Dual-rate burst upstream

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Introduction

- An Ad-hoc was formed to consider the burst mode reception at 2 bit rates problem
- This presentation discusses the basic design of optical receivers, to develop scaling rules for bandwidths and design variants
- This should allow the membership to make educated judgments when choosing alternatives that impact speed/sensitivity

Photodetectors

- PIN diode
  - Responsivity (A/W)
  - Dark current (nA)
  - Intrinsic capacitance (pF)
  - Transit time (ps)
- APD
  - All the above, plus…
  - Gain ()
  - Excess Noise Factor ()

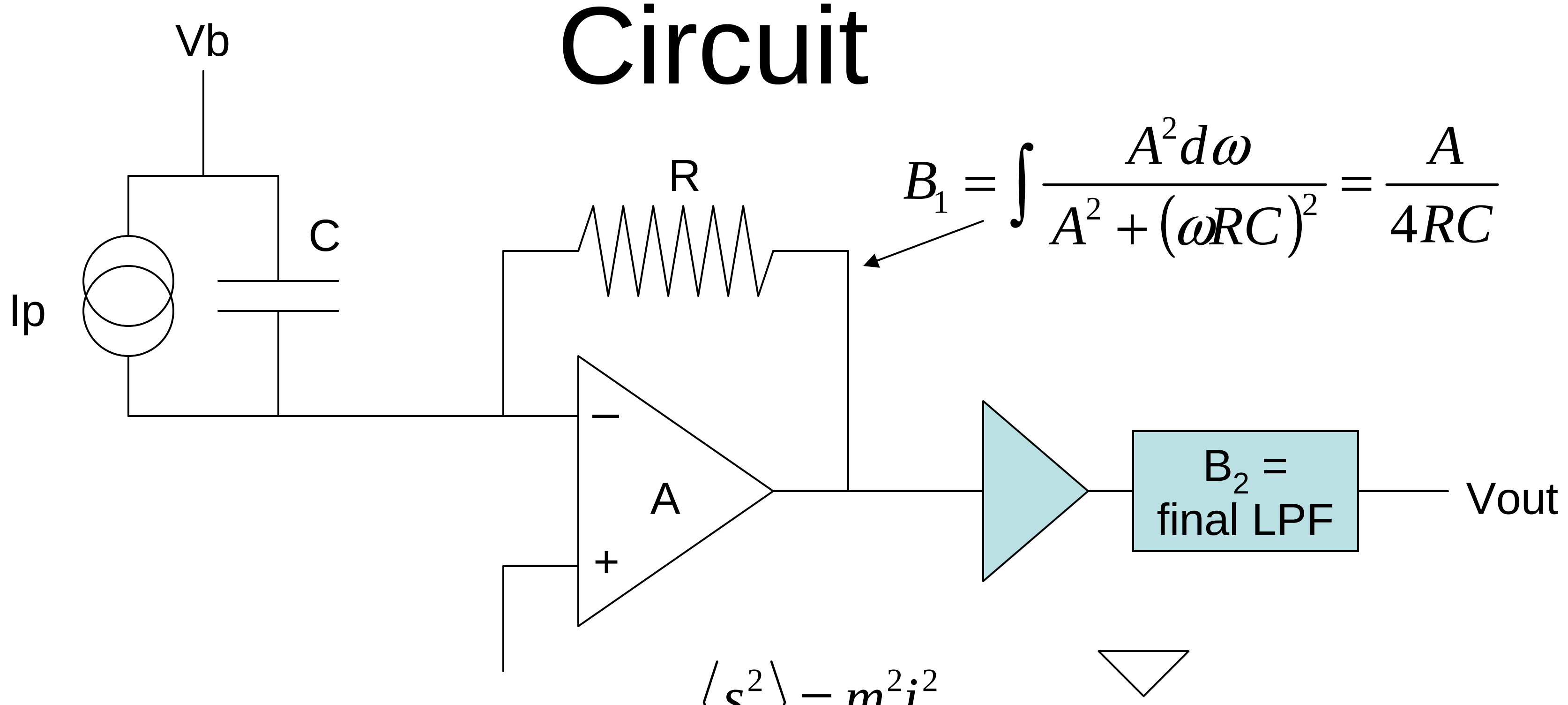
Noise, and the first amplifier

- There are several noise sources
  - RIN noise (from the transmitter)
  - Shot noise (from signal and dark current)
  - Excess noise (from avalanche gain process)
  - Thermal noise (from the circuit itself)
- In PIN receivers, thermal noise dominates
- In APDs, shot and excess noise play a role
- The SNR out of the first amplifier tells the story in any (properly designed) circuit

Trans-Impedance Amplifier

- All modern optical PMDs use this topology
- The key idea is that the amplifier’s gain reduces the effective impedance as regards the speed of response
- Thus, a higher impedance value can be used (better SNR) while maintaining a high response speed (faster)

Circuit



$$B_1 = \int \frac{A^2\,d\omega}{A^2 + \left(\omega RC\right)^2} = \frac{A}{4RC}$$

$$\left\langle s^2 \right\rangle = m_s^2 i_s^2$$

$$\left\langle n^2 \right\rangle = \left(\cancel{RIN^2 i_s^2} + \frac{4kT}{R} F_N + 2 e i_p M^2 F_A \right) B_2$$

$$i_p = i_s + i_d = \Re P_s \cancel{+ i_d}$$

Signal to Noise Ratio

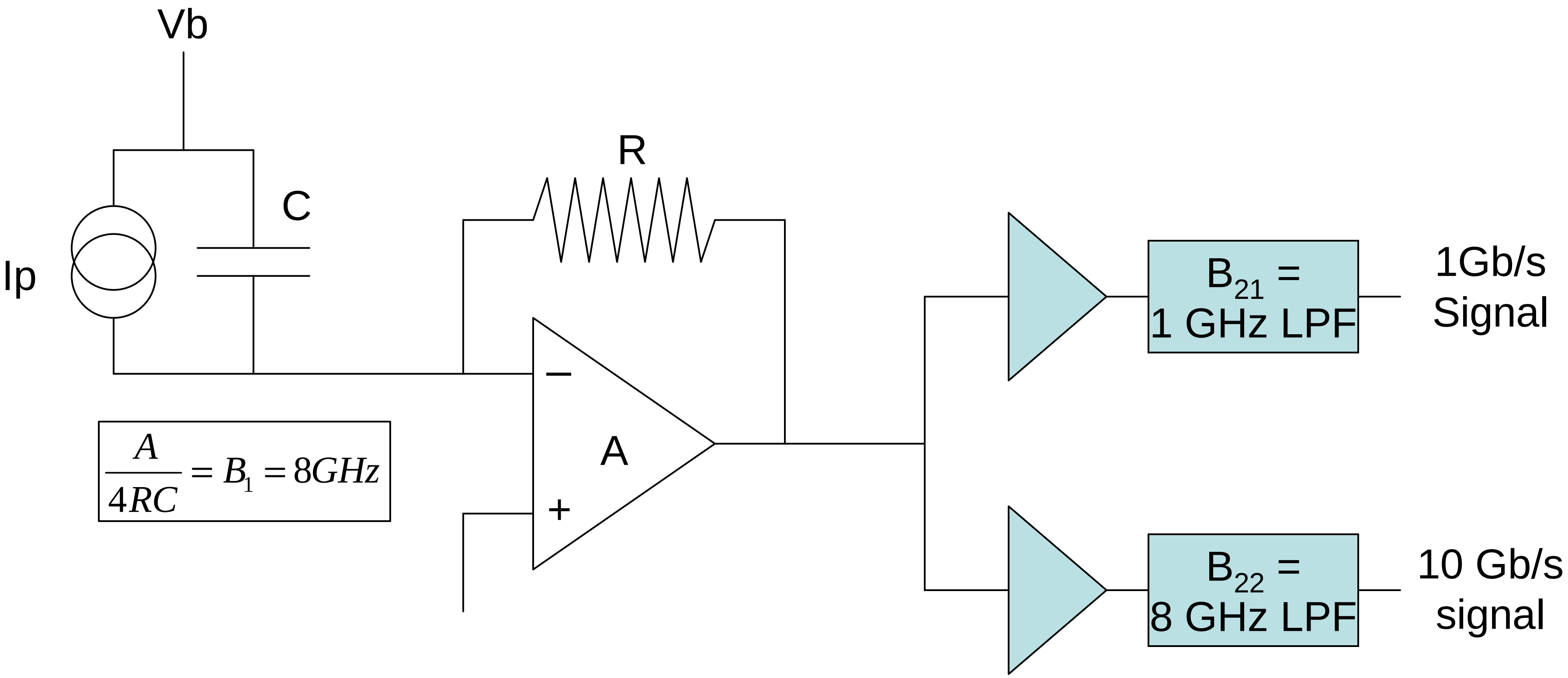
$$\boxed{\frac{\langle s^2 \rangle}{\langle n^2 \rangle} = \frac{(m_s \Re M P_s)^2}{(2e\Re M^2 F_A P_s + 4kTF_N / R)B_2} = \frac{(m_s \Re M P_s)^2}{(2e\Re M^2 F_A P_s + 16kTCB_1 F_N / A)B_2}}$$

- When thermal noise limited, $\frac{\langle s^2 \rangle}{\langle n^2 \rangle} = \frac{R(m_s \Re M P_s)^2}{4kTF_N B_2} = \frac{A(m_s \Re M P_s)^2}{16CkTF_N B_1 B_2}$
  - SNR ~ $P_s^2 R/B_2$ ~ (P_s/B_1) (P_s/B_2)
  - For a fixed SNR: P_s~$(B_1B_2)^{1/2}$
- When shot noise limited, $\frac{\langle s^2 \rangle}{\langle n^2 \rangle} = \frac{\Re P_s m_s^2}{2eF_A B_2}$
  - SNR ~ P_s/B_2
  - For a fixed SNR: P_s~B_2

The dual-rate problem

- Signals come in at different rates
- OLT must either
  - Parallel process signal at both speeds (and decide later which was right), or
  - Serially process signals at one speed
- This decision has to do with choice of detector technology, and whether we are thermal noise limited or shot noise limited

Parallel PMD Circuit

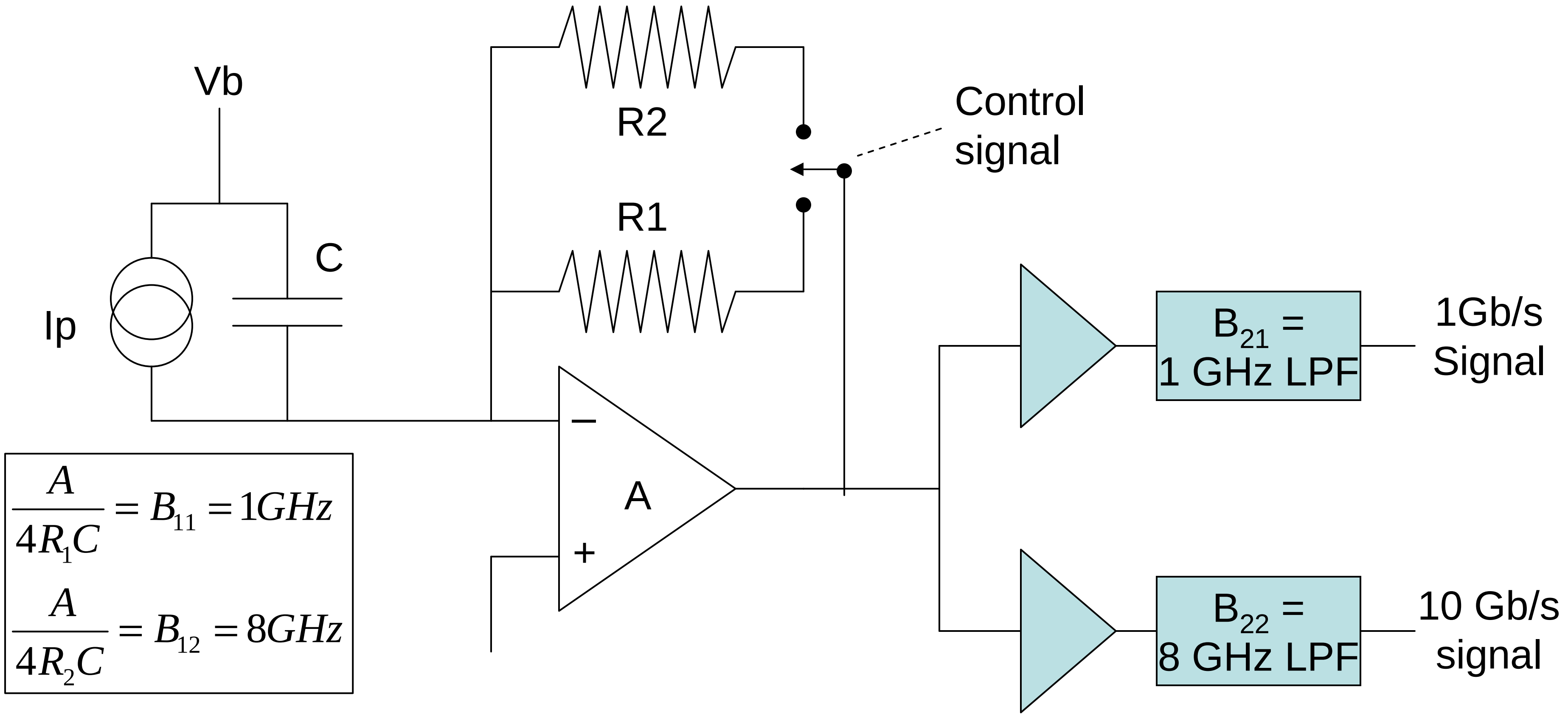


$$\frac{A}{4RC} = B_1 = 8GHz$$

Thermal-limited: $SNR_{1G} = C_{th}\frac{P_s^2}{B_1 B_{21}}$ $\quad SNR_{10G} = C_{th}\frac{P_s^2}{B_1 B_{22}}$

Shot-limited: $SNR_{1G} = C_{sh}\frac{P_s}{B_{21}}$ $\quad SNR_{10G} = C_{sh}\frac{P_s}{B_{22}}$

Serial PMD Circuit



$$\frac{A}{4R_1C} = B_{11} = 1GHz$$

$$\frac{A}{4R_2C} = B_{12} = 8GHz$$

Thermal-limited: $SNR_{1G} = C_{th}\frac{P_s^2}{B_{11}B_{21}}$ $\qquad SNR_{10G} = C_{th}\frac{P_s^2}{B_{12}B_{22}}$

Shot-limited: $SNR_{1G} = C_{sh}\frac{P_s}{B_{21}}$ $\qquad SNR_{10G} = C_{sh}\frac{P_s}{B_{22}}$

Comparison of Serial and Parallel

- In shot-limited case, there is no difference
  - Pre-amp circuit does not impact SNR
- In thermal-limited case, the Parallel circuit 1G SNR is degraded by factor $B_1/B_{12} = 8$
  - Constant SNR power penalty = 4.5 dB

APD receivers

- Practical APD receivers fall midway between these two extremes
- The setting of the multiplication factor M balances thermal noise versus excess noise (akin to shot noise)
- So, in APD receivers, we have THREE effective bandwidths to play with
  - B_2: The bandwidth of the post-amp (easy)
  - B_1: The bandwidth of the pre-amp (moderate)
  - B_0: The 'bandwidth' of the M setting (hard to do)

SNR for APD with an optimized gain

$$\left\{\begin{array}{l} \dfrac{\langle s^2\rangle}{\langle n^2\rangle} = \dfrac{(m_s \Re M P_s)^2}{\left(2e\Re M^2 F_A P_s + 4kTF_N / R_1\right)B_2} \\[2ex] M_{Opt} \approx \sqrt[3]{\dfrac{4kTF_N}{K_A \underline{eR}_0 \Re P_s}}, \qquad F_A \approx K_A M \\[2ex] \underline{2e\Re M}^2_{Opt} F_{A,Opt} \underline{P_s} \approx 2\dfrac{4kTF_N}{eR_0} \end{array}\right.$$

This resistance would be the ideal TIA resistance for whatever speed we are optimizing.

$$\left.\frac{\langle s^2\rangle}{\langle n^2\rangle}\right|_{Opt} = \frac{(m_s \Re P_s)^2}{\left(\dfrac{2}{R_0}+\dfrac{1}{R_1}\right)\cdot 4kTF_N \cdot B_2}\left(\frac{4kTF_N}{K_A e R_0 \Re P_s}\right)^{2/3}$$

$$\left.\frac{\langle s^2\rangle}{\langle n^2\rangle}\right|_{Opt} = \frac{m_s^2 \Re^{4/3}}{\left(4kTF_N K_A^2 e^2\right)^{1/3}} \frac{1}{\left(\dfrac{2}{R_0}+\dfrac{1}{R_1}\right)\cdot R_0^{2/3}} \frac{P_s^{4/3}}{B_2}$$

Converting Resistances into Bandwidths

$$\boxed{R_0 = \frac{A}{4CB_0}, \quad R_1 = \frac{A}{4CB_1}}$$

$$\left.\frac{\langle s^2\rangle}{\langle n^2\rangle}\right|_{Opt} = \frac{m_s^2 \Re^{4/3}}{\left(4kTF_N K_A^2 e^2\right)^{1/3}} \frac{1}{\left(\frac{2}{R_0}+\frac{1}{R_1}\right)\cdot R_0^{2/3}} \frac{P_s^{4/3}}{B_2}$$

$$= \frac{m_s^2 \Re^{4/3}}{\left(4kTF_N K_A^2 e^2\right)^{1/3}} \left(2\frac{4CB_0}{A}+\frac{4CB_1}{A}\right)\left(\frac{A}{4CB_0}\right)^{2/3} \frac{P_s^{4/3}}{B_2}$$

$$= \frac{m_s^2 \Re^{4/3}}{\left(4kTF_N K_A^2 e^2\right)^{1/3}} \left(\frac{A}{4C}\right)^{1/3}\left(\frac{B_0^{2/3}}{2B_0+B_1}\right) \frac{P_s^{4/3}}{B_2}$$

$$= \frac{m_s^2 \Re^{4/3}}{\left(4kTF_N K_A^2 e^2\right)^{1/3}} \left(\frac{A}{4C}\right)^{1/3}\left(\frac{B_0^{2/3}B_1^{1/3}}{2B_0+B_1}\right) \frac{P_s^{4/3}}{B_1^{1/3}B_2}$$

$$= C_{Opt}\left(\frac{B_0^{2/3}B_1^{1/3}}{2B_0+B_1}\right) \frac{P_s^{4/3}}{B_1^{1/3}B_2}$$

Sensitivity as a function of the three bandwidths

- For an B_0 Gbit/s optimized APD:

$$SNR \sim \left(\frac{B_0^{\frac{2}{3}} \cdot B_1^{\frac{1}{3}}}{2B_0 + B_1} \right) \cdot \left(\frac{P_s^{\frac{4}{3}}}{B_1^{\frac{1}{3}} B_2} \right)$$

  - For fixed *SNR*:

$$P_s \sim \left(\frac{2B_0 + B_1}{B_0^{\frac{2}{3}} \cdot B_1^{\frac{1}{3}}} \right)^{\frac{3}{4}} \cdot \left(B_1 \cdot B_2^3 \right)^{\frac{1}{4}} = \left(\frac{2B_0 + B_1}{B_0^{\frac{2}{3}}} B_2 \right)^{\frac{3}{4}}$$

Receiver Topologies

	1G Mode			10G Mode			Sensitivity	
Topology	APD BW	TIA BW	Filter BW	APD BW	TIA BW	Filter BW	Ratio (dB)	Notes
APD full serial (dual control)	1	1	1	8	8	8	9	Ideal, quite hard to do
APD half serial (controlled TIA)	8	1	1	8	8	8	7.9	1dB imperfect, moderate to do
APD half serial (controlled Bias)	1	8	1	8	8	8	5.1	4dB imperfect, hard to do
APD parallel	8	8	1	8	8	8	6.8	2dB imperfect, easy to do
PIN serial	n/a	1	1	n/a	8	8	9	Ideal, but insensitive
PIN Parallel	n/a	8	1	n/a	8	8	4.5	4.5dB imperfect, and insensitive

Achieving the 29 dB budget

- The 29 dB budget of 1G-EPON is achieved with -27.6 dBm OMA (this is -29.7 dBm sensitivity at ER=10dB)
- Scaling this to 10G, we obtain

Topology	10G sensitivity
Fully serial	-20.7 dBm
Half serial	-21.8 dBm
Parallel	-22.9 dBm

- None of these seem unbelievable
- Parallel receiver may squeeze margins

Conclusions

- We can utilize serial and parallel configurations with APDs for upstream 10G/1G coexistence
  - The parallel configuration with 10G optimized APD is simpler compared to serial configuration
  - Half-serial configuration provides about 1 dB more sensitivity in 1G mode
- But we need to realize comparatively higher sensitivity receivers or higher power transmitter to realize 29 dB CIL even if we apply FEC to 10G receivers