	0		K_B	1.3806E-23
	P_{DIS} (mW)	10.1550		Qe/K_B	1.1605E+04
	R_{JS} (K/W) w/c	2500		ºC to Kelvin	273.15
	ΔT_{AS} (ºC)	20			

Calculation according to [1], slide 23. Model extracted from [5].

Reliability result

	Temperature profile					Failure rate						
	Percentage	Time per Temperature (h)	T_A (ºC)	T_S (ºC)	T_J (ºC)	TTF x% (hours)	TTF x% (years)	Equivalent time in max T (hours)	Log-normal mu', ln (hours)	Failure-rate wear out (FIT)	Failure-rate maverick (FIT)	Total ppm
T_0	6 %	720	-40	-20	5.4	1.566E+12	1.788E+08	0.00	28.9403			
T_1	20 %	2400	23	43	68.4	2.156E+07	2.461E+03	0.23	17.7471			
T_2	65 %	7800	70	90	115.4	6.392E+04	7.296E+00	249.59	11.9261			
T_3	8 %	960	100	120	145.4	3.221E+03	3.677E-01	609.56	8.9382			
T_4	1 %	120	105	125	150.4	2.045E+03	2.335E-01	120.00	8.4840			
Cummulative	100 %	12000						979.38	8.4840	5.0	5.0	119.61

New mission profile

VCSEL reliability analysis based on TRUMPF data [2]

Reliability parameters

Operation	**Operation total time (h)**	**32000**	**Reliability model**	**Wear out Ea (eV) @ T_J**	1.180
	Service life (years)	15		**Wear out n @ T_J**	1.640
	Min oxide aperture diam. (um)	6.5		**TTF x%, location**	50.0
	I_{OP} (mA) max	**5.6820**		**Log-normal σ', ln (hours)**	0.5
	J_{OP} (kA/cm²)	17.13		**J_0 (kA/cm²)**	19.49
	J_{OP} (mA/um²)	0.17		**T_{J0} (ºC)**	193
	ΔT_{AS} (ºC)	20.0		**TTF_0 x% (hours)**	965
VCSEL model fitting	**R_{JS} (K/W) @ room Ts reference**	1950		**Arrhenius C factor (hours) @ T_J**	2.198993E-08
	R_{JS} factor	100 %		**Qe**	1.6022E-19
	R_{JS} (K/W) @ room Ts	1950		**K_B**	1.3806E-23
	R_{JS} room Ts (ºC)	20.0		**Qe/K_B**	1.1605E+04
	R_{JS} Exponent	1.067		**ºC to Kelvin**	273.15
	R_{JS} Current fitting p0	0.01754	**VCSEL model fitting**	**P_{DIS} poly-fitting p11**	-0.006889
	R_{JS} Current fitting p1	0.9636		**P_{DIS} poly-fitting p02**	-5.203E-05
	P_{DIS} poly-fitting p00	-0.3481		**P_{DIS} poly-fitting p21**	0.0001612
	P_{DIS} poly-fitting p10	1.291		**P_{DIS} poly-fitting p12**	3.641E-05
	P_{DIS} poly-fitting p01	0.01552		**P_{DIS} poly-fitting p03**	1.736E-15
	P_{DIS} poly-fitting p20	0.05763			

Reliability result

	Temperature profile							**Failure rate**						
	Percentage	**Operation time per Temperature (h)**	**T_A (ºC)**	**T_S (ºC)**	**R_{JS} (K/W)**	**P_{DIS} (mW)**	**T_J (ºC)**	**TTF x% (hours)**	**TTF x% (years)**	**Equivalent time in max T (hours)**	**Log-normal mu', ln (hours)**	**Failure-rate wear out (FIT)**	**Failure-rate maverick (FIT)**	**ppm**
T0	**6 %**	1920	**-40**	-20.0	1772.9	9.28	-3.6	2.384E+12	2.721E+08	0.00	28.4996			
T1	**20 %**	6400	**23**	43.0	2247.4	8.34	61.7	1.192E+08	1.361E+04	1.19	18.5963			
T2	**65 %**	20800	**50**	70.0	2452.7	8.32	90.4	4.751E+06	5.423E+02	97.41	15.3738			
T3	**8 %**	2560	**100**	120.0	2835.9	8.87	145.1	3.434E+04	3.920E+00	1658.43	10.4442			
T4	**1 %**	320	**105**	125.0	2874.4	8.97	150.8	2.225E+04	2.540E+00	320.00	10.0100			
Cummulative	100 %	32000								**2077.03**	**10.0100**	**5.0**	**5.0**	**320.54**

Original mission profile

VCSEL reliability analysis based on TRUMPF data [2]

Reliability parameters

Operation	**Operation total time (h)**	**12000**	**Reliability model**	**Wear out Ea (eV) @ T_J**	1.180
	Service life (years)	15		**Wear out n @ T_J**	1.640
	Min oxide aperture diam. (um)	6.5		**TTF x%, location**	50.0
	I_{OP} (mA) max	**6.5200**		**Log-normal σ', ln (hours)**	0.5
	J_{OP} (kA/cm²)	19.66		**J_0 (kA/cm²)**	19.49
	J_{OP} (mA/um²)	0.20		**T_{J0} (ºC)**	193
	ΔT_{AS} (ºC)	20.0		**TTF_0 x% (hours)**	965
VCSEL model fitting	**R_{JS} (K/W) @ room Ts reference**	1950		**Arrhenius C factor (hours) @ T_J**	2.198993E-08
	R_{JS} factor	100 %		**Qe**	1.6022E-19
	R_{JS} (K/W) @ room Ts	1950		**K_B**	1.3806E-23
	R_{JS} room Ts (ºC)	20.0		**Qe/K_B**	1.1605E+04
	R_{JS} Exponent	1.067		**ºC to Kelvin**	273.15
	R_{JS} Current fitting p0	0.01754	**VCSEL model fitting**	**P_{DIS} poly-fitting p11**	-0.006889
	R_{JS} Current fitting p1	0.9636		**P_{DIS} poly-fitting p02**	-5.203E-05
	P_{DIS} poly-fitting p00	-0.3481		**P_{DIS} poly-fitting p21**	0.0001612
	P_{DIS} poly-fitting p10	1.291		**P_{DIS} poly-fitting p12**	3.641E-05
	P_{DIS} poly-fitting p01	0.01552		**P_{DIS} poly-fitting p03**	1.736E-15
	P_{DIS} poly-fitting p20	0.05763			

Reliability result

	Temperature profile										Failure rate			
	Percentage	**Operation time per Temperature (h)**	**T_A (ºC)**	**T_S (ºC)**	**R_{JS} (K/W)**	**P_{DIS} (mW)**	**T_J (ºC)**	**TTF x% (hours)**	**TTF x% (years)**	**Equivalent time in max T (hours)**	**Log-normal mu', ln (hours)**	**Failure-rate wear out (FIT)**	**Failure-rate maverick (FIT)**	**ppm**
T0	**6 %**	720	**-40**	-20.0	1797.5	11.04	-0.1	1.010E+12	1.153E+08	0.00	27.6412			
T1	**20 %**	2400	**23**	43.0	2278.4	9.89	65.5	6.019E+07	6.871E+03	0.48	17.9130			
T2	**65 %**	7800	70	90.0	2641.6	9.99	116.4	3.071E+05	3.506E+01	306.88	12.6349			
T3	**8 %**	960	**100**	120.0	2875.1	10.48	150.1	1.863E+04	2.127E+00	622.63	9.8324			
T4	**1 %**	120	**105**	125.0	2914.1	10.60	155.9	1.208E+04	1.379E+00	120.00	9.3995			
Cummulative	100 %	12000								**1049.99**	**9.3995**	**5.0**	**5.0**	**119.77**

New mission profile

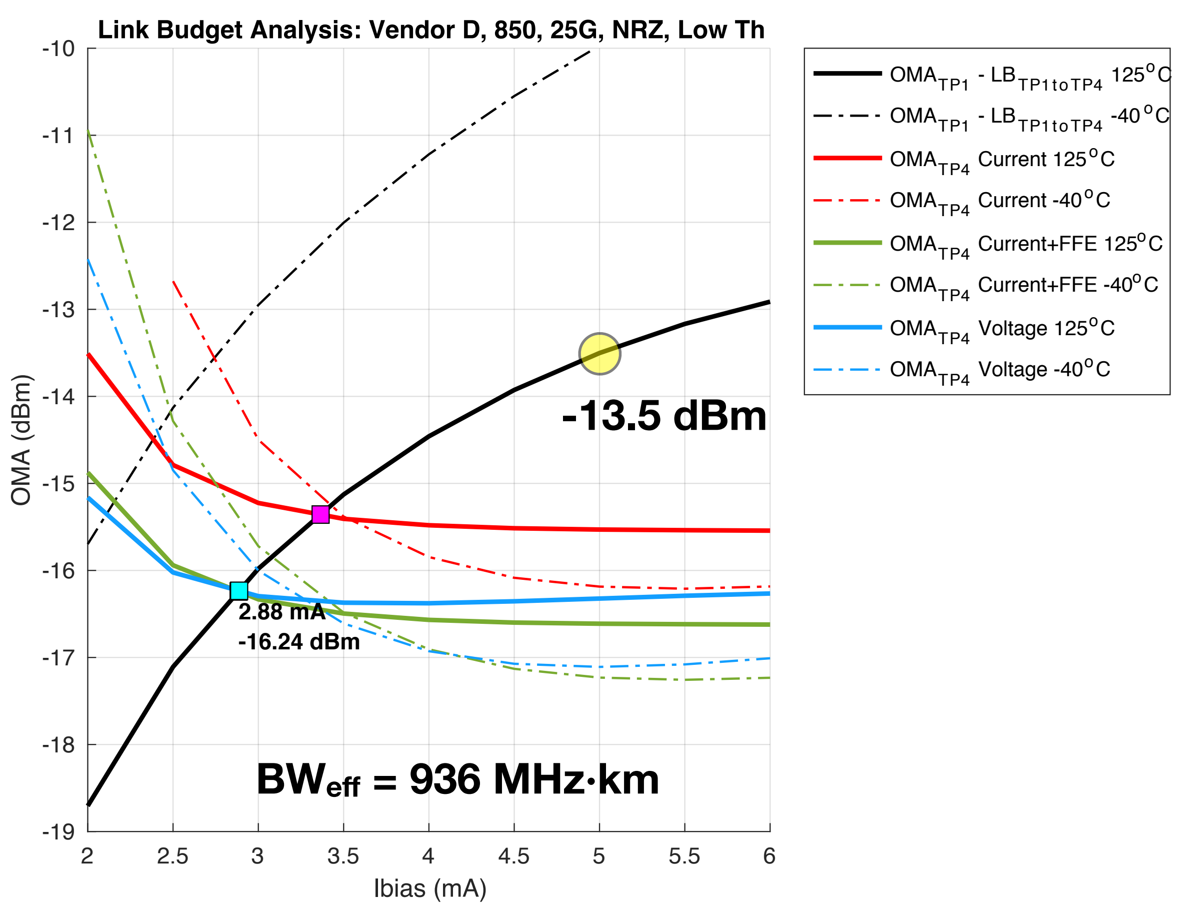
Conclusions on max I_{BIAS}

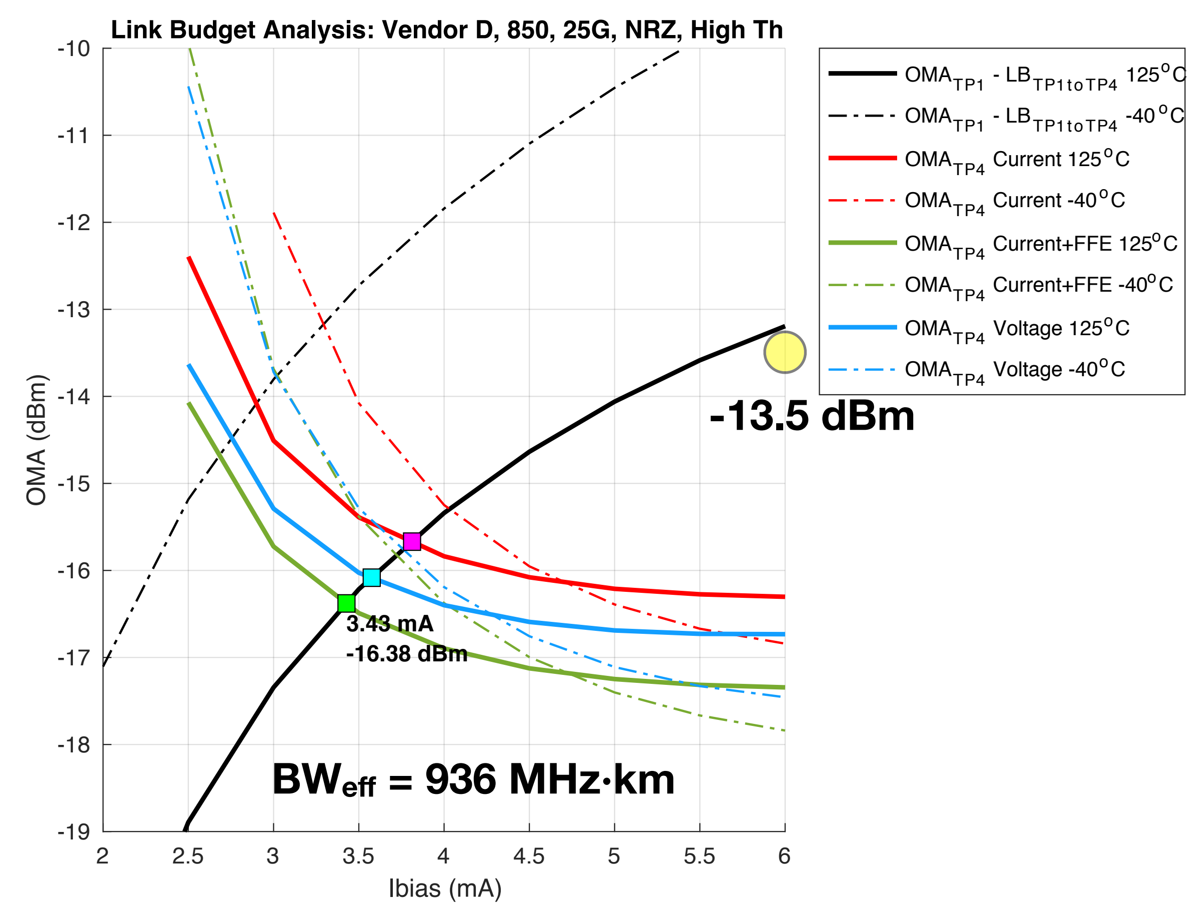
- For the original mission profile presented in [1], i.e. 32000 hours:
  - According to models considered in [1]: max current density is between 13.5 and 13.8 kA/cm^2
    - max I_{BIAS} between 4.5 and 4.6 mA, for 6.5 um aperture
  - TRUMPF 850 nm 25G VCSEL: max current density is 17.1 kA/cm^2
    - max I_{BIAS} is 5.7 mA, for 6.5 um aperture
- Considering the new mission profile proposed in [3], which is more suitable for multi-gigabit applications, i.e. 12000 hours:
  - According to models considered in [1]: max current density is between 14.5 and 15.3 kA/cm^2
    - max I_{BIAS} between 4.8 and 5.1 mA, for 6.5 um aperture
  - TRUMPF 850 nm 25G VCSEL: max current density is 19.7 kA/cm^2
    - max I_{BIAS} is 6.5 mA, for 6.5 um aperture
- Let's consider a conservative (i.e. 5 FIT random failures not verified so far) max current density of 15.2 kA/cm^2 for TRUMPF 850nm 25G VCSELs:
  - I_{BIAS} = 5 mA for low threshold devices, 6.5 um aperture
  - I_{BIAS} = 6 mA for high threshold devices, 7.5 um aperture

Reliability constrained link budget assessment

Link budget assessment for 25 Gb/s

- From [6], we have $IL_{TP1\text{-}to\text{-}TP4}$ = 11.84 dB, so based on the following curves we can calculate OMA_{TP1} for ER = 3dB





Link budget assessment for 25 Gb/s

- Proposal considering ER = 3dB:
  - $(OMA_{TP1} - IL_{TP1\text{-to-}TP4})_{min}$ = -13.5 dBm
  - $OMA_{TP1,min}$ = -13.5 + 11.84 = -1.7 dBm
  - $IL_{TP1\text{-to-}TP2,max}$ = 4.0 dB = 0.5 + 1.0 + 2.5 (SE variation + aging + coupling loss)
  - $OMA_{TP2,min}$ = -1.7 - 4.0 = **-5.7 dBm**
  - $OMA_{TP4,max}$ = -16.5 dBm
  - $IL_{TP3\text{-to-}TP4,\ max}$ = 2.5 dB (more realistic with actual knowledge)
  - $OMA_{TP3,max}$ = -16.5 + 2.5 = **-14.0 dBm**
  - Power Budget = **-5.7 + 14.0 = 8.3 dB**
- For I_{BIAS} >= 5 mA, it is reasonable to increase the ER to 4dB without receiver sensitivity degradation caused by VCSEL non-linear response, therefore:
  - $OMA_{TP2,min}$ = -5.7 + 1.125 = **-4.6 dBm**
    - Where $10\cdot\log10((10^{(3/10)} + 1)/(10^{(3/10)} - 1)\cdot(10^{(4/10)} - 1)/(10^{(4/10)} + 1))$ = 1.125 dB
  - $OMA_{TP3,max}$ = = **-13.5 dBm**
    - With extra OMA at TP2, we give margin 0.5 dB to the RX implementation, equivalent to $OMA_{TP4,max}$ = -16 dBm
  - Power budget = **-4.6 + 13.5 = 8.9 dB**
- Channel attenuation = 8.28 dB (fiber att. + 0.2 dB bending + 4×2dB inline connections)
- Unallocated margin = 8.9 - 8.28 = **0.62 dB**

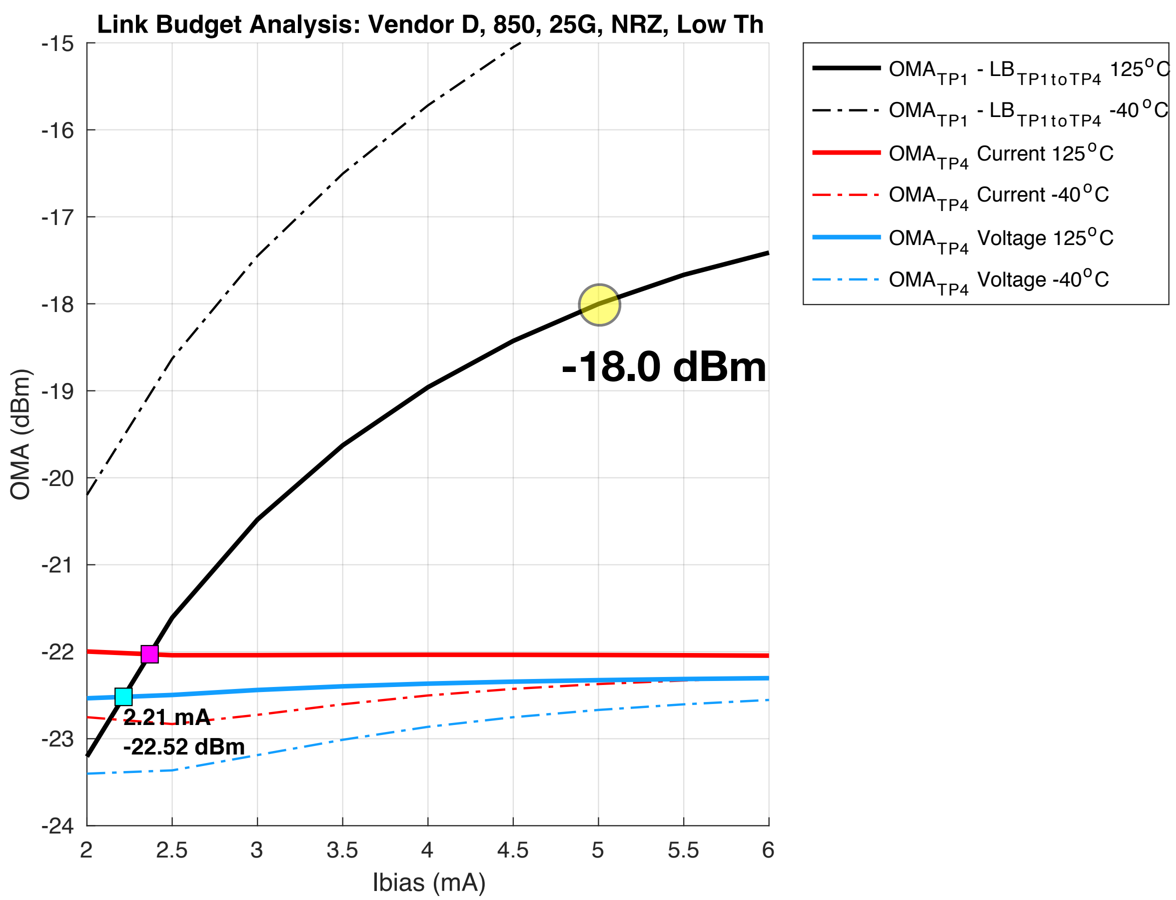
Link budget assessment for 25 Gb/s

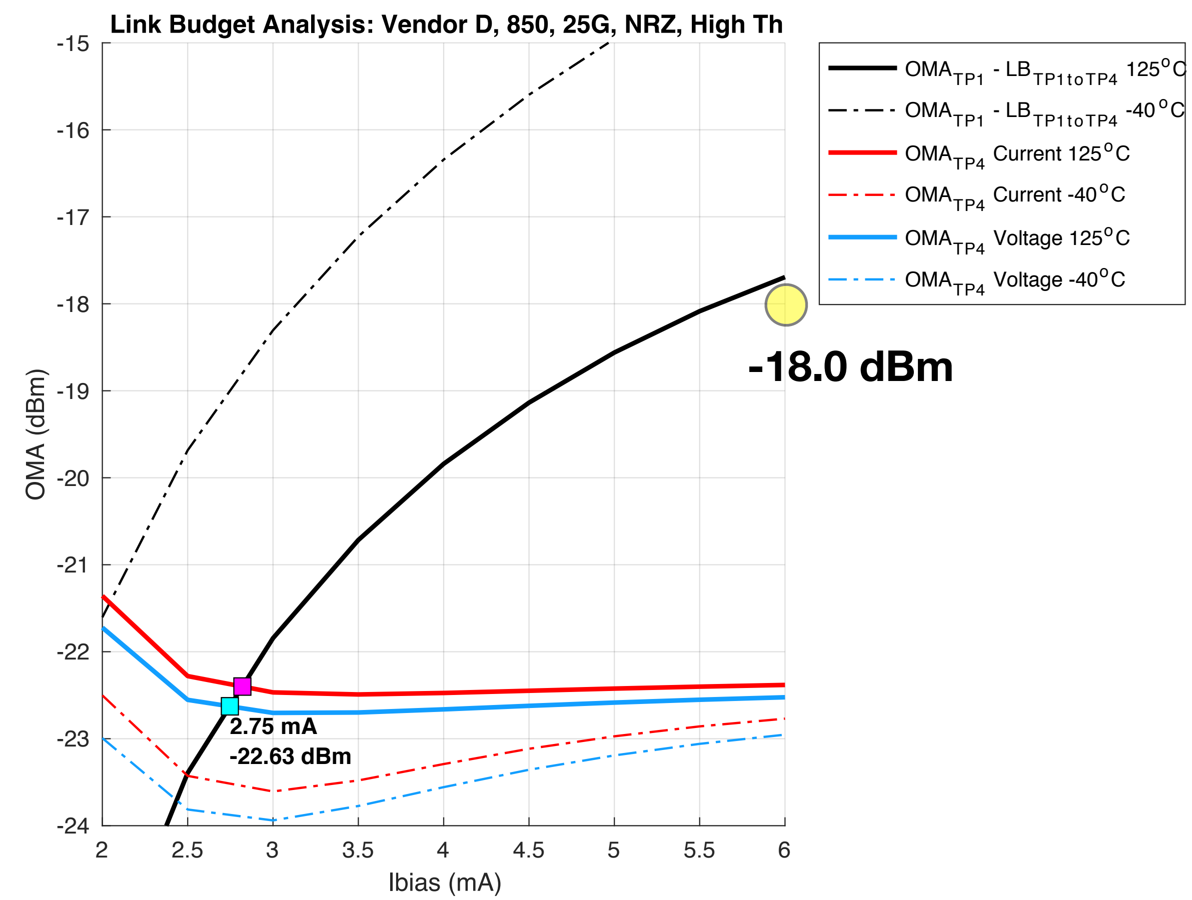
25 Gb/s link budget assessment

Parameter	Value	
VCSEL SE variation in the same bin (dB)	0.50	A
VCSEL aging (dB)	1.00	B
VCSEL to TP2 max coupling loss (dB)	2.50	C
$IL_{TP1\text{-}to\text{-}TP2}$, max (dB)	4.00	D = A + B + C
$IL_{TP3\text{-}to\text{-}TP4}$, max (dB)	2.50	E
Insertion loss per inline connection, IL_{IC} max (dB)	2.00	F
Number of inline connections (N_{IC})	4	G
Macrobend insertion loss, max (dB)	0.20	H
Microbend insertion loss, max (dB)	0.00	I
Bending insertion loss, IL_{BEND} max (dB)	0.20	J = H + I
Fiber attenuation (dB/km)	2.00	K
Channel attenuation, $IL_{TP2\text{-}to\text{-}TP3}$, max (dB)	8.28	L = (F × G) + J + (40/1000 × K)
$IL_{TP1\text{-}to\text{-}TP4}$, max (dB)	14.78	M = D + E + L
OMA_{TP1} min (dBm)	-0.60	N
OMA_{TP2} min (dBm)	-4.60	O = N - D
OMA_{TP4} max (dBm)	-16.00	P
OMA_{TP3} max (dBm)	-13.50	Q = P + E
Power budget (dB)	8.90	R = O - Q
Unallocated margin (dB)	0.62	S = R - L

Link budget assessment for 10 Gb/s

- From [7], we have $IL_{TP1\text{-}to\text{-}TP4}$ = 16.34 dB, so based on the following curves we can calculate OMA_{TP1} for ER = 3dB





Link budget assessment for 10 Gb/s

- Proposal considering ER = 3dB:
  - $(OMA_{TP1} - IL_{TP1\text{-}to\text{-}TP4})_{min}$ = -18.0 dBm
  - $OMA_{TP1,min}$ = -18.0 + 16.34 = -1.7 dBm
  - $IL_{TP1\text{-}to\text{-}TP2,max}$ = 5.0 dB = 0.5 + 1.0 + 3.5 (SE variation + aging + relaxed coupling loss)
  - $OMA_{TP2,min}$ = -1.7 - 5.5 = **-7.2 dBm**
  - $OMA_{TP4,max}$ = -22.0 dBm
  - $IL_{TP3\text{-}to\text{-}TP4, max}$ = 3.5 dB (relaxed design of receiver coupling elements)
  - $OMA_{TP3,max}$ = -22.0 + 3.5 = **-18.5 dBm**
  - Power budget = **-7.2 + 18.0 = 11.8 dB**
- Channel attenuation = 11.28 dB (fiber att. + 0.2 dB bending + 4×2.75dB inline connections)
- Unallocated margin = 11.8 - 11.28 = **0.52 dB**

Link budget assessment for 10 Gb/s

10 Gb/s link budget assessment

Parameter	Value	
VCSEL SE variation in the same bin (dB)	0.50	**A**
VCSEL aging (dB)	1.00	**B**
VCSEL to TP2 max coupling loss (dB)	3.50	**C**
$IL_{TP1\text{-}to\text{-}TP2}$, max (dB)	**5.00**	**D = A + B + C**
$IL_{TP3\text{-}to\text{-}TP4}$, max (dB)	**3.50**	**E**
Insertion loss per inline connection, IL_{IC} max (dB)	**2.75**	**F**
Number of inline connections (N_{IC})	**4**	**G**
Macrobend insertion loss, max (dB)	0.20	**H**
Microbend insertion loss, max (dB)	0.00	**I**
Bending insertion loss, IL_{BEND} max (dB)	0.20	**J = H + I**
Fiber attenuation (dB/km)	2.00	**K**
Channel attenuation, $IL_{TP2\text{-}to\text{-}TP3}$, max (dB)	**11.28**	**L = (F × G) + J + (40/1000 × K)**
$IL_{TP1\text{-}to\text{-}TP4}$, max (dB)	**19.78**	**M = D + E + L**
OMA_{TP1} min (dBm)	**-1.70**	**N**
OMA_{TP2} min (dBm)	**-6.70**	**O = N - D**
OMA_{TP4} max (dBm)	**-22.00**	**P**
OMA_{TP3} max (dBm)	**-18.50**	**Q = P + E**
Power budget (dB)	**11.80**	**R = O - Q**
Unallocated margin (dB)	**0.52**	**S = R - L**

Conclusions

- VCSEL wear out reliability analysis for proposed mission profile in [3] has been presented to determine max bias current that might be used to meet the reliability requirements
- Specifically, reliability analysis for TRUMPF 850nm 25G VCSEL has been presented
- Based on max bias current, link budget assessment has be presented for 25 and 10 Gb/s operations

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Thank you!