O3K: Standard APD-Frontends Sensitivity

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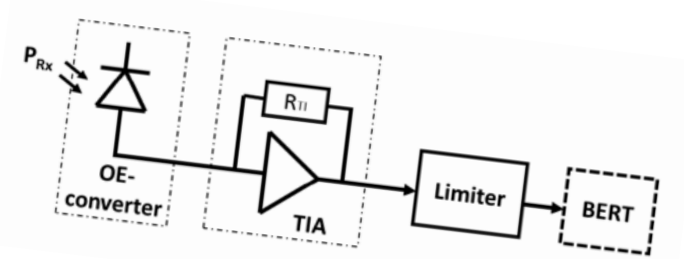
Motivation:

- For simulation of O3K-receiver system performance, besides the power fading vectors, also the Receiver Frontend (RFE) behavior model must be agreed
- A free-space bulk RFE will be based on APD-diodes. These exhibit a sensitivity behavior between a pure thermal limited PIN, and a perfect shot-noise limited receiver (such as for coherent BPSK)
- Two models exist for describing the sensitivity-run of such APD-RFEs:
    - (simple) analytical formula from receiver theory (6)
    - empirical $P_{Q=2}$ model (5) and [10], as favorable to derive a model from measurements
- regarding channel rates as typical for O3K (TIA-noise depends on bandwidth / datarate)
- trying to find reasonable parameter values for measured APD-RFE behavior did not succeed (see the end of this presentation)

Regarding RFE-behavior



- RFE converts optical P_{Rx} into electrical signal voltage, with noise that is either constant, or partly dependent on the signal photons (… and on background-light and dark current). We assume Gaussian noise since number of received signal photons is always high (>~50Ph/bit)

- in a DD binary receiver with OOK and optimum decision threshold this means *:

$$BER = \frac{1}{2} \cdot erfc\left(\frac{Q}{\sqrt{2}}\right) = \frac{1}{2} \cdot erfc\left(\frac{f(\bar{P}_{Rx})}{\sqrt{2}}\right)$$ with quality factor *Q=sqrt(SNR)* *(4)*

- **thermal-noise limited** RFEs run as Q~$\bar{P}_{Rx}$, while **coherent receivers** run as Q~sqrt($\bar{P}_{Rx}$);
APD-RFEs run in-between, thus can be modelled as $Q(\bar{P}_{Rx}) = 2\left(\frac{\bar{P}_{Rx}}{\bar{P}_{Q=2}}\right)^n$ with 0.5<n<1 *(5)*

- simple Formula for Q of APD is a rational term: $$Q_{st,OOK} = \frac{M\,R \cdot (2\bar{P}_{Rx})}{\sigma_t + \sqrt{\sigma_{s,1}^{\ 2} + \sigma_t^{\ 2}}}$$ *(6)*

(disregarding minor effects such as dark-current or distortions by binary decider / limiter, since these shall be negligible)

* $\bar{P}_{Rx}$ is the mean Rx-power, averaged over longer than bit-time but shorter than scintillation speed; thus it is the mean of ~100µs

$\sigma_t = i_n \cdot \sqrt{B}$: thermal noise current, with thermal noise current density i_n
$\sigma_{s,1}^{\ 2} = 2eM^2F_ARB \cdot (2\bar{P}_{Rx})$: signal shot noise current variance in an APD,

Derivation of common APD-RFE parameters

- modelling the Q-formula (6) by datasheets parameters
- RFE is with Hard Decision (limiter-element)
- parameters for three O3K channel rates: 78.125Mbps – 1.25Gbps – 10Gbps
- TIA-datasheets indicate input-referred noise densities:
  - 2pA/sqrt(Hz) at ~100MHz   → 1.5pA/sqrt(Hz) at 78Mbps
  - 5.9pA/sqrt(Hz) for ~1GHz / 1.25Gbps CWDM-PIN-receiver
  - 10pA/sqrt(Hz) at 6GHz / 10Gbps
    Values for 78Mbps and 10Gbps are approximated from TIA-data sheets close to such bandwidths
- InGaAs-APDs datasheets indicate M=20 for advanced APD types; although high-voltage and thus M can be optimized to P_{Rx}, here it is assumed fixed.
- InGaAs-APDs datasheets indicate excess noise factor F=5...5.5 for M=20
- Responsitivity R=0.9A/W
- assuming *quality selection* of COTS APDs, so best values shall be achieved

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APD-RFE parameters to use for simulations (λ=1550nm)

	Symbol	unit	78.125Mbps / B=39.065MHz	1.25Gbps / B=625MHz	10Gbps / B=5GHz
Responsivity	R	A/W	0.9	0.9	0.9
TIA noise density	$i_{n,th}$	A/sqrt(Hz)	1.5E-12	5E-12	10E-12
multip. factor	M	1	20	20	20
excess noise factor	F	1	5	5	5
… from these calculate $P_{Q=2}$-modell parameters for a hard-decision OOK Frontend [10]:					
Rx-Power for Q=2	$P_{Q=2}$	W	1.18E-9	16.1E-9	96.4E-9
Photons per bit	$N_{Q=2}$	1	116	100	75
sensit. slope expon.	n	1	0.839	0.818	0.777
span P_{Q6}/P_{Q2}	s	1	3.71	3.83	4.1
for comparison: values for a thermal-limited RFE (PIN-diode): $Q_{th,OOK} = R * \overline{P}_{Rx} \,/\, (\, i_{n,th} * sqrt(B)\,)$					
Thermal noise	$i_{n,th}$	A/sqrt(Hz)	1.5E-12	5E-12	10E-12

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For comparison only: Measured APD-RFE $P_{Q=2}$ Modelling (as for magenta curves) [10]

$$Q(\bar{P}_{Rx}) = 2\left(\frac{\bar{P}_{Rx}}{\bar{P}_{Q=2}}\right)^n$$

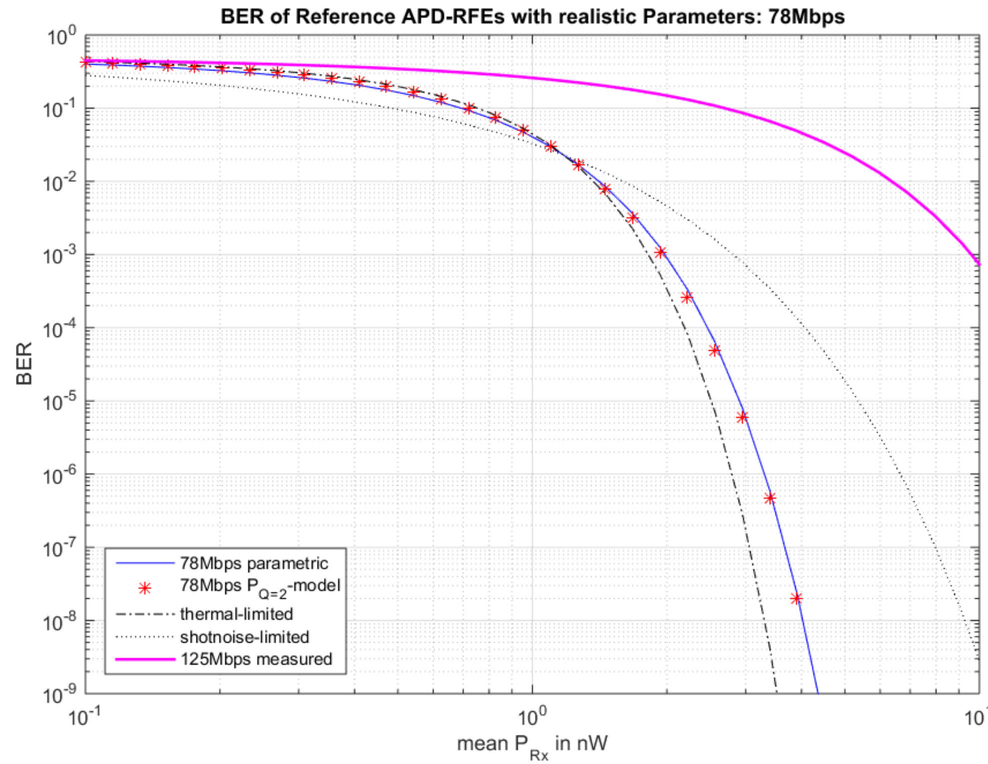
	Symbol	unit	125Mbps	1.25Gbps	10Gbps *
Rx-Power for Q=2	$P_{Q=2}$	W	5.13E-9	28.1E-9	273E-9
Photons per bit for Q=2	$N_{Q=2}$	1	320	175	213
sensitivity slope exponent	n	1	0.692	0.569	0.729
span P_{Q6}/P_{Q2}	s	1	4.9	6.9	4.5

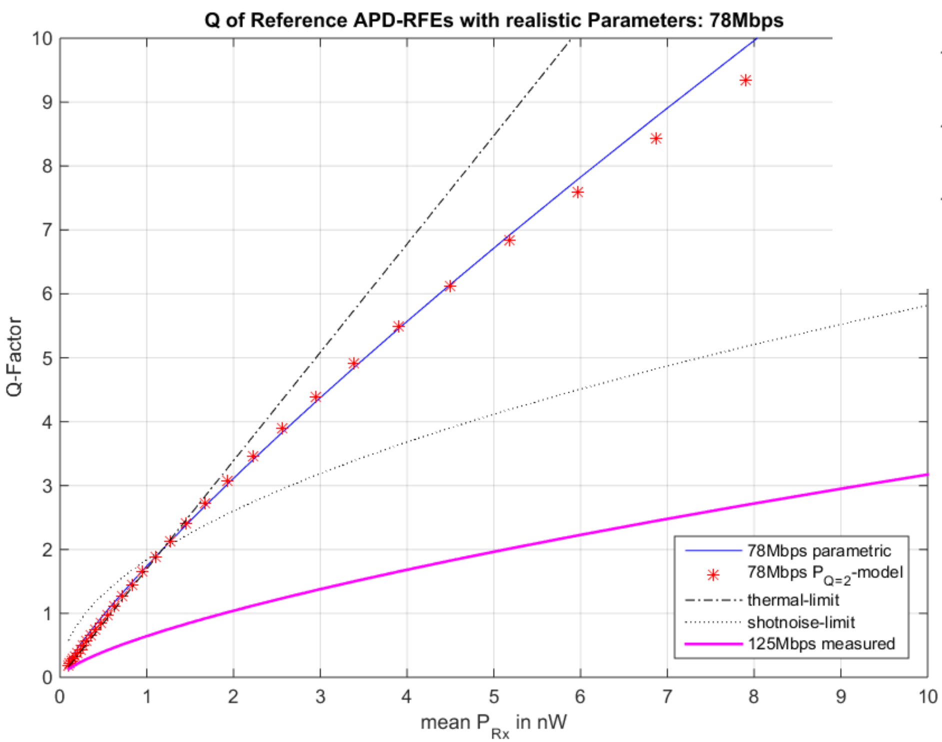
** in datasheet for M=5 only, better should be possible with higher M / APD-voltage*

RFE Reference for 78Mbps

(for (6) with values from table slide 5)

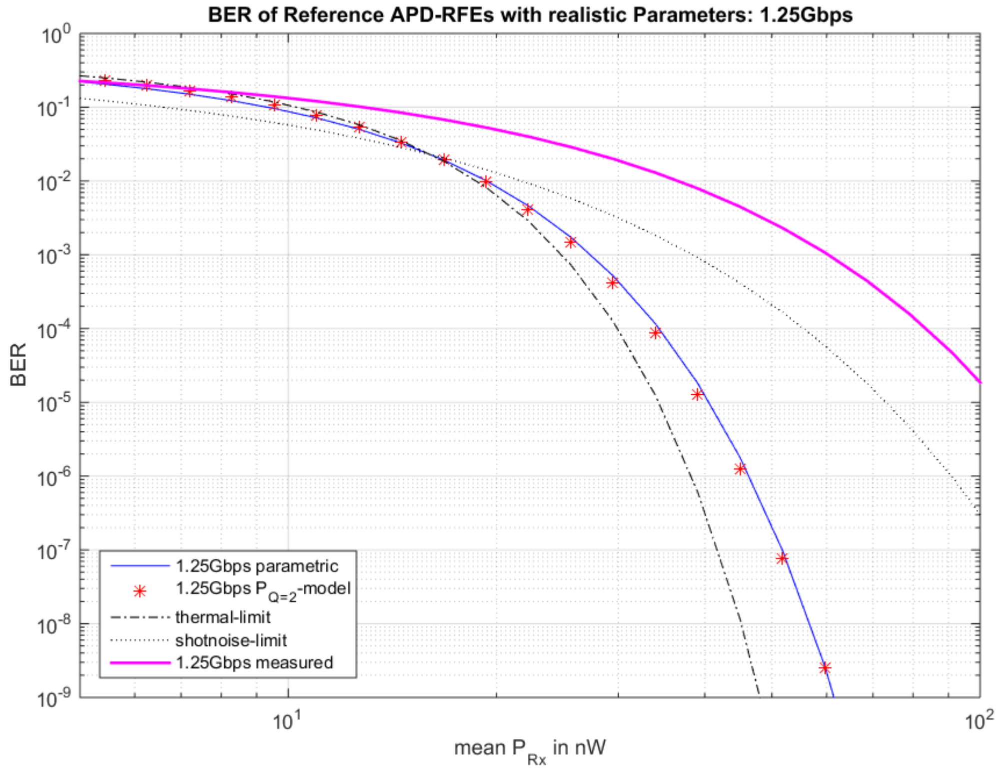
- RFE with parameters as preceeding table slide
* the $P_{Q=2}$-model for above RFE-parameters
-.-. pure thermal noise, for same $P_{Q=2}$
…. pure signal-dep. shotnoise, for same $P_{Q=2}$
- measured RFE, or data sheet (for comparison only)

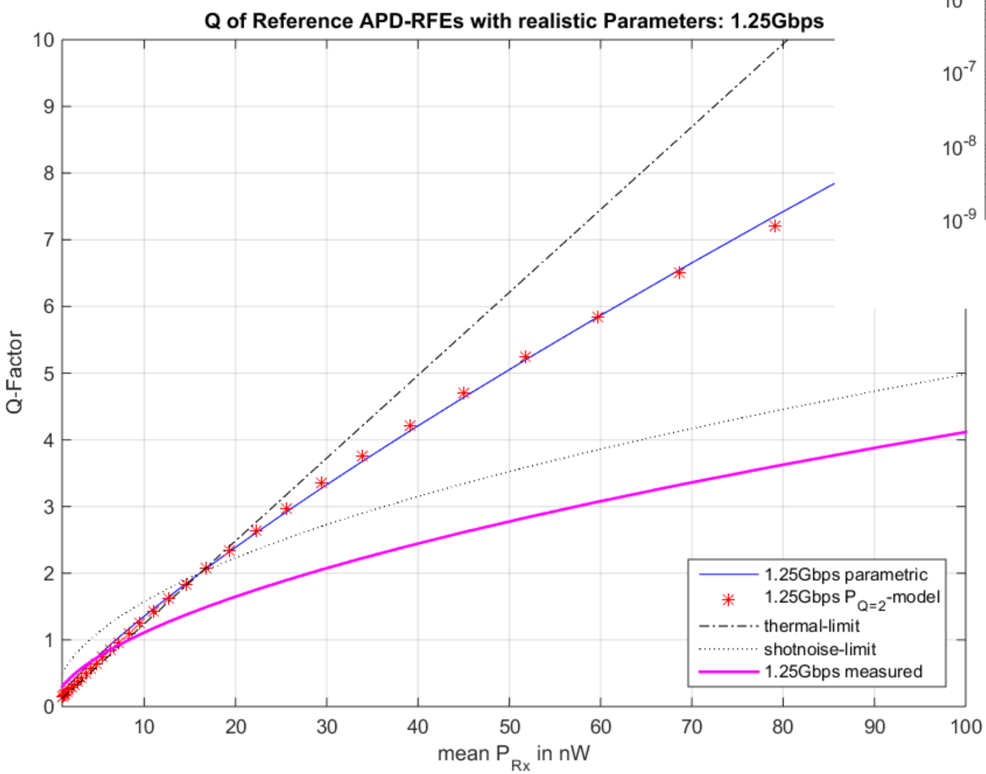




thermal- and shotnoise-limited curves are normalized to same $P_{Q=2}$, thus are for slope-comparison only, they do not indicate absolute sensitivity

RFE Reference 1.25Gbps





measured and parametric RFEs differ in slope: measured RFE slope appears more like shot-noise limited, while its absolute sensitivity ($P_{Q=2}$) is worse. The slope behavior but is caused by real-world electronics effects

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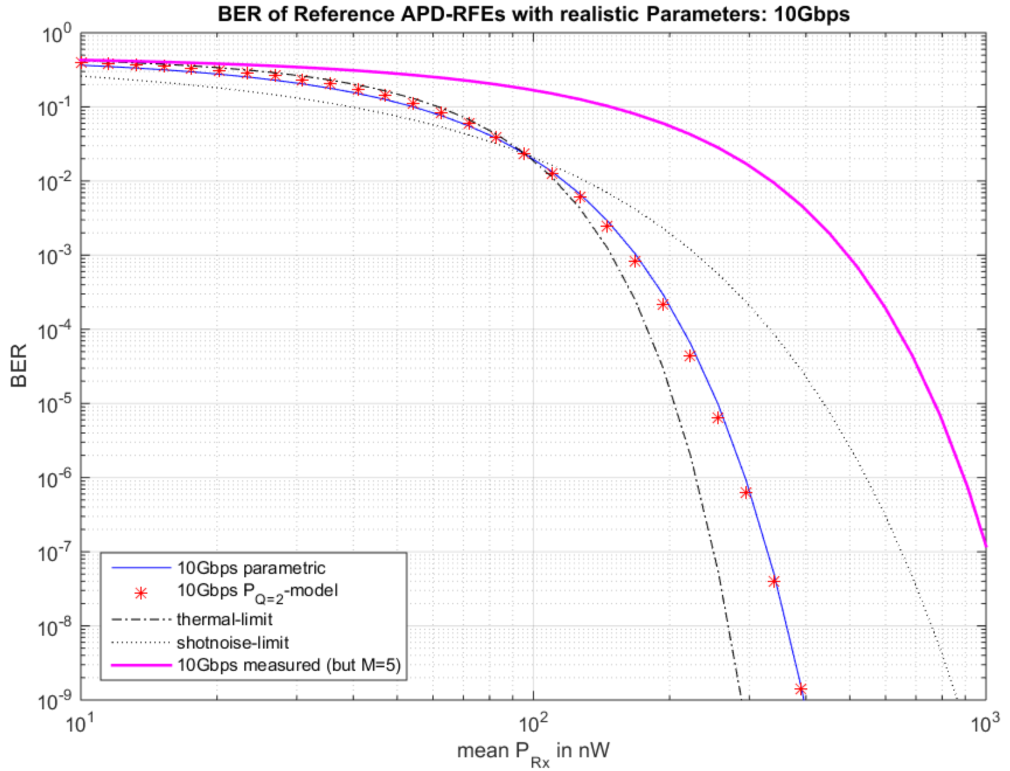
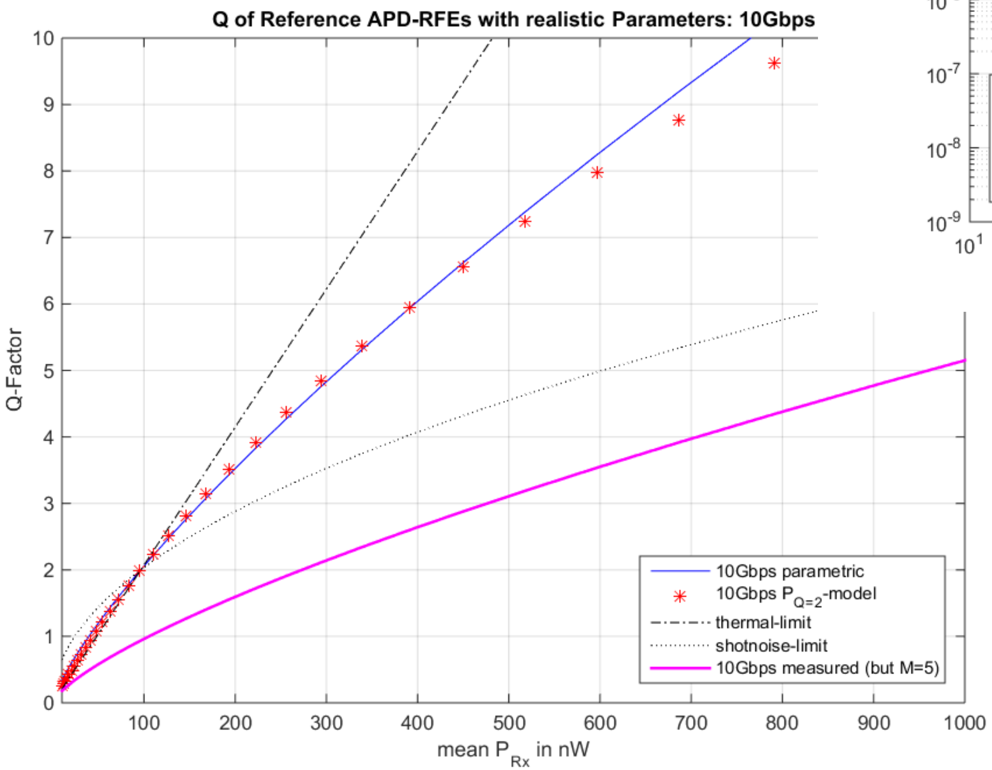
RFE Reference 10Gbps





The APD-RFE data for 10Gbps (as represented by above magenta plot) is for a constant M=5 as given in its datasheet. Therefore its sensitivity for this curve is much less than expected for M=20

Summary “APD-RFE sensitivity run”

- The above absolute assessment of APD-RFE-behavior helps to estimate linkbudgets and required link-parameters such as transmit power, beam divergence, and Rx-aperture. Thus it is assumed green-book material.
- To estimate coding gain, sensitivity curves are also relevant for FEC evaluation under fading
- above sensitivity curves are for optimum threshold binary decision of bits (HD).

- M=20 is kept constant since scintillation changes P_{Rx} quickly. But sensitivity of RFEs could be improved by dynamically optimizing M to P_{Rx}.

- *Measurement* from RFEs could NOT be used as reference parameters, since no fitting to *expected* parameter ranges was achieved (see end of this presentation).

References & Abbreviations

[1] D. Giggenbach, S. Parthasarathy, A. Shrestha, F. Moll, R. Mata Calvo, “Power Vector Generation Tool for Free-Space Optical Links – PVGeT”, IEEE-Xplore, ICSOS 2017

[2] D. Giggenbach, F. Moll, “Scintillation Loss in Optical Low Earth Orbit Data Downlinks with Avalanche Photodiode Receivers”, IEEE-Xplore, ICSOS 2017

[3] F. Moll, “Experimental analysis of channel coherence time and fading behavior in the LEO-ground link”, ICSOS 2014

[4] A. Mustafa, D. Giggenbach, J. Poliak, S. ten Brink, Quantifying the Effect of Atmospherically-Induced Pointing Errors in Optical Geostationary Satellite Feeder Links Using Transmitter Diversity”, IEEE-Xplore, ICSOS 2017 Japan.

[5] Normalized jitter values and bandwidth: verbal communication with K. Saucke of TESAT

[6] M. Toyoshima and K. Araki, “Effects of time averaging on optical scintillation in a ground-to-satellite atmospheric propagation,” Appl. Opt., vol. 39, no. 12, pp. 1911–1919, 2000.

[7] M. Toyoshima, "Long-Term Statistics of Laser Beam Propagation in an Optical Ground-to-Geostationary Satellite Communications Link", IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION, VOL. 53, NO. 2, FEBRUARY 2005

[8] U.G. Gujar, R.I. Kavanagh, “Generation of Random Signals with Specified Probability Density Functions and Power Density Spectra”, *IEEE Transactions on Auto*matic Control, 1968

[9] B. Epple, “Simplified Channel Model for Simulation of Free-Space Optical Communications”, J. Opt. Commun. Netw., 2010, 2

[10] D. Giggenbach, R. Mata-Calvo, “Sensitivity Modeling of Binary Optical Receivers”, Applied Optics, Vol. 54, No. 28, pp 8254-8259 / October 1, 2015

ACOV	AutoCOVariance
DL	DownLink
FWHM	Full-Width Half-Maximum
HWHM	Half-Width Half-Maximum
ILV	InterLeaVer
IRT	Index-of-Refraction Turbulence
PE	Pointing Error
PSI	Power Scintillation Index
PV	Power Vector

OLD (Sept2019) attempt to fit parameters to measured sensitivity-runs – on following slides

- since models for $P_{Q=2}$ and n are existing based on measurements of various implemented APD-RFEs [10], we tried to find the formula-(6) parameter values, (M, i_n, F_A) that fit best to those measurements.
- however such derived parameters would be far from what has to be expected for such parameters - these attempts are shown on the next slides. While absolute sensitivity in terms of $P_{Q=2}$ is close to expectation, the sensitivity-run (slope) for higher received powers differs substantially from those given by formula-parameters.
- we expect that specific "real-world" electronic behavior is responsible for the APD-RFE behavior
- due to this mal-fitting, we decided to elaborate APD-RFE models that are purely based on values from datasheets → first slides of this presentation

OLD and for EXPLANATION ONLY:
Parameters for RFEs at 100Mbps / 1Gbps / 10Gbps

trying to fit M, F, i_n to *measured* slopes is problematic since …

- realistic M, F, i_n do not result in the measured low slope "n" and sensitivity P_{Q2} - that would require unrealistic parameters to fit the formula (6) to measured curve runs (… this was the initial reason why P_{Q2}-model was developed)
- rational term does not perfectly fit to exponential term (this is only minor issue)

We tried different modelling:

1) Find parameters M, F, i_n that fit formula (6) and then model the RFEs at ~~100Mbps, 1Gbps, 10Gbps~~ which are based on the measured ***P_{Q2}* and *n*** as from table below

2) leave *P_{Q2}*-sensitivity as based-on-measured, but fitted *n* to realistic parameter-values

3) used typical M, F, i_n from datasheets and calculated resulting P_{Q2} and n

MEASURED RECEIVER MODEL PARAMETERS SUMMARY, SORTED BY MEAN ENERGY PER BIT $\bar{E}_{Q=2}$ see [10]

No.	RFE-Type	data rate	$\bar{P}_{Q=2}$	s	$\bar{E}_{Q=2}$	$\bar{N}_{Q=2}$	n	RMSRE
{1}	Homodyne BPSK SyncBit (1064nm)	2Mbps	0.672pW	8.0	0.336aJ	1.80	0.529	7.2%
{2}	APD-RFE-SILEX (820nm), M-fix	4Mbps	48.8pW	7.1	12.2aJ	50.3	0.558	4.3%
{3}	APD-RFExG-200µm@700MHz, M-opt	1.6Gbps	35.3nW	7.8	22.1aJ	172	0.536	0%
{4}	APD-RFExG-80µm@2500MHz, M-opt	3.2Gbps	71.2nW	8.8	22.2aJ	173	0.507	2.1%
{5}	APD-RFExG-200µm @700MHz, M-opt	1.25Gbps	28.1nW	6.9	22.5aJ	175	0.569	1.4%
{6}	commercial APD-TIA module, M-fix	10Gbps	273nW	4.5	27.3aJ	213	0.729	6.3%
{7}	APD-RFE100@65MHz, M-opt	125Mbps	5.13nW	4.9	41.0aJ	320	0.692	2.8%
{8}	APD-RFE1G@650MHz filter, M-opt	1.3Gbps	57.1nW	6.6	43.9aJ	342	0.581	2.2%
{9}	APD-RFE1G@100MHz filter, M-opt	200Mbps	12.8nW	7.9	64.0aJ	499	0.529	3.0%
{10}	APD-RFE1G@20MHz filter, M-opt	40Mbps	4.36nW	8.7	109aJ	849	0.508	2.9%
{11}	commercial CWDM-PIN-receiver	1.25Gbps	296nW	3.2	237aJ	1.85E3	0.951	3.2%
{12}	ASK-PIN-RFE	40Gbps	24.9µW	4.6	623aJ	4.86E3	0.720	2.0%

Remark:

(6) does not take into account dark-current,

however also a formula including dark current does not improve the fitting

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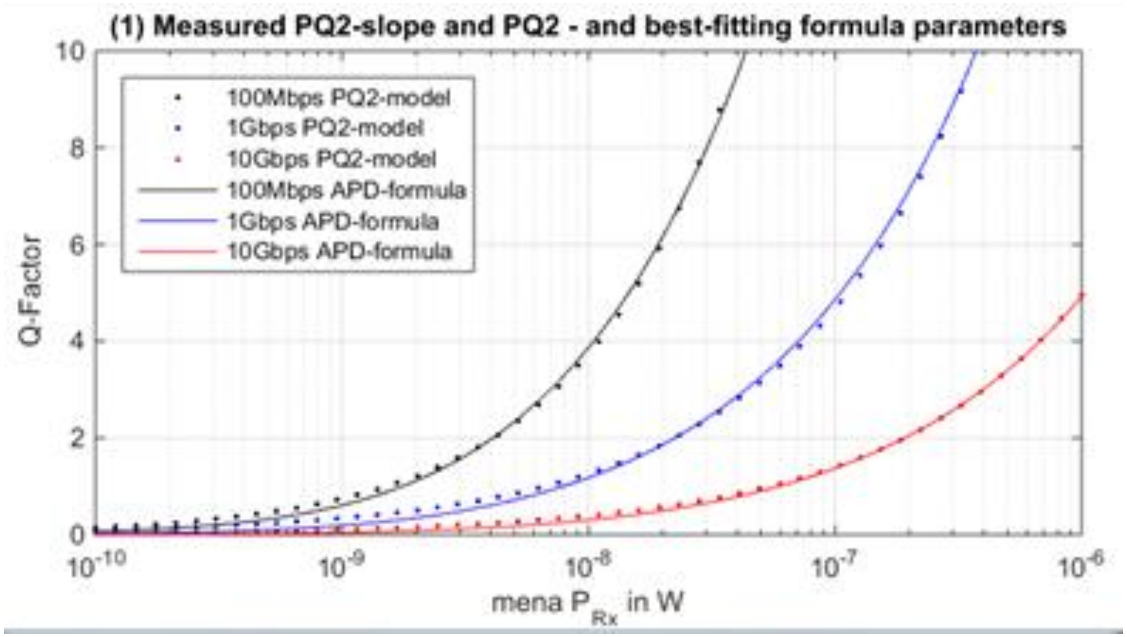
1) Find parameters M, F, i_n that fit formula (6) and then model the RFEs at 100Mbps, 1Gbps, 10Gbps

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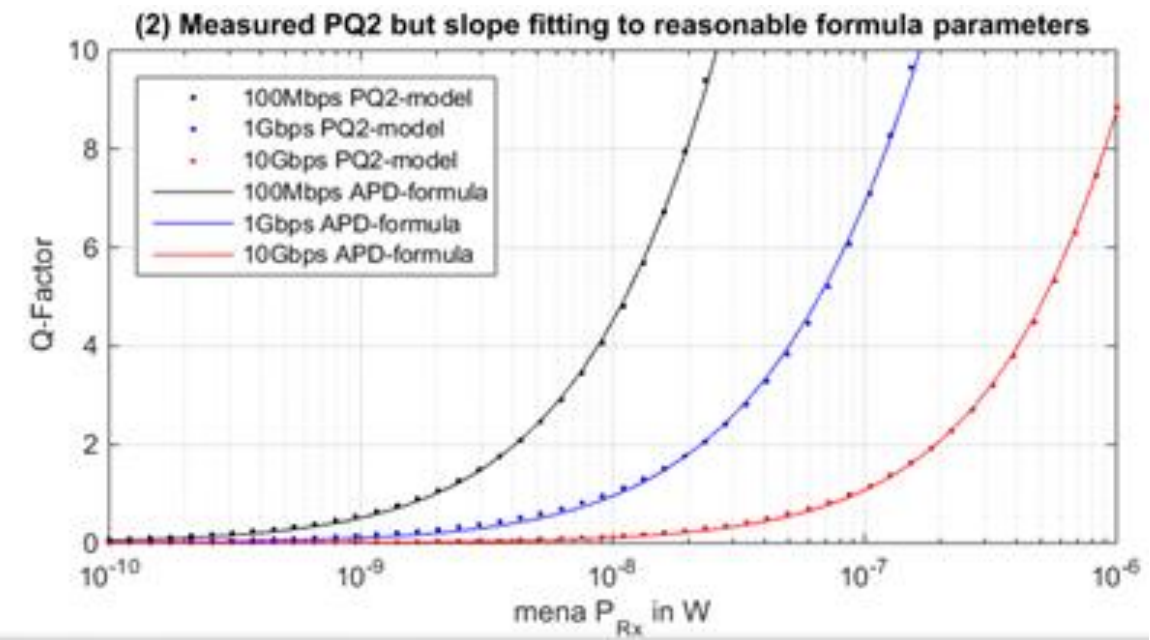
*** (1) measured PQ2 and n, and somehow fitting formula-parameters ***
datarates [Gps]    :  0.1           1           10
P_Q2 [nW]          :  4.1          22.4          192
exponent n [1]     :  0.7        0.57        0.55
Exc Noise F [1]    :  35.9929      40.9937      45.9944
Multip. M [1]      :  70  80  90
Noise [W/sq(Hz)]   :  1.4585e-11  1.6572e-11  2.8395e-11
```

2) P_{Q2}-sensitivity as based-on-measured, but fitted n to realistic parameter-values

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*** (2) measured PQ2 but n fitted to a set of reasonable formula-parameters ***
datarates [Gps]    :  0.1              1              10
P_Q2 [nW]          :  4.1            22.4             192
exponent n [1]     :  0.89           0.82           0.9
Exc Noise F [1]    :  8.4667         8.4667          3.4
Multip. M [1]      :  15   15   5
Noise [W/sq(Hz)]   :  4.0609e-12   6.6032e-12   6.403e-12
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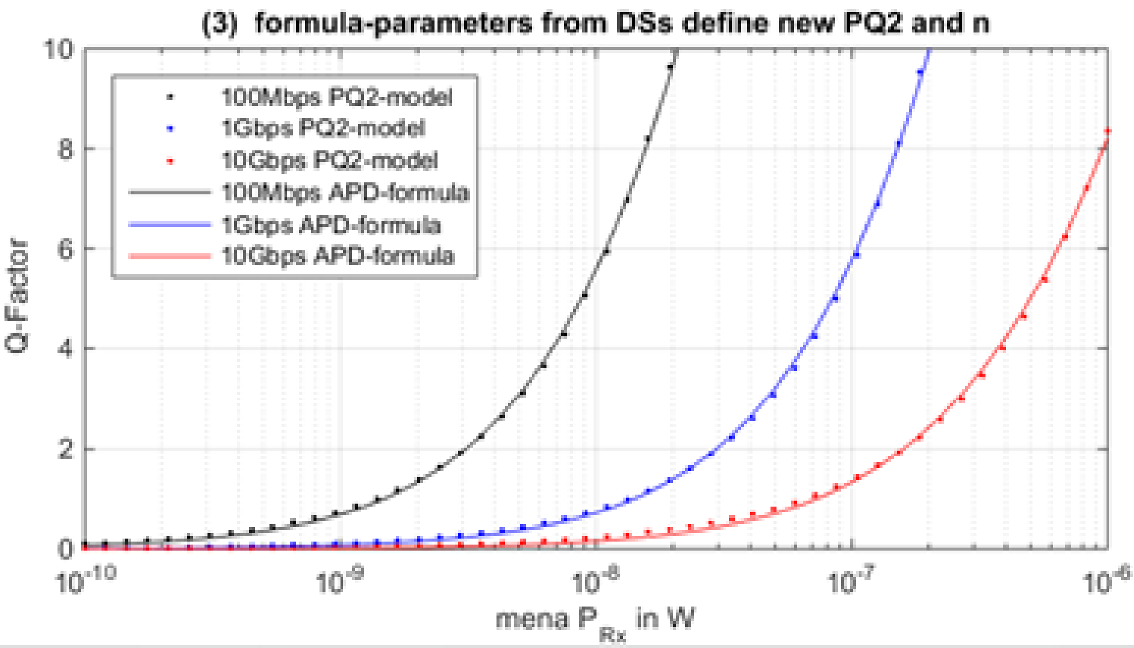
3) Typical M, F, i_n from datasheets and calculate P_{Q2} , n

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*** (3) formula-parameters from DSs define new PQ2 and n ***
datarates [Gps]   :  0.1             1            10
P_Q2 [nW]         :  3.1             30            160
exponent n [1]    :  0.86          0.86         0.78
Exc Noise F [1]   :  8.4667        8.4667       8.4667
Multip. M [1]     :  15  15  15
Noise [W/sq(Hz)]  :  3e-12         9e-12      1.4e-11
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Results of APD-run evaluations (20191021)

- measured APD-RFEs do not fit to noise-behavior from formulas: parameters from datasheets would result in steeper slopes than measured

  → only unrealistic noise-parameters emulate measured behavior (1)
- realistic parameters result in acceptable PQ2, but in not-measured slope *n* (3)
- *could we evaluate other measured APD-sensitivity curves ?*

→

- suggest to generate parameters for channel rates:

  10GGbps – 1.25Gbps – 78.125Mbps
- if no other RFE data is provided: suggest DLR fixes and provides a "compromise parameter set" from datasheets and measurements