Lecture Series

Wireless Communications - Part IV - OWC - Visible Light Communication – Optical Rx

Prof. Zabih Ghassemlooy[1]
Prof. Stanislav Zvanovec[2]
Dr. Luis Nero Alves[3]
Dr. Ali Khalighi[4]

[1]*Emeritus Professor of Optical Communications*
Photonics Technology Laboratory, Optical Communications Research Group
Faculty of Engineering and Environment, Northumbria University, Newcastle upon Tyne, UK
z.ghassemlooy@northumbria.ac.uk

[2]Department of Electromagnetic Field, Czech Technical University in Prague, Czech Republic
xzvanove@fel.cvut.cz

[3]*Department of Electronics Telecommunications and Informatics*
University of Aveiro
Portugal
nero@ua.pt

[4]*Ecole Centrale Méditerranée, Fresnel Institute research lab, Marseille*
France
Ali.Khalighi@fresnel.fr

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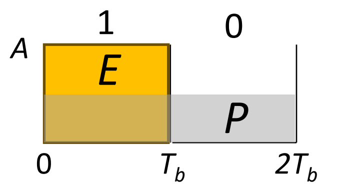
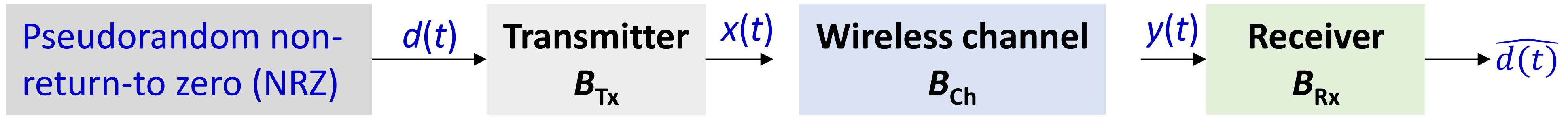
- OWC – Receiver
- Types of front end Rxs
    - Low-impedance
    - High-impedance
    - Trans-impedance
- Equivalent circuit
- Noise sources
- Performance matrix
    - SNR
    - BER
    - Eye diagram
    - Trade-off

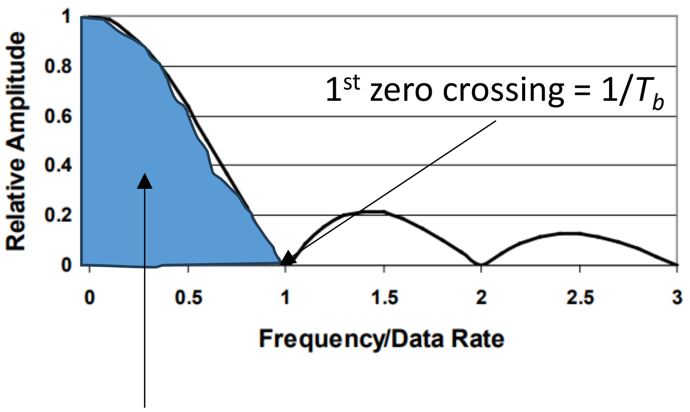
OWC - System Block Diagram



Energy $E = A^2 T_b$
Average power $P = A^2/2$



Frequency spectrum
Sinx/x



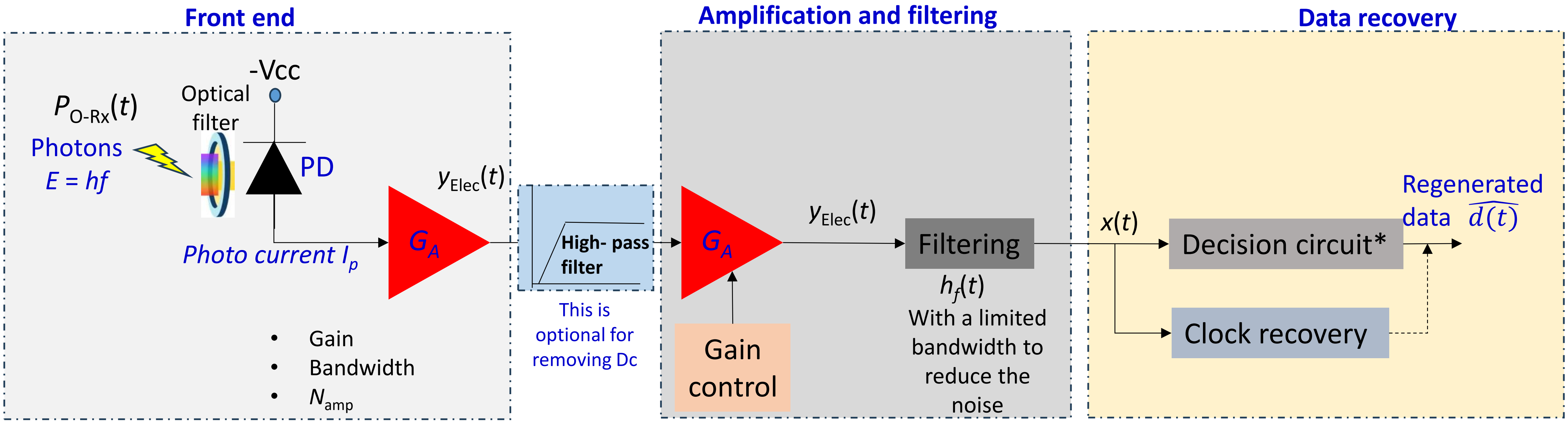
~ 93 of the power is accumulated at 75% of the data rate.

- For the data to be faithfully transmitted the channel needs to transmit the portion of the spectrum that contains most of the energy with minimal distortion, i.e.,

$$B_{Ch} = 1/T_b = R_b$$

- A non-flat frequency response → ISI
- $B_{Rx} = 0.75\ R_b$

OWC – Receiver – Block Diagram



*This could be based on:

- A simple slicer
- A matched filter + slicer

OWC – Receiver – Block Diagram

Average signal current

The average transmit power $P_t = \overline{I(t)}$

Channel gain

Transmit optical intensity

Received optical signal intensity $I_{\text{O-Rx}}(t) = h_{\text{ch}} I_{\text{op}}(t)$

Received digital pulse stream $P_{\text{O-Rx}}(t) = \sum_{n=-\infty}^{\infty} A_n \, p_{o-\text{Rx}}(t - nT_b)$

Pulse shape

Bit duration

Photocurrent for:

- PIN PD $i_p(t) = \mathcal{R} \cdot P_{o-\text{Rx}}(t)$
- APD $i_p(t) = \mathcal{R} \cdot G_{\text{APD}} \cdot P_{o-\text{Rx}}(t)$

Average electrical power $P_{\text{elec}} = \overline{\left(i_p(t)\right)^2}$

For a desired BER

The average optical power $P_{\text{ave}} = \dfrac{\text{SNR} \cdot i_n}{\mathcal{R}}$

Photocurrent I_p = Average photocurrent (DC current) $I_{p\text{-DC}}$ + Signal current $i_{p\text{-AC}}(t)$

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O C R G

OWC – Rx – Types of Front End

Current to voltage conversion

Amplification

Must have low noise

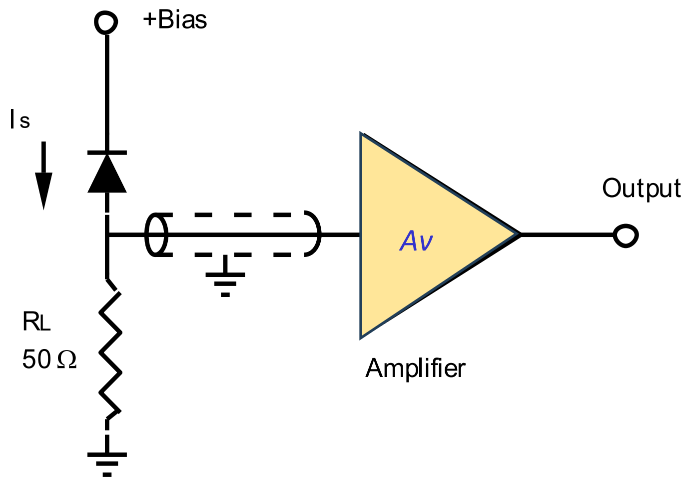
Low Impedance Voltage Amplifier

High Impedance Voltage Amplifier with Equalizer

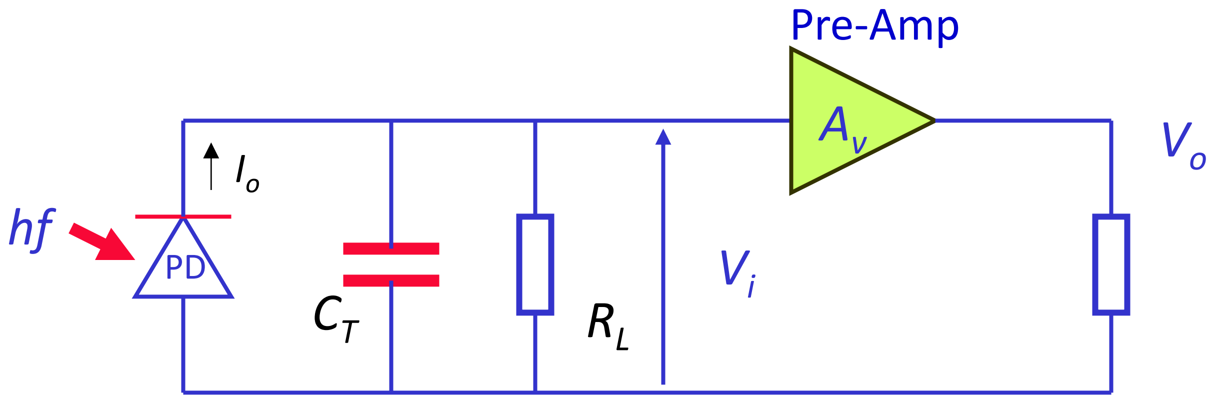
Transimpedance Feedback Amplifier

OWC – Rx – Low Impedance Voltage Amplifier

- Simple
- Low sensitivity
- Limited dynamic range
- A large bandwidth
- It is prone to overload and saturation



OWC – Rx – Low Impedance Voltage Amplifier



For equivalent circuit model for PD and amplifier see the lecture note on Optical PDs

$R_T = R_{PD} \,||\, R_{PD} \,||\, R_{amp}$ R_{amp}= High $C_T = C_{PD} + C_{amp}$

Has normally a low value, typically 50 Ω

RC limited bandwidth $B_{\text{Rx-LIVA}} = \frac{1}{2\pi C_T R_T}$

Assuming $B_{amp} >> B_{\text{Rx-LIVA}}$

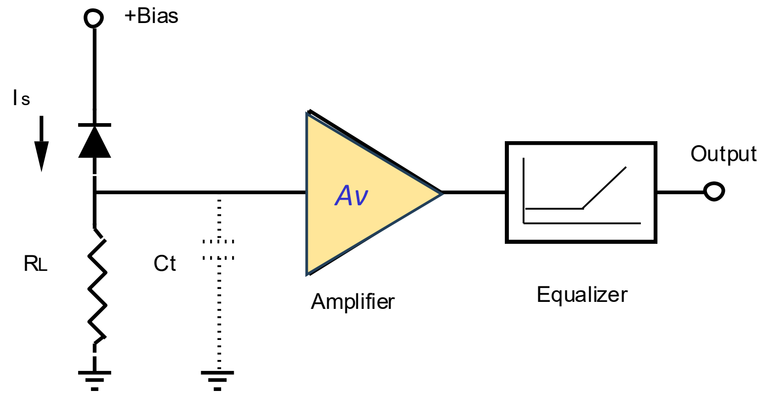
Note, thermal noise $i_{\text{th}}^2 = \frac{4kTB_{\text{Rx}}}{R_L}$

So, R_L ⇧ ⇨ i_{th}^2 ⇩ ⇨ $B_{\text{Rx-LIVA}}$ ⇩

→ As in high-impedance Rx

OWC – Rx – High Impedance Voltage Amplifier (HIVA) with Equalizer

- Uses a resistor to develop a voltage proportional to the light detector current
- High sensitivity, due to lower i_{th}^2
- If R_{in} of the high impedance circuit is too high:
  - the leakage current, caused by ambient light, could saturate the PIN diode, preventing the modulated signal from ever being detected
  - Saturation occurs when V_{RL}, due to the photodiode leakage current, approaches V_{bias}
  - To prevent saturation, the PIN must maintain a bias voltage of at least a few volts
- Low dynamic range
- A smaller bandwidth → Using an equalizer
- Detector output is integrated over a long time constant, and is restored by differentiation



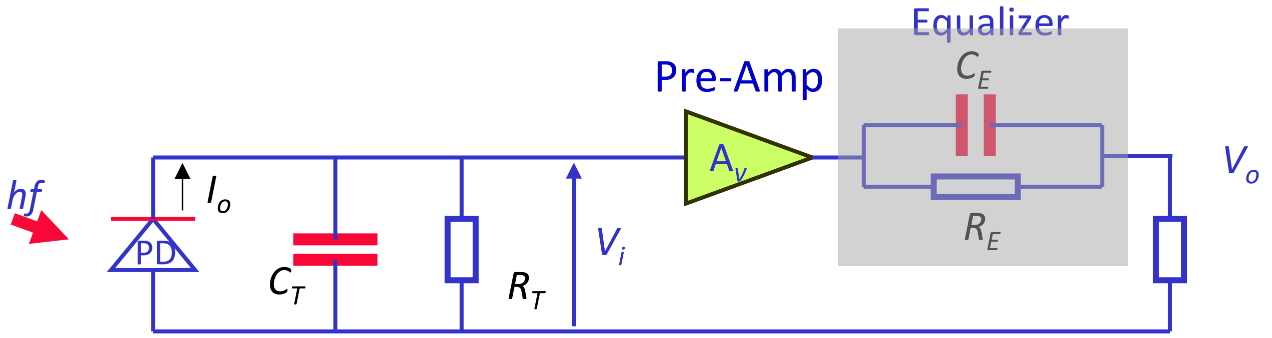
$R_T = R_{\mathrm{PD}} \,||\, R_{\mathrm{PD}} \,||\, R_{\mathrm{amp}}$ $\quad R_{\mathrm{amp}}$ = High

$C_T = C_{\mathrm{PD}} + C_{\mathrm{amp}}$

$$B_{\mathrm{Rx-HIVA}} = \frac{1}{2\pi C_T R_T}$$

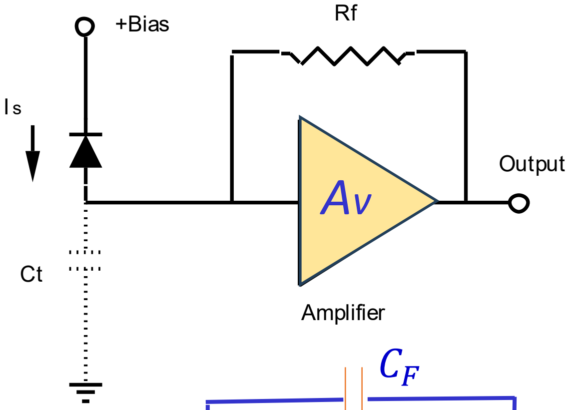
Assuming

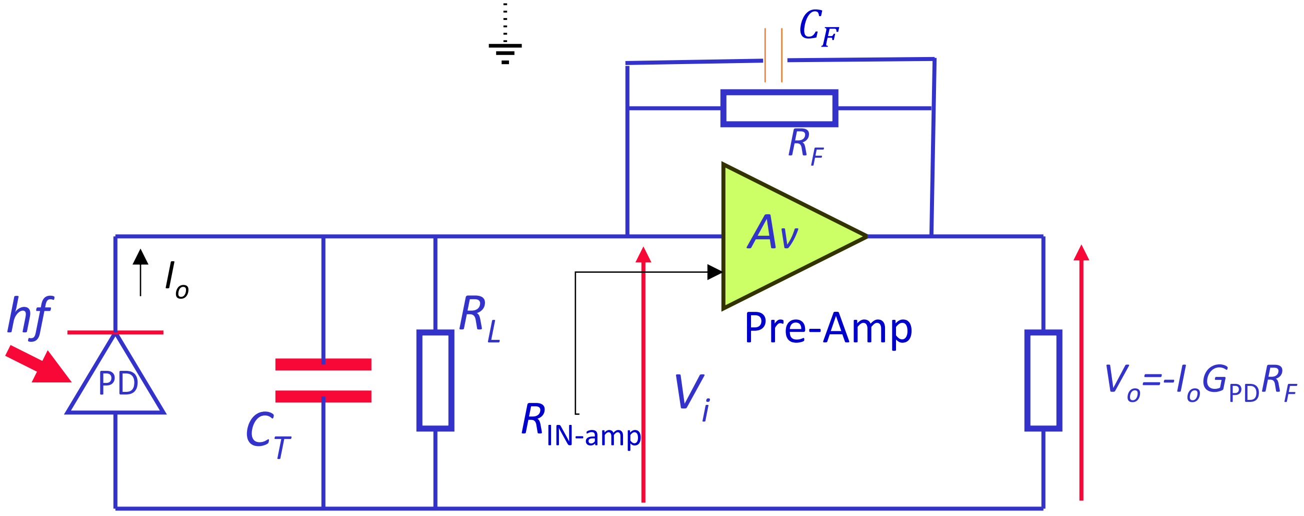
$B_{\mathrm{amp}} >> B_{\mathrm{Rx-HIVA}}$



OWC – Rx – Transimpedance Feedback Amplifier (TIFA)

- Best sensitivity → most widely used ✔
- Amplifier acts as a buffer – $V_o \propto I_s$
- Low capacitance → Wide bandwidth
- Input bandwidth is extended by the factor A_v+1
- Transimpedance is ~ R_F
- R_F can be made large → lower current noise
- With finite bandwidth amplifier, the TI transfer function is a 2nd order low-pass function → peaking in frequency domain and overshoot/ringing in time domain
- Susceptible to saturation
- No equalization
- Greater dynamic range (same gain at all frequencies)
- Reduced dynamic range
- Slightly higher noise figure than HIVA.



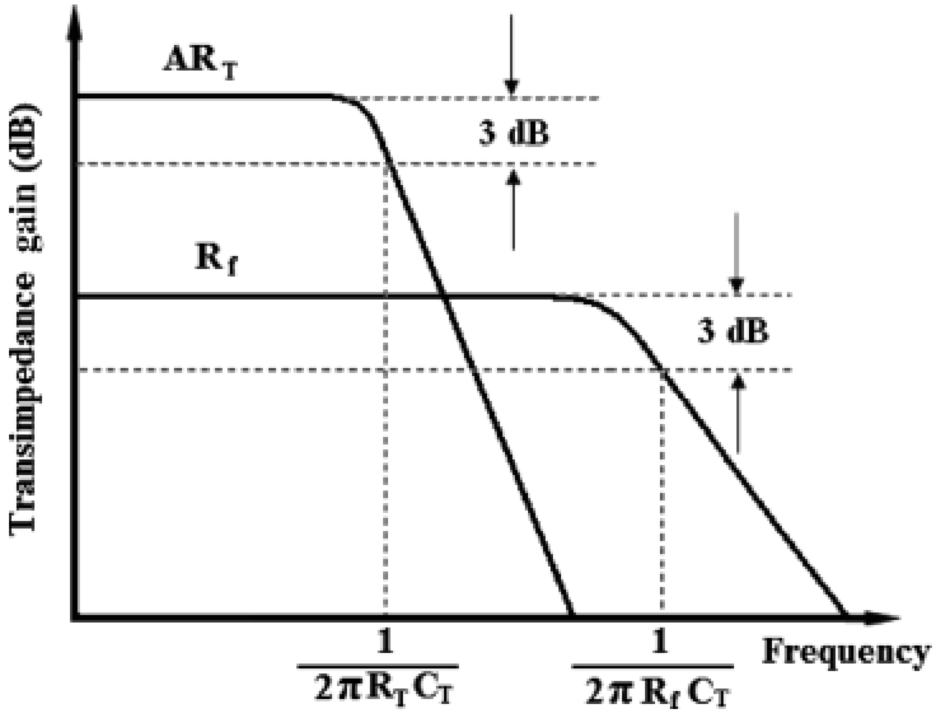


$C_T = C_{PD} + C_{amp} + C_F$ $R_{IN\text{-}amp}$ is large

Bandwidth $B_{TIFA} = \frac{Av}{2\pi C_T R_F} \cong \frac{Av}{2\pi C_F R_F}$

For equivalent circuit model for PD and amplifier see the lecture note on Optical PDs

OWC – Rx – Frequency Response



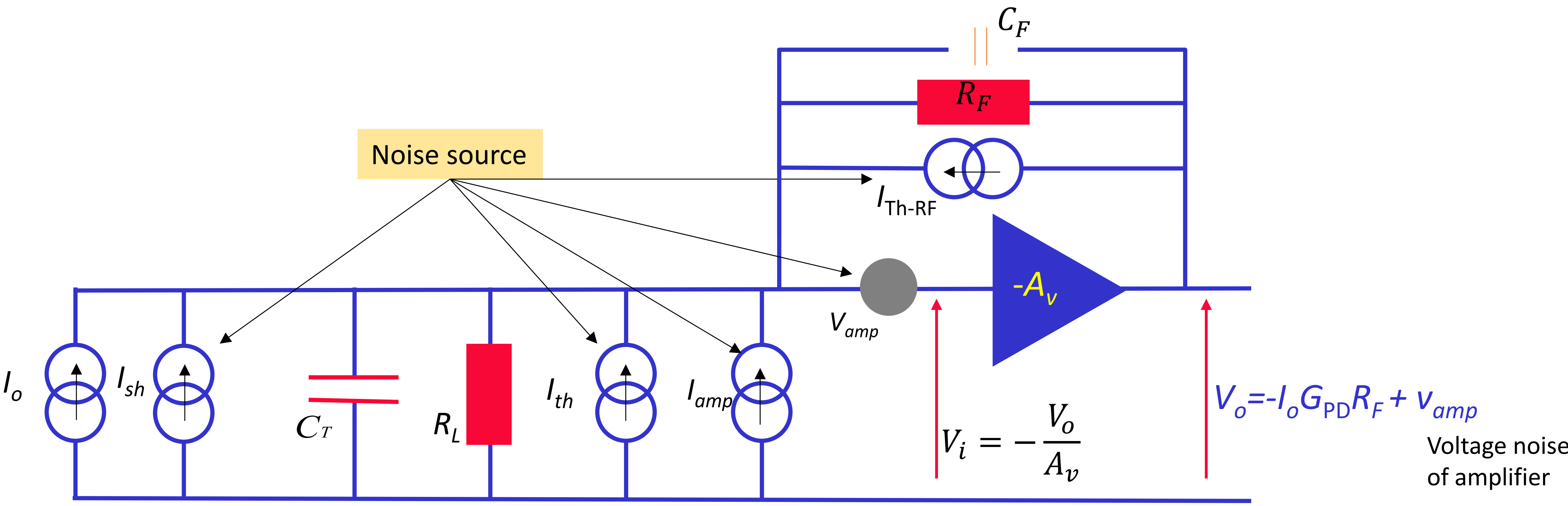
- TIFA has a lower gain and wide bandwidth.
- TIVA has a higher gain and lower bandwidth.

The gain ratio of HIVA to TIFA $R_G = A_v \frac{R_T}{R_f} \gg 1$

The bandwidth ratio of HIVA to TIFA $R_B = \frac{(1 + A_v)\, R_T}{R_f} \gg 1$

https://bdt.semi.ac.cn/library/upload/files/2022/1/1082755147.pdf

OWC – Rx – TIFA – Equivalent Circuit



$C_T = C_{PD} + C_{amp} + C_F$ $R_T = R_{PD} \,||\, R_{PD} \,||\, R_{amp} \,||\, R_F$

$$\overline{i_{sh}}^2 = 2qI_pFB \quad (\text{A}^2)$$

$$\overline{i_{th}}^2 = \frac{4KTB_{Rx}}{R_T}$$

Note, $R_L >> R_F$, therefore $\overline{i_{th}}^2 = \frac{4KTB_{Rx}}{R_F}$ and $V_o = \frac{-R_F G_{PD} I_o}{\left(1 + \frac{j2\pi f C_T R_F}{A_v}\right)}$

OWC – Rx – TIFA – Equivalent Circuit

For PIN PD, G_{PD}= 1

Amp. noise current $\overline{i_{n-\text{amp}}^2}$ } Frequency dependent noise

Total noise power [bandwidth is considered In all noise terms]

$$\overline{i_{\text{nT}}^2} = \underbrace{\overline{i_{\text{sh}}^2} + \overline{i_{\text{dc}}^2} + \overline{i_{\text{th}}^2}}_{\text{PD noise current } \overline{i_{n-PD}^2}} + \overbrace{\overline{i_{\text{amp}}^2} + \overline{v_{\text{amp}}^2}/R_F}^{\text{Amp. noise current } \overline{i_{n-\text{amp}}^2}}$$

Total input noise current $i_{n-\text{in}} = \sqrt{\overline{i_{nT}^2}}$ ⇨ Total output noise voltage $v_{n-\text{out}} = i_{n-in}R_F$

RMS noise voltage $v_{n-\text{out}-\text{RMS}} = v_{n-\text{out}}\sqrt{B_n}$ (Noise bandwidth: B_n)

OWC – Rx – TIFA – Noise

Noise is determined by

- Input capacitance $C_{in} = C_{PD} + C_{amp}$
- Feedback capacitance C_F
- Shunt resistance R_L
- Feedback resistance R_F

Shape the noise gain G_n

Cause a peak in G_n: $R_F(C_{in} + C_F)$

$$G_n = \frac{v_{n-\text{out}}}{v_{n-\text{amp}}} = \frac{R_F(C_{in} + C_F) + 1}{R_F C_F + 1}$$

Zero frequency

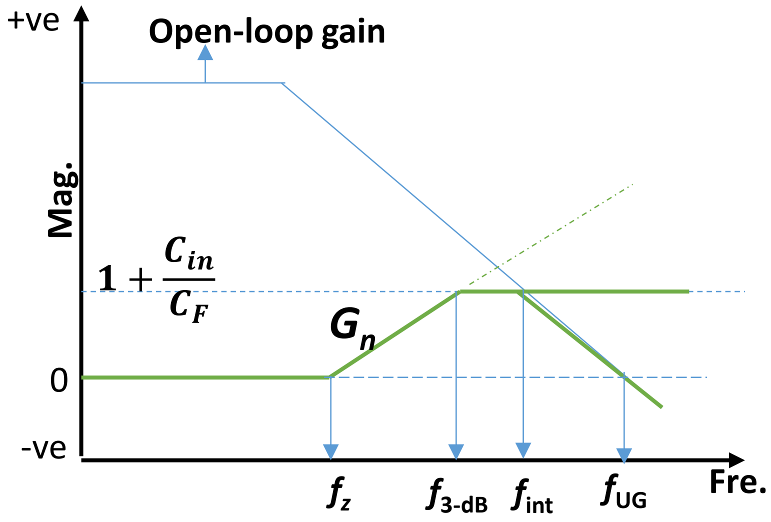
$$f_z = \frac{1}{2\pi R_F(C_{in} + C_F)}$$

Pole (3-dB) frequency

$$f_{3-\text{dB}} = \frac{1}{2\pi R_F C_F}$$

https://www.youtube.com/watch?v=sQu82i1Ba8E

OWC – Rx – TIFA – Noise



$$f_{\text{int}} = f_{\text{UG}} \frac{C_F}{C_F + C_{\text{in}}}$$

f_{UG} → Unity gain frequency

$$C_{F-\min} \cong \sqrt{\frac{C_{\text{in}}}{2\pi R_F f_{\text{UG}}}}$$

Is very small → Stable amplifier

OWC – Rx – TIFA – Noise

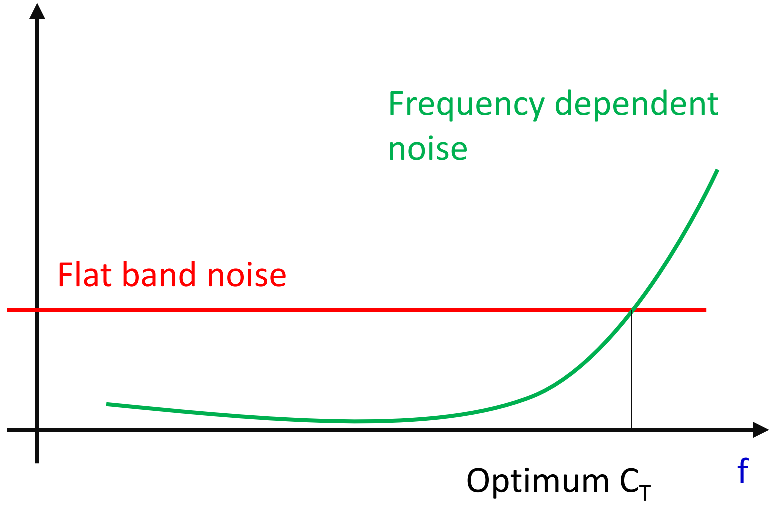
Total current noise PSD

$$i_{nT}^2 = N_{\mathrm{iT}} B_{\mathrm{Rx}} + \frac{\left(2\pi v_{\mathrm{amp}} C_T\right)^2}{3} {B_{\mathrm{Rx}}}^3$$

$C_{PD} >> C_{T,opt}$	Voltage noise dominates
$C_{PD} << C_{T,opt}$	C_{amp} becomes critical – Keep it small

$$C_{T,\mathrm{opt}} = \frac{\sqrt{3N_{\mathrm{iT}}}}{2\pi v_{\mathrm{amp}} B_{\mathrm{Rx}}}$$

Optimized to meet the flat band noise



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OCRG

OWC – Rx – TIFA – Equivalent Circuit

R_F ↑ → i_{th}^2 ↓ → B_{Rx} ↓ → Keeping B_{Rx} constant

R_F ↑ → V_o ↑ → Offsetting the effect of R_F on B_{Rx} → B_{Rx} ↑ → Keeping B_{Rx} constant

C_{PD} ↑ → Large C at the input of amplifier → Unstable amplifier

$C_F > C_{F\text{-min}}$ → Stability design margin for Amplifier

Trade-Offs in TIA Design

- $B \alpha 1 / R_F$
- $\mathcal{R} \alpha R_F$
- Overload α 1 / R_F
- $C_F > C_{F\text{-min}}$

$P_{o\text{-max}}$ for which it will deliver an acceptable BER. Overload can also be defined by an acceptable limit on jitter.

OWC – Rx – Performance Metrics - SNR

There is no universal definition of SNR, therefore, have adopt a convention for both electrical and optical SNRs:

Note:

Noise power spectral density (PSD)

Noise power $N = N_o \times B$

Signal power $P_{\text{ave}} = \frac{I}{T}\int_0^T v^2(t)dt$ Or $P = \int_{0a}^{b} PSD_s df$

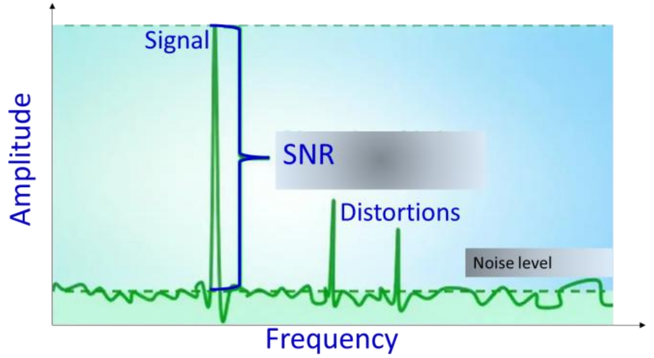
$$\text{SNR}_{\text{ele}} = \frac{\text{Avg. signal power}}{\text{Electrical noise power}} = \frac{P_{\text{avg}}}{N_{\text{ele}}}$$

Noise variance

Note: $N_{ele} = (\sigma_{ele})^2$

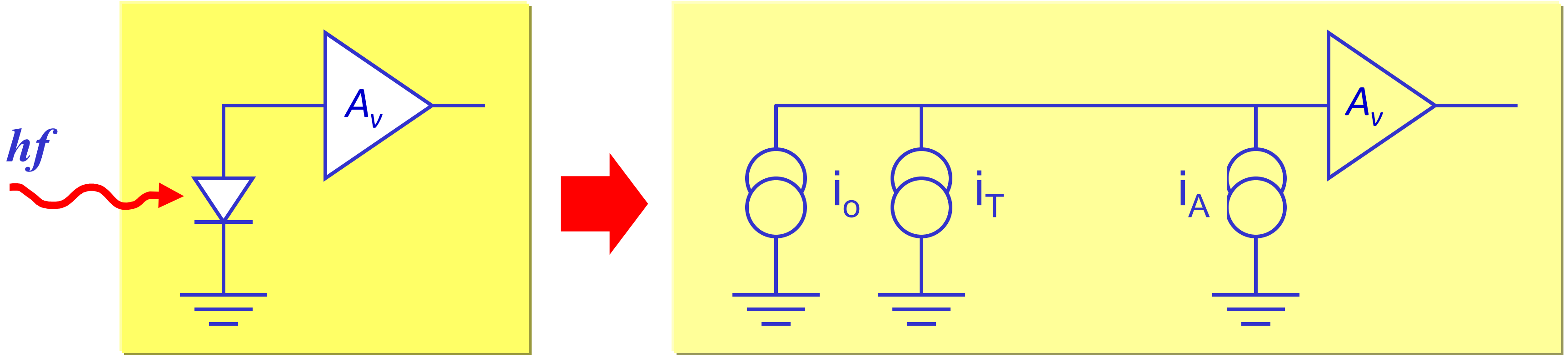
$$\text{SNR}_{\text{opt}} = \frac{\text{Avg. signal power}}{\text{Optical noise power}} = \frac{P_{\text{o}}}{N_{\text{opt}}}$$

Note: $N_{opt} = \sigma \propto P_o$



*One fundamental design limit would be for the noise at the "0" level to be negligible (i.e., $\sigma_0 = 0$ compared to the noise at the "1" level. This would be for an **ideal noiseless detector** and is called the **"shot noise limit"**. This is an ultimate goal or fundamental limit that is used as a base to compare real systems.*

OWC – Rx – PM - SNR



$$\text{SNR} = \frac{\overline{i_p}^2}{\overline{i_{\text{nT}}}^2}$$

- **PIN**

$$\text{SNR}_{\text{PIN}} = \frac{I_o{}^2}{2qB(I_p + I_{dc}) + \frac{4KTB}{R_L} + \overline{i^2}_A}$$

- **APD**

$$\text{SNR}_{\text{APD}} = \frac{G_{\text{APD}}^2 I_o{}^2}{2qB[(I_p + I_{dc})G_{\text{APD}}^2 F] + \frac{4KTB}{R_L}F + \overline{i^2}_A}$$

Note: SNR cannot be improved by amplification, since noise is also amplified!

SNR - Quantum Limit – Shot noise

$$SNR_{QL} = \frac{I_p(I_p)}{2qI_pB} = \frac{RP_o/hf}{2B} = \frac{re}{B} = \frac{n_{\text{electron}/s}}{\text{bit}/s} = \frac{n_{\text{electron}}}{\text{bit}} = N$$ Poisson

OWC – Rx – PM - SNR

Lead to ➔

For large signal level ➔ Photo current I_p ↑ ➔ Signal shot noise ↑ **Dominant** ➔

$$\mathrm{SNR_{PIN}} \cong \frac{I_p}{2qB} = \frac{\mathcal{R}P_o}{2qB}$$

For small signal level ➔ Photo current I_p ↓ ➔ Thermal noise ↑ **Dominant** ➔

$$\mathrm{SNR_{PIN}} \cong \frac{I_p^2}{4kTB}$$

For lower received $P_{\text{O-Rx}}$ ↓ ➔ Optical Rx is basically a photon counter. ➔ Outputs - statistically depending on the received number of photons in a given time interval.

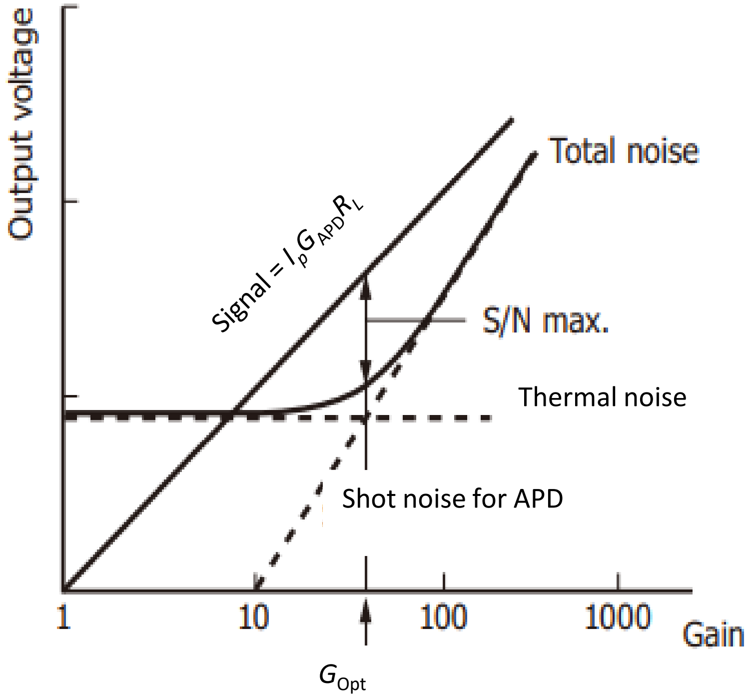
Received $P_{\text{O-Rx}}$ + Background light P_{BL} ➔ Photo current $I_p = I_{p\text{-s}} + I_{p\text{-BL}}$ ➔ BL shot noise ↑ **Dominant** ➔

$$\mathrm{SNR_{PIN}} \cong \frac{I_{p-s}^2}{2qBI_{p-\mathrm{BL}}}$$

BL is modelled as a source with a constant photon arrival rate.

OWC – Rx – PM - SNR

For APD – The shot noise could be at the same level as the thermal noise due to the internal gain → improved SNR

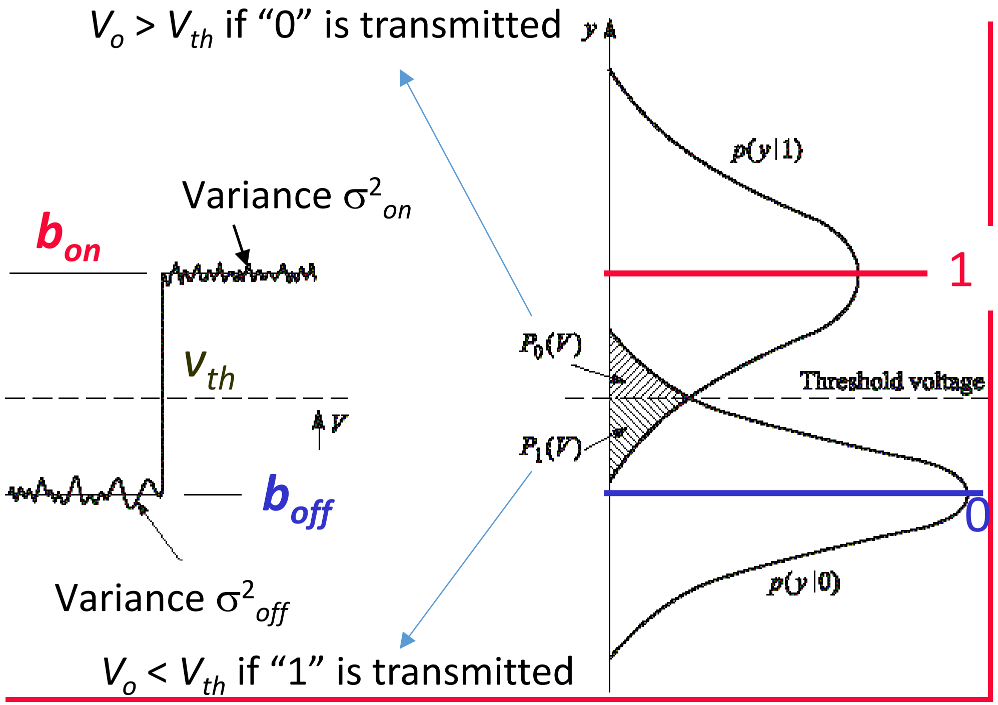


Optimum gain $G_{\text{opt}} = \left[\frac{4kT}{q(I_p + I_{\text{dc}})R_L}\right]^{\frac{1}{2+x}}$

OWC – Rx – PM - BER

Using a simple threshold detection at the Rx

Probability of Error (or bit error rate (BER)) = Probability that the output signal level (voltage) is less than the threshold when a 1 is sent + probability that the output voltage is more than the threshold when a 0 has been sent



Assuming that the probabilities of 0 and 1 pulses are equally likely, we have:

$$\text{BER} = P_e = \frac{1}{2}\left[1 - \text{erf}\left(\frac{Q}{\sqrt{2}}\right)\right]$$

$$Q = \left[\frac{v_{th} - b_{off}}{\sigma_{off}}\right] = \left[\frac{b_{on} - v_{th}}{\sigma_{on}}\right]$$

$$P_e = q_1 P_1(v_{th}) + q_0 P_0(v_{th})$$
$$= q_1 \int_{-\infty}^{v_{th}} p(y|1)dy + q_0 \int_{v_{th}}^{\infty} p(y|1)dy$$

where q_1 and q_0 are probabilities that the transmitter sends 0 and 1 respectively. Note, q_0 = 1- q_1.

OWC – Rx – SNR – PM - BER

For

- $\sigma_{off} = \sigma_{on} = \sigma$ i.e., the RMS noise
- b_{on} = V, and b_{off} = 0
- Thus, $v_{th} = V/2$ and $Q = V/2\sigma$

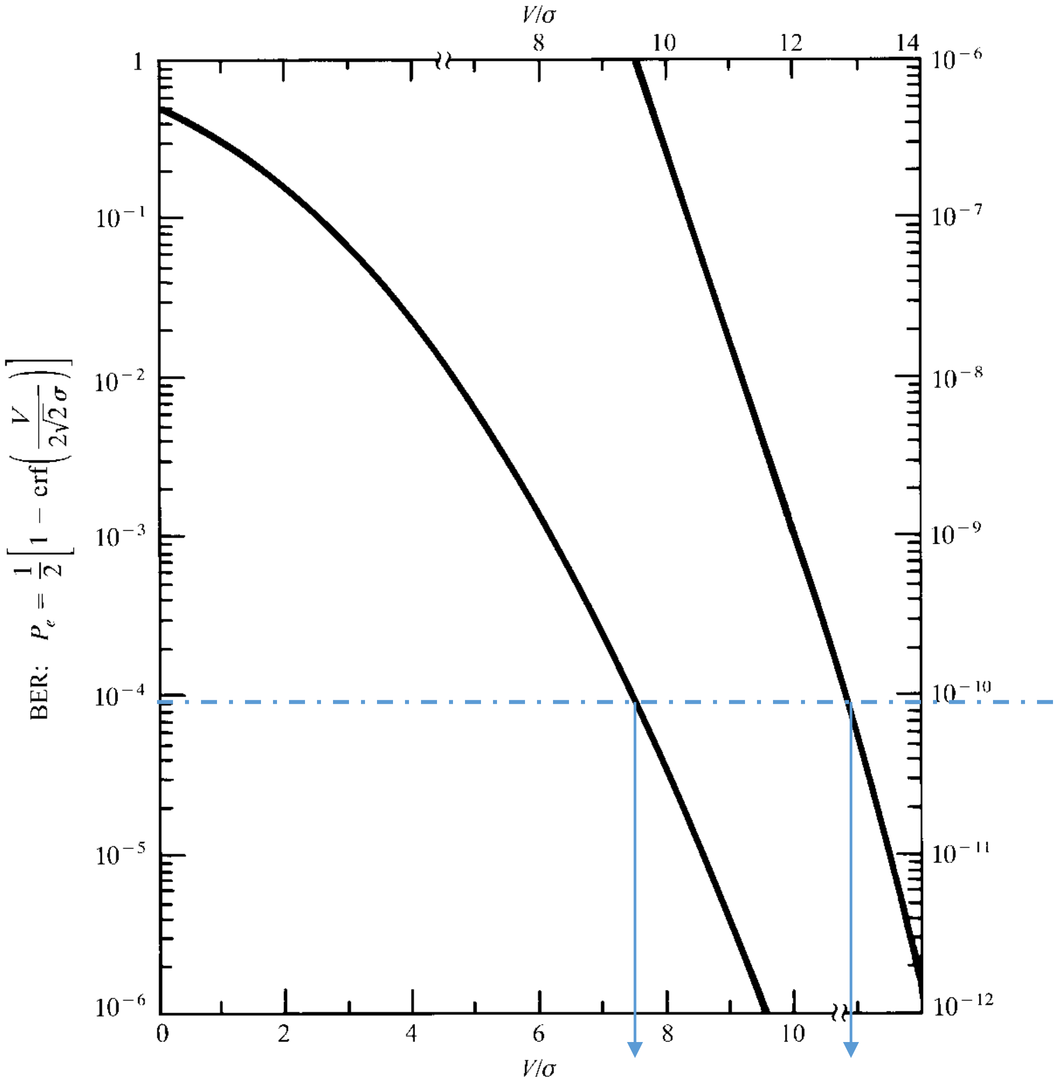
Therefore: $$\mathrm{BER} = P_e = \frac{1}{2}\left[1 - \mathrm{erf}\left(\frac{V}{2\sqrt{2}\sigma}\right)\right]$$

In terms of power signal-to-noise ratio (SNR), we have:

$$BER = P_e = \frac{1}{2}\left[1 - \mathrm{erf}\left(0.345\sqrt{SNR}\right)\right]$$

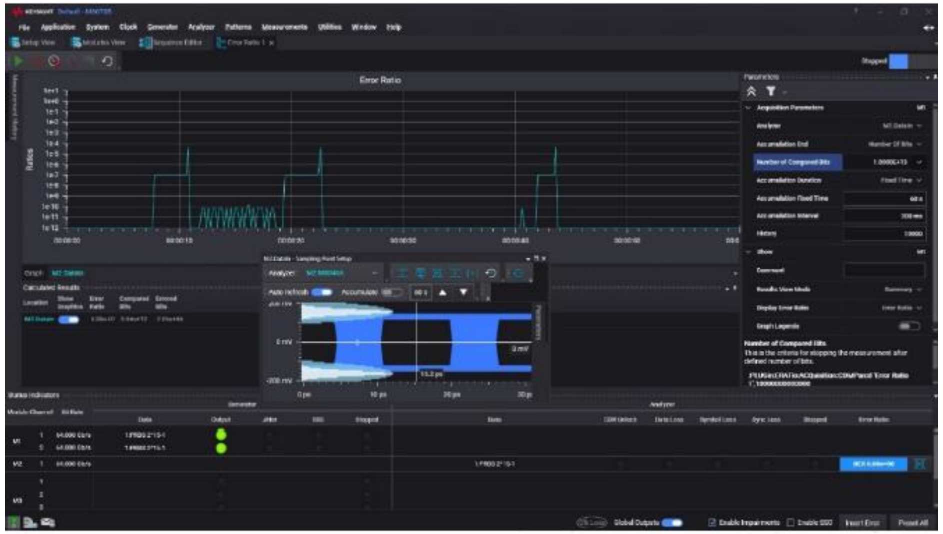
BER can also be defined in terms of Energy per bit E_b and noise power spectral density N_o :

$$BER = \frac{1}{2}\left[1 - \mathrm{erf}\left(\sqrt{\frac{E_b}{N_o}}\right)\right]$$



G Keiser , 2000

OWC – Rx – SNR – PM – BER Measurement



With Real-Time Oscilloscope Integrated in M8070B Software
Keysight Technologies

For BER measurement:

↓

Use a PRBS test pattern generator

↓

Use a real-time digital oscilloscope to capture and stores at least two error-free copies of an identical repeating patterns

↓

Compares the subsequently measured bit patterns with those saved patterns

↓

Determines the BER

OWC – Rx – SNR – PM - BER

Optical network

Target BER= $\leq 10^{-12}$

Bit rate R_b dependency

For 1 Gbps → No. of errors / min = ~0.06

For 100 Gbps → No. of errors / min = ~6

- There is a big difference.
- So, how to ensure that 1 Gbps measurement is as reliable as 100 Gbps.

Need to consider the Confidence Level (CL) – A statistical value

$$CL = 1 - e - N_{\text{bits}} * \text{BER}$$

Then, determine the number of bits required for a given BER – Use the Poisson distribution

$$N_{\text{bits}} = -\frac{\ln(1-\text{CL})}{\text{BER}}$$

Next, determine the measurement time $T_m = N_{\text{bits}} / R_b$

https://www.keysight.com/in/en/assets/7018-06435/white-papers/5992-3524.pdf

OWC – Rx – SNR – PM - BER

Confidence level (CL) %	Required bits for BER, e.g., ≤ 10^{-12}
90	2.3×10^{12}
95	3×10^{12}
99	4.6×10^{12}
99.9	6.9×10^{12}

$$N_{\text{bits}} = -\frac{\ln(1-\text{CL})}{\text{BER}}$$

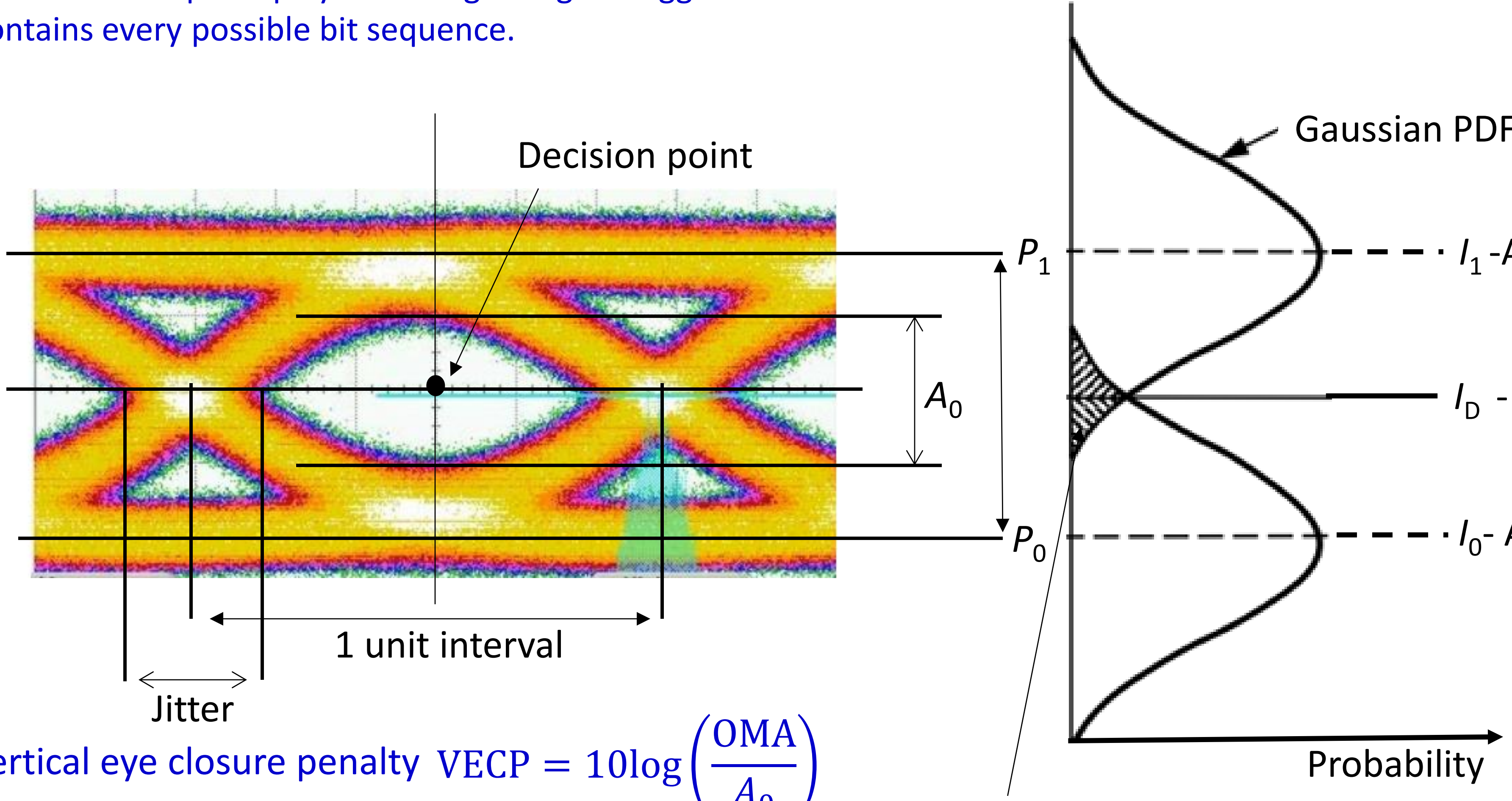
Data rate	Measurement time T_m
1 Gbps	38.5 m
100 Gbps	23 s

$$T_m = N_{bits} / R_b$$

OWC – Rx – SNR – PM – Eye Diagram

The eye diagram. It:

- provides a quick and intuitive method to assess the quality of a digital communications
- is an oscilloscope display of the digital signal triggered at the clock rate or a divided clock rate
- contains every possible bit sequence.



$$Q = \frac{|I_D - I_1|}{\sigma_1} = \frac{|I_D - I_0|}{\sigma_0}$$

Vertical eye closure penalty $\mathrm{VECP} = 10\log\left(\frac{\mathrm{OMA}}{A_0}\right)$

$\mathrm{OMA} = P_1 - P_0$

https://e2e.ti.com/cfs-file/__key/telligent-evolution-components-attachments/00-138-01-00-01-32-72-02/Optical-Receivers.pdfq

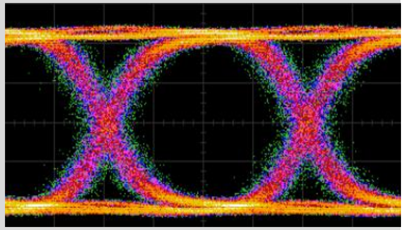
OWC – Rx – SNR – PM – Eye Diagram - Jitter

- Jitter is the variation in the data transition instant (1 to 0 or 0 to 1) with respect to its expected position.
- The Rx specifications will specify certain tolerance of the amount of jitter across a certain jitter modulation range.

Jitter $j_T = j_R + j_D$

Random jitter j_R

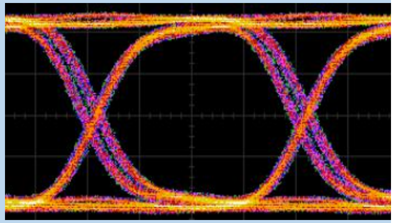
Unpredictable
Gaussian probability density function
Unbounded
Typically measured as a rms value
Due to electronic or optical noise



- Thermal noise
- Shot noise
- Flicker noise

Deterministic jitter j_D

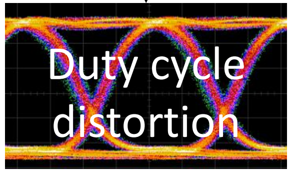
Predictable
Bounded
Typically measured as a peak- to -peak value



Periodic jitter

Due to Unwanted modulation from power supplies or EMI
Not dominant in optical transceivers

Data dependent jitter



Intersymbol interference (Pulse spreading)

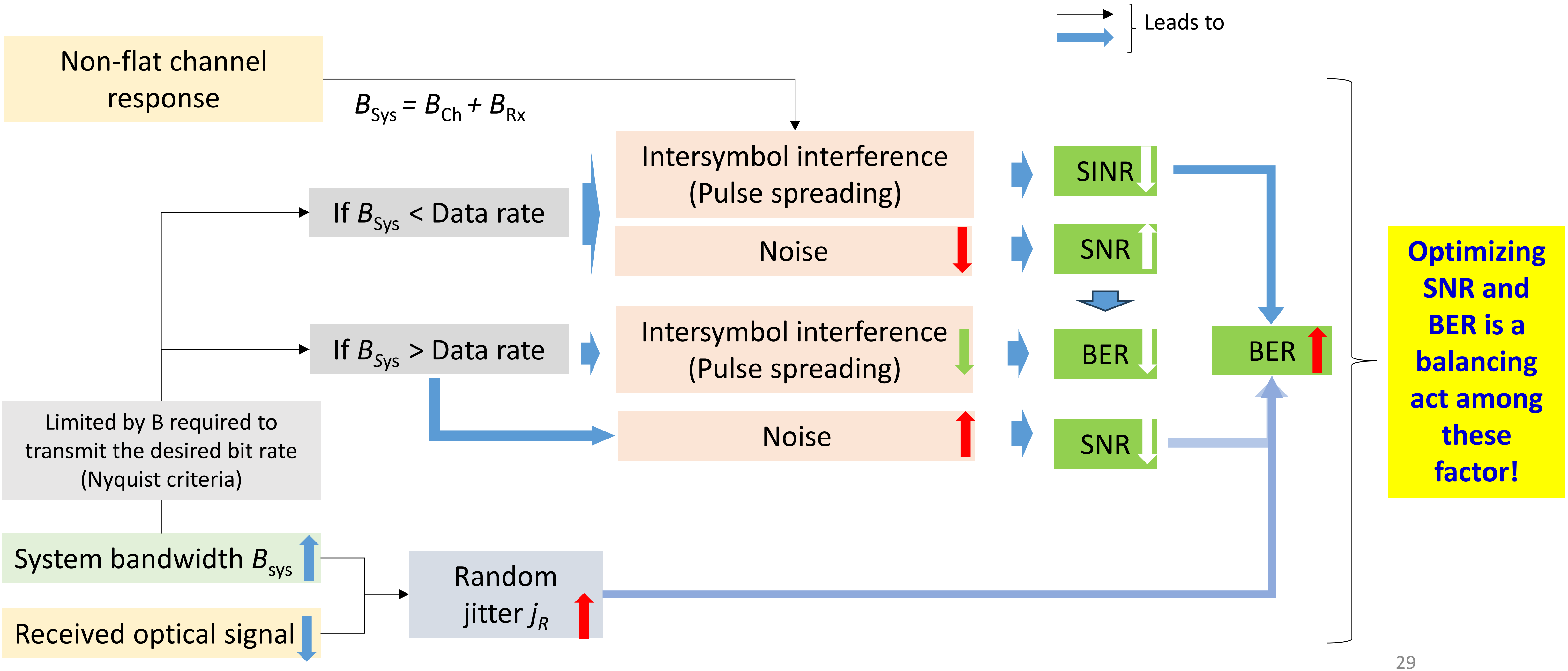
Unbounded uncorrelated jitter

Crosstalk

Limited transmission link span

OWC - VLC - Rx

Performance indicators



OWC - VLC - Rx

$$\mathrm{BER} = \frac{1}{2}\left[1 - \mathrm{erf}\left(\sqrt{\frac{E_b}{N_o}}\right)\right]$$

$$\mathrm{SINR}_{\mathrm{opt}} = \frac{P_o}{I_i + N_{\mathrm{opt}}}$$

$$\mathrm{SINR}_{\mathrm{ele}} = \frac{(\mathcal{R}P_o)^2}{(I_i)^2 + N_{\mathrm{ele}}}$$

I_i = Interference intensity from the i^{th} channel

$N_{ele} = B \times N_o$

How to improve BER ?

- N ↓ → BER ↓
  - But, limited by Nyquist criteria $B_{sig} =< B_{ch}$ Or $B_{sig} = B_{Rx}$
- P_{Tx} ↑ → Inter-channel interference → SINR → BER ↑
- R_b ↓ → E_b ↓ → BER ↑
  - → Channel capacity ↓

Optimizing E_b/N_o is a balancing act among these factor!

Thank you!