

OPTICAL RECEIVER OPERATION

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Optical Receiver Operation

Optical receiver consist of:

- 1. Photodetector**
- 2. Amplifier**
- 3. Signal Processing circuitry**

Receiver Task:

1. Converting the **optical energy** emerging from the end of a fiber into **electrical signal**.
2. **Amplifying** the signal
3. **Signal processing** by electronic circuit following the receiver amplifier

Optical Receiver Operation

Noise role in receiver:

various noises and distortions will unavoidably be introduced due to **imperfect component responses**. This can lead to **errors in the interpretation** of the received signal.

Noise considerations are thus **important in the design of optical receivers**, Since the noise sources operating in the receiver generally **set the lowest limit for the signal that can be processed**.

Optical Receiver Operation

Performance Measuring:

The most meaningful criterion for measuring the performance of a **digital communication** system is the average error probability.

In an **analog system** the fidelity criterion usually is specified in terms of a peak **signal-to-noise ratio**.

Fundamental Receiver Operation

The design of optical receiver is much **more complicated** than that of an **optical Transmitter**.

Why?

Because the:

- 1. Receiver has to detect weak signal.**
- 2. Receiver has to detect distorted signal.**
- 3. Decision making on the basis of amplified and reshaped version of distorted signal.**

What happens to a signal as it is sent through an optical fiber Link? (see next)

Digital Signal Transmission

One of the simplest techniques for sending data is **amplitude shift keying (ASK) or on off keying (OOK)**.

Voltage level is switched between two values, which are usually on and off.

Signal path through an optical data link:

1. Transmitter

The function of the optical transmitter is to convert the **electrical signal to an optical signal**.

Directly modulating the **light source drive current** with the **information stream** to produce a varying optical output.

Signal path through an optical data link:

Optical signal emerging from LED or Laser transmitter:

1 is represented by a pulse of optical power (light) of duration T_b

0 is represented by the absence of any light.

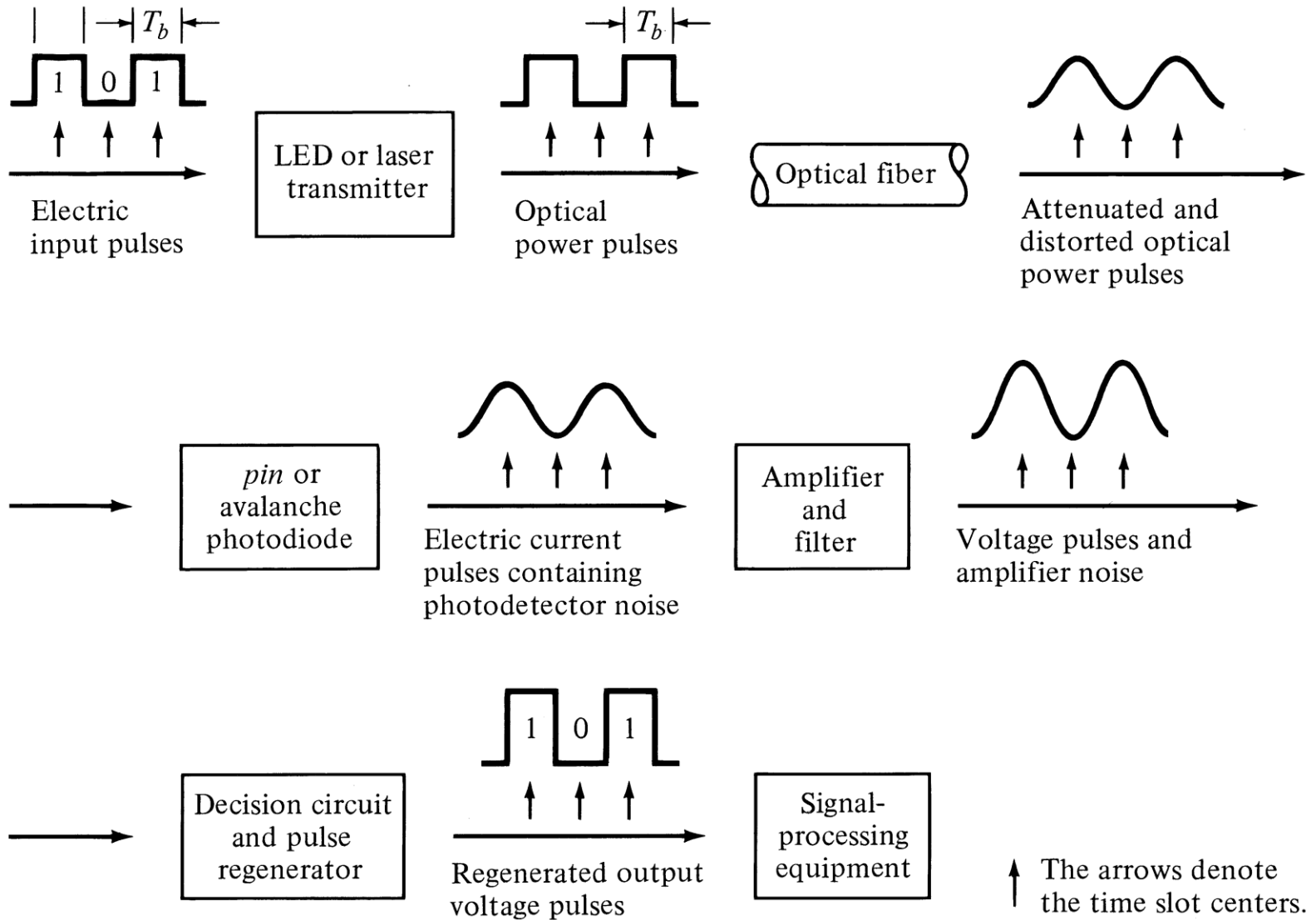
2. Fiber

The optical signal that is coupled from the light source to the fiber becomes attenuated and distorted as it propagated along the fiber waveguide.

3. Receiver

Upon arriving at the end of a fiber, a receiver converts the optical signal back to the electrical format.

Signal path through an optical link



Digital Signal Transmission

Basic components of an optical receiver:

1. Photodetector:

The first element is either a **pin or avalanche photodiode**. It produces an **electric current** that is **proportional to the received power level**.

2. Front end amplifier:

As the electric current is very weak , a front end amplifier is used to **boost it to a level** that can be used in **next electronic components**

Basic components of an optical receiver:

3. Low pass filter:

After the electric signal produced by the photodiode is amplified, it passes through the low pass filter **to reduce the noise that is outside the signal bandwidth**.

This filter thus **defines the receiver bandwidth**.

Minimize the effect of **intersymbol interference (ISI)**.

Equalization: Reshape the pulses that have become distorted (pulse spreading) as they traveled through the fiber.

4. Sampling circuit:

It samples the signal level at the mid point of each time slot

Basic components of an optical receiver:

5. Decision circuit

It **compares the samples** with a certain reference voltage known as the threshold level.

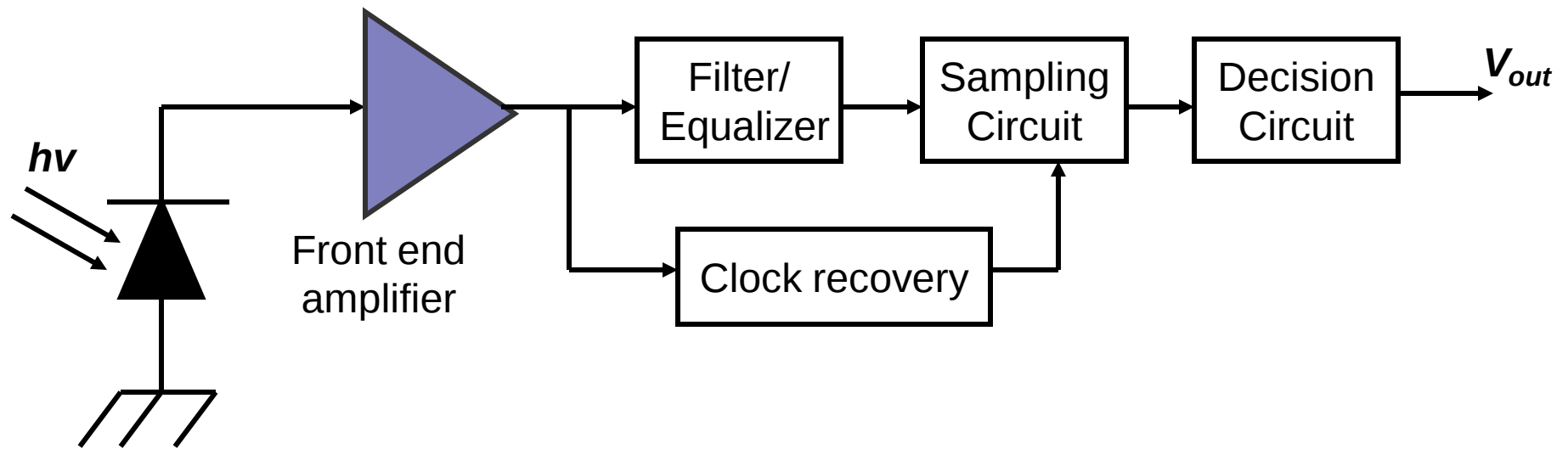
If the received signal level is **greater than the threshold** level, **1** is received.

If the received signal level is **below the threshold level**, **0** is received.

6. Clock recovery or timing recovery

To accomplish bit interpretation, the receiver must know **where the bit boundaries** are.

This is done with the assistance of **periodic waveform** called clock, which has the **periodicity equal to the bit interval**.



Photodetector

The basic section of an optical receiver

Error sources

Errors in the detection mechanism can arise from **various noises** and **disturbances** associated with the signal detection system.

Noise:

Unwanted components of an electric signal that tend to disturb the transmission and processing of the signal in a physical system, **over which we have incomplete control.**

External Noise:

The noise source which is external to the system, for example, **Electric power lines, motors, radio transmitters, lightning.**

Internal Noise:

The noise source which is internal to the system, for example, **thermal noise, shot noise, dark current** etc

Shot Noise source

1. **Random arrival rate of signal photons** produces a quantum or shot noise at the photodetector.
2. Shot noise also arises from the **statistical nature of the multiplication process in AVPD.**

Thermal Noise source

1. Thermal noise arising from the **detector load resistor**
2. In **amplifier electronics**

Dark current

The photodiode dark current arises from **electrons and holes** that are **thermally generated at the pn junction** of the photodiode. **Small as compared to other noises.**

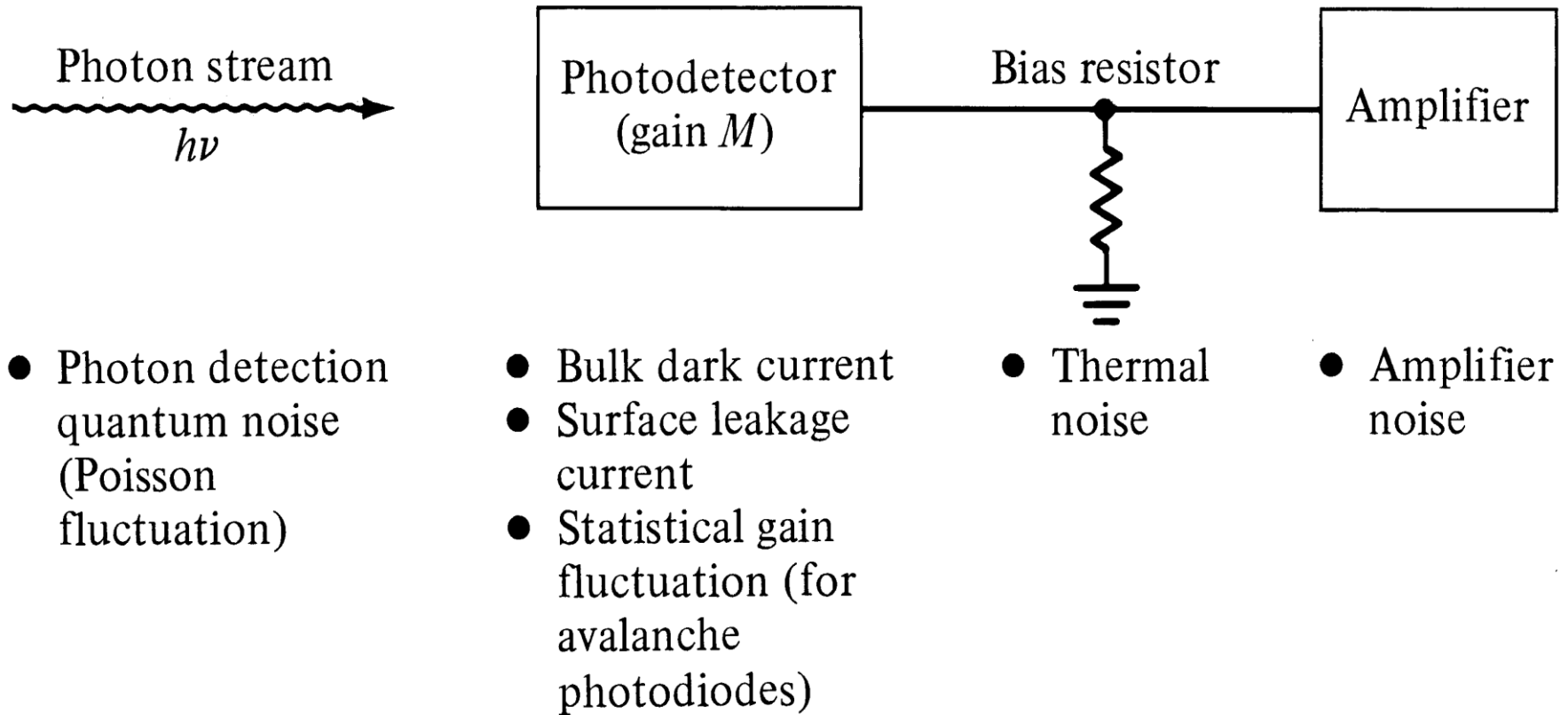
Thermal noises are of a Gaussian nature , and can be treated by standard techniques.

The analysis of the noises and the resulting **error probabilities associated** with the **primary photocurrent generation** and the **avalanche multiplication** are complicated, since **neither of these processes is Gaussian**. (instead, time varying Poisson process)

A **further error source** is attributed to **intersymbol interference (ISI)**, which results from **pulse spreading in the optical fiber**.

Because of the pulse spreading induced by the fiber, some of the **transmitted energy** will progressively **spread into neighboring time slots** as the pulse propagates along the fiber.

Noise sources and disturbances



Front- End Amplifier

Noise sources at the front end of a receiver **dominate the sensitivity and bandwidth.**

Major engineering emphasis has been on the design of a **low noise front end amplifier.**

Goal:

Maximize the receiver sensitivity while maintaining a suitable bandwidth.

Front end amplifiers classified into two broad categories:

- 1. High impedance**
- 2. Transimpedance**

Front- End Amplifier

Basic concern in front end design:

To choose load resistor R_L .

Thermal noise is inversely proportional to the load resistance.

Thus, R_L should be as large as possible to minimize thermal noise

1. High impedance amplifier:

Trade off must be between noise and receiver bandwidth, since the bandwidth is inversely proportional to the resistance R_p seen by the photodiode.

High load resistance results in low noise but also gives a low receiver bandwidth

Front- End Amplifier

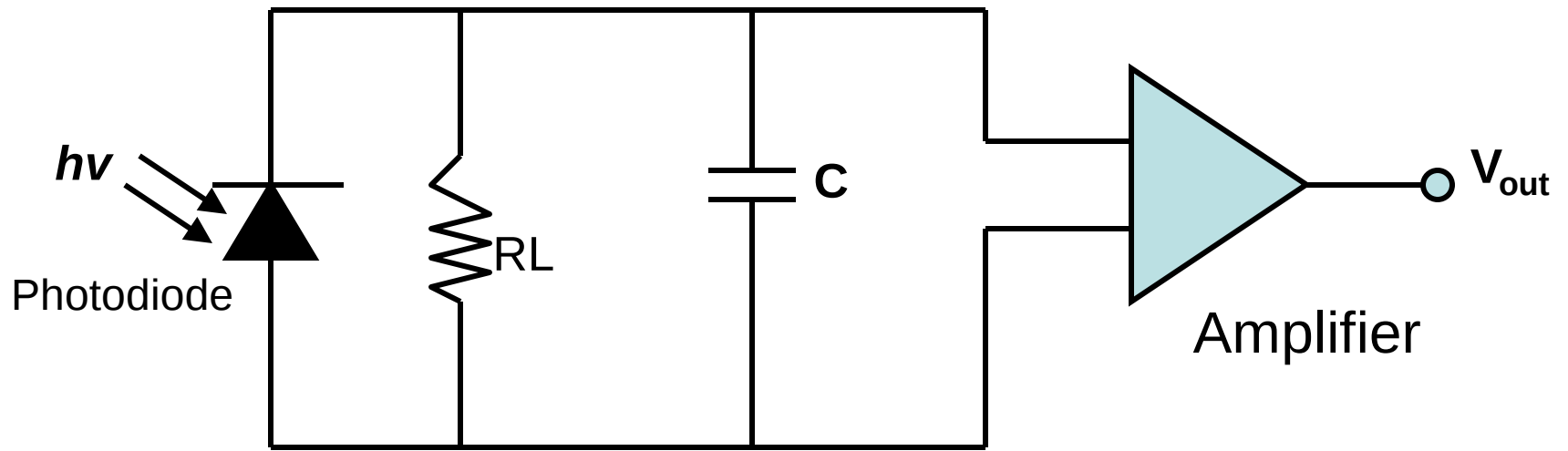
2. Transimpedance amplifier:

It largely **overcomes the drawbacks** of the high impedance amplifier.

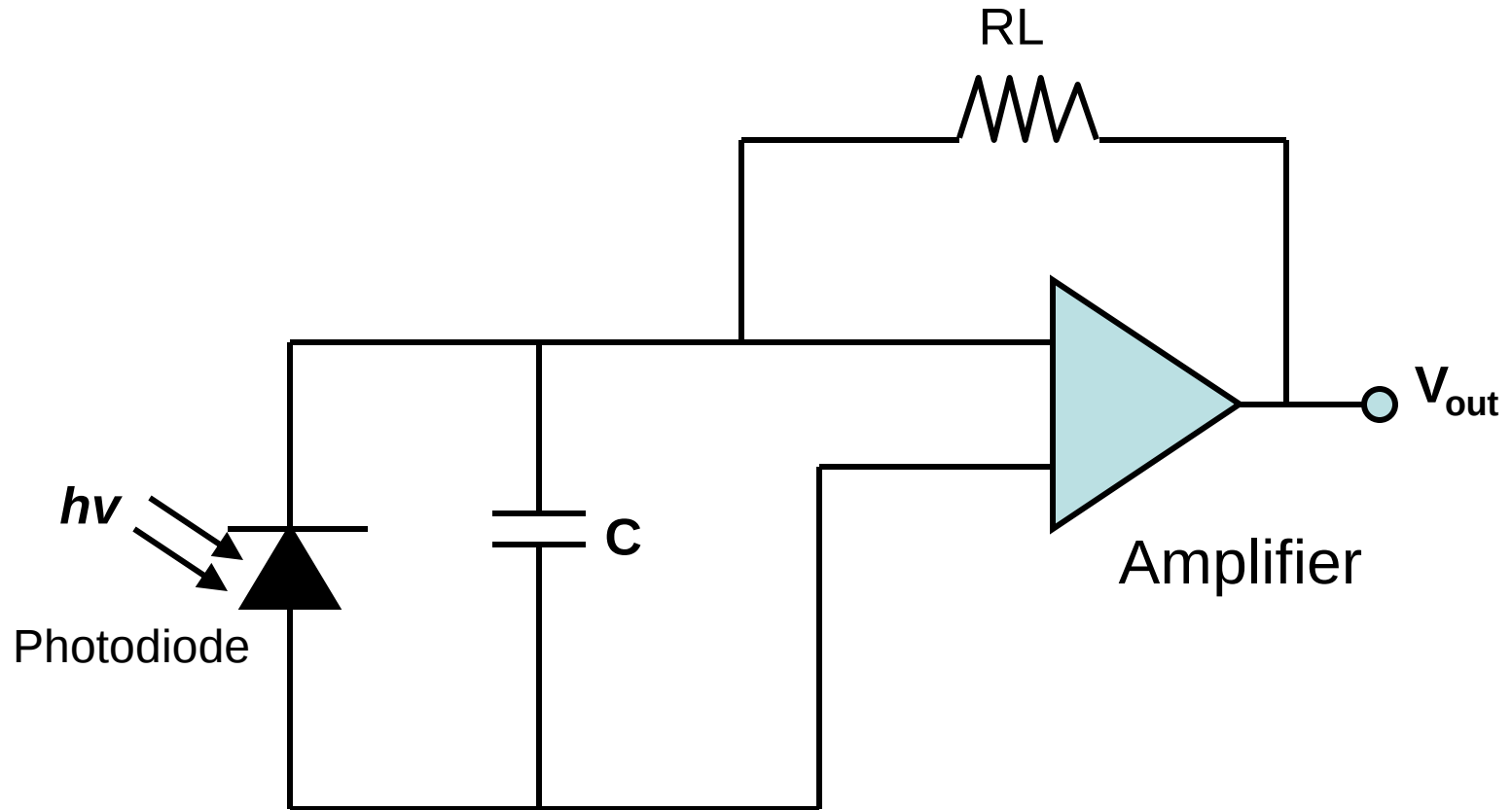
In this case R_L is used as a **negative feedback resistor** around an inverting amplifier.

Now R_L can be large since the **negative feedback reduces the effective resistance** seen by the photodiode by a factor G , so that **$R_p = R_L / (G + 1)$** , where G is the gain of an amplifier.

Transimpedance amplifier is the choice for optical fiber transmission links.



Generic structure of a high-impedance amplifier



Generic structure of a trans-impedance amplifier

Front- End Amplifier

The electronic components in the front end amplifier that follows the photodetector **also add further thermal noise.**

The magnitude of this additional noise **depends on the design of the amplifier** (incorporation of bipolar or field effect transistor in design)

This noise increase can be accounted for by introducing an amplifier noise figure.

Amplifier noise figure:

The ratio of input SNR to the out put SNR of the amplifier.

Typical values of the amplifier noise figure range from 3 to 5 dB

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Digital Receiver Performance

Ideally, in a digital receiver the decision circuit output signal voltage $V_{\text{out}}(t)$

- Would always exceed the threshold voltage when 1 is present
- Would be less than the threshold when no pulse, 0 was sent

Deviation from the average value of $v_{\text{out}}(t)$ (decision circuit output) are caused by:

1. Various noises
2. Interference from adjacent pulses
3. Condition when the light source is not completely extinguished during a zero pulse.

*Probability of Error

Measuring the rate of error occurrences in a digital data stream.

A simple approach is to divide the number N_e of errors occurring over a certain time interval t by the number N_t of pulses (ones and zeros) during this interval.

This is called either error rate or the bit-error rate (BER)

$$\text{BER} = N_e / N_t = N_e / Bt$$

Where $B = 1/T_b$ is the bit rate (pulse transmission rate)

***Probability of Error**

The error rate is expressed by a number such as 10^{-9} .

(one error occurs for every billion pulses sent)

Typical error rates for optical fiber telecommunication systems range from:

10^{-9} to 10^{-12}

Standards which define acceptable bit error rates include ITU-T O.150 and O.201 Recommendations.

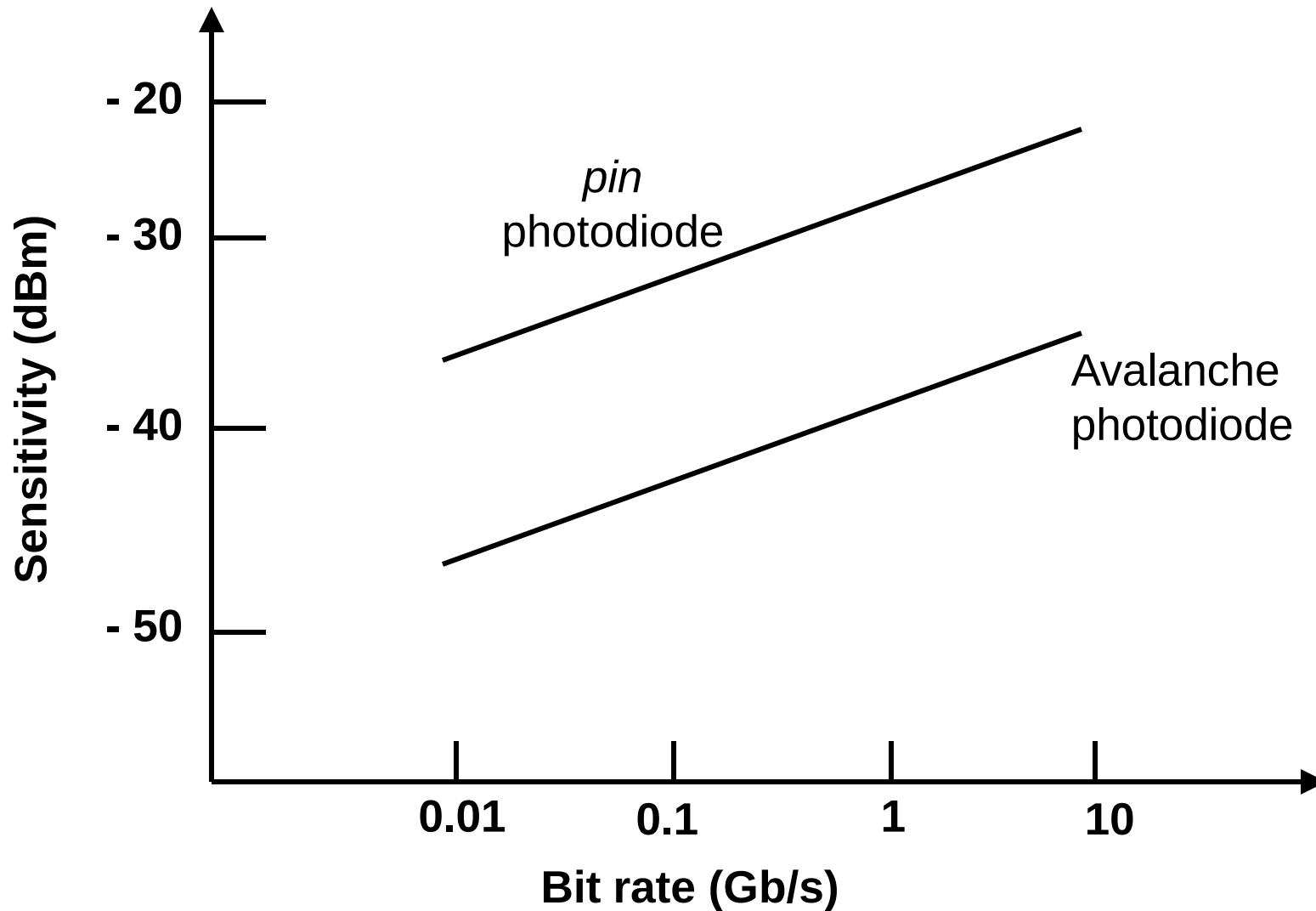
*Receiver sensitivity

To achieve a desired BER at a given Data rate, a **specific minimum average optical power level must arrive at the photodetector.**

The value of this minimum power level is called the receiver Sensitivity.

A common method of defining the receiver sensitivity is as an **average optical power (P_{ave}) in dBm** incident on the photodetector.

The receiver sensitivity gives a measure of the minimum average power needed to maintain a maximum (worst case) BER at a specific data rate.



Sensitivities as a function of bit rate for generic *pin* and avalanche InGaAs photodiodes at 1550 nm for a 10^{-12} BER

The Quantum Limit

It is calculated by **assuming zero dark** current i.e no electron hole pairs generated in the absence of an optical pulse.

It is the minimum received optical power required for a specific bit-error performance in a digital system.

This minimum received power level is known as the quantum limit, by assuming all system parameters ideal.

***Sensitivity** of most receivers is around **20 dB higher than the quantum limit** because of various nonlinear distortions and noise effects in the transmission link.

When specifying the quantum limit, **distinguish between average power and peak power**. Quantum limit based on the peak power

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Eye Diagrams

The eye diagram is **powerful measurement tool** for assessing the **data handling ability** of a **digital transmission system**.

It is used extensively for evaluating the performance of **wireline systems** and also applies to **optical fiber data links**.

Eye Pattern Features

The eye pattern **measurements are made in the time domain** and allow the effects of waveform distortion to be shown immediately on the **display screen of standard BER test equipment**.

Width of the eye opening:

It defines the **time interval** over which the received signal can be sampled without error due to **interference from the adjacent pulses** (ISI).

The best time to sample the received waveform is when the height of the **eye opening is largest**. The more the eye closes, the more difficult it is to distinguish between ones and zeros in the signal.

Eye Pattern Features

Height of the eye opening:

The height of the eye opening at the specified sampling time shows the **noise margin or immunity to the noise**.

Noise margin:

It is the **percentage ratio of peak signal voltage V_1** for an alternating bit sequence **to the maximum signal voltage V_2** as measured from the threshold level.

$$\text{Noise margin (percent)} = V_1 / V_2 \times 100 \text{ percent}$$

Eye Pattern Features

Timing errors:

The rate at which the eye closes as the sampling time is varied (i.e the slope of the eye pattern sides) determines the sensitivity of the system to timing errors.

The possibility of timing errors increases as the slope becomes more horizontal

Timing Jitter:

It is also referred to as edge jitter or phase distortion. It arises from the noise in the receiver and pulse distortion in the optical fiber.

Causes: Bit errors, produce uncertainties in clock timing, receiver can lose synchronization with the incoming bit stream thereby incorrectly interpreting logic 1 and 0 pulses.

Eye Pattern Features

The amount of distortion ΔT at the threshold level indicates the **amount of jitter**.

$$\text{Timing jitter (percent)} = \Delta T / T_b \times 100 \text{ percent}$$

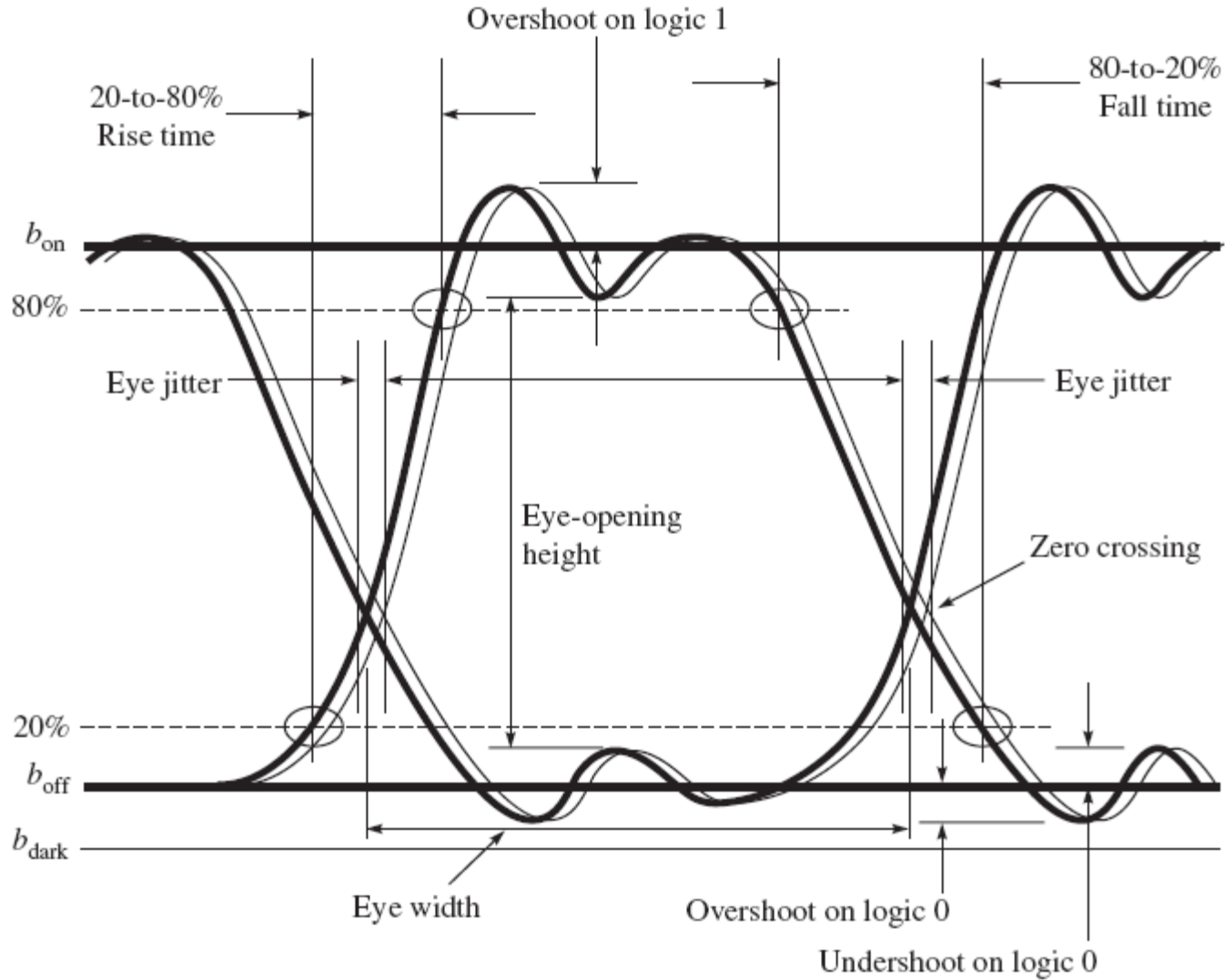
Rise Time

It is defined as the time interval between the points where the rising edge of the signal reaches **10 percent of its final amplitude** to the time where it reaches **90 percent of its final amplitude**.

Conversion from 20 to 80 percent rise time to 10 – 90 percent rise time. Approximately

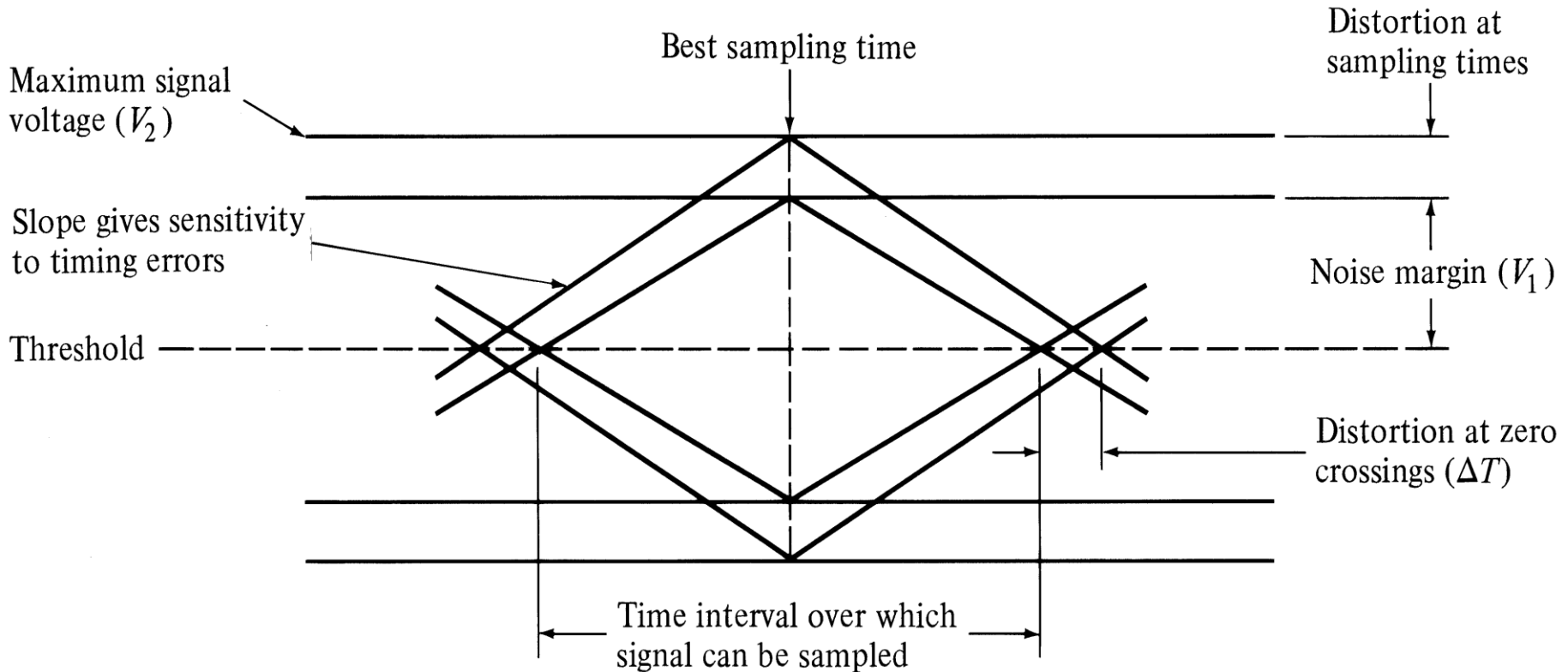
$$T_{10-90} = 1.25 \times T_{20-80}$$

EYE Diagram



General configuration of an eye diagram showing the definitions of fundamental measurement parameters

Simplified eye diagram



Simplified eye diagram showing the key performance parameters

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Burst – Mode Receivers

For PON applications, the operational characteristics of an **OLT optical receiver** differ significantly from those used in conventional point-to-point links.

Amplitude and **phase of information** packets received in **successive time slots** from different user locations can **vary widely from packet to packet.**

Conventional optical receiver is not capable of instantaneous handling of rapidly changing differences in **signal amplitude** and **clock phase alignment**, **a specially designed burst-mode receiver is needed.**

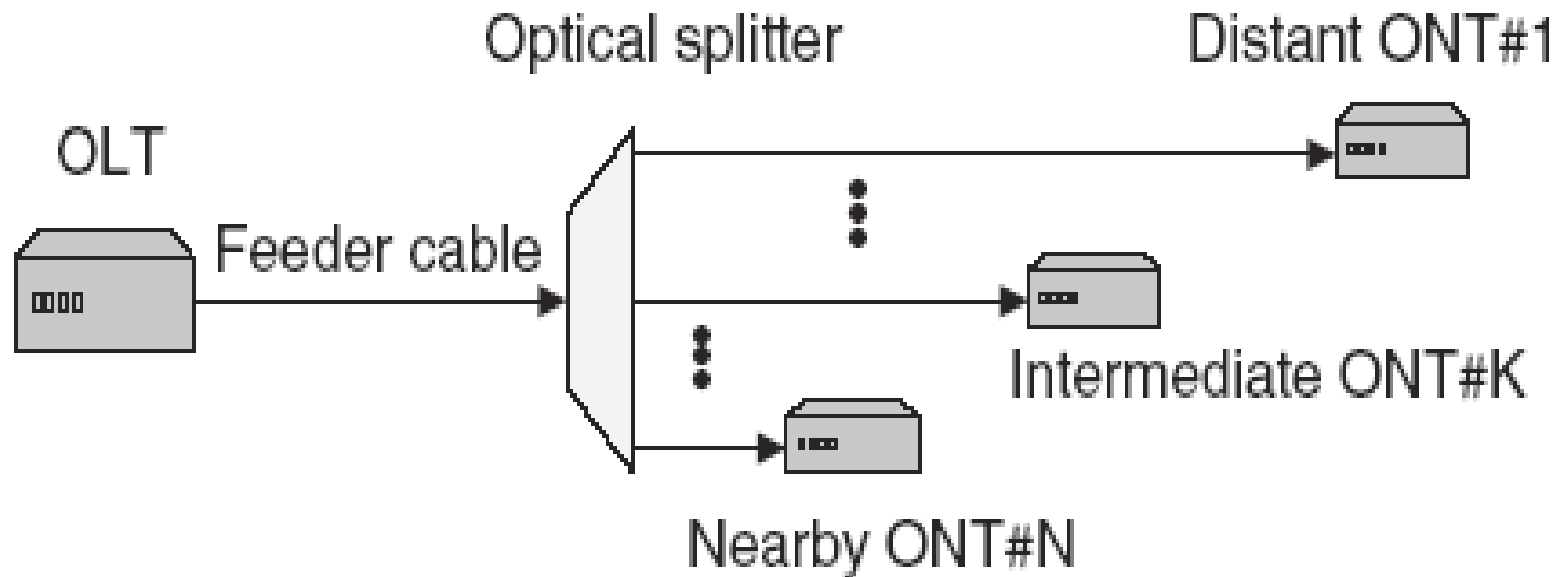
Burst – Mode Receivers

These receivers can quickly **extract the decision threshold** and determine the signal phase from a set of **overhead bits** placed at the beginning of each packet burst.

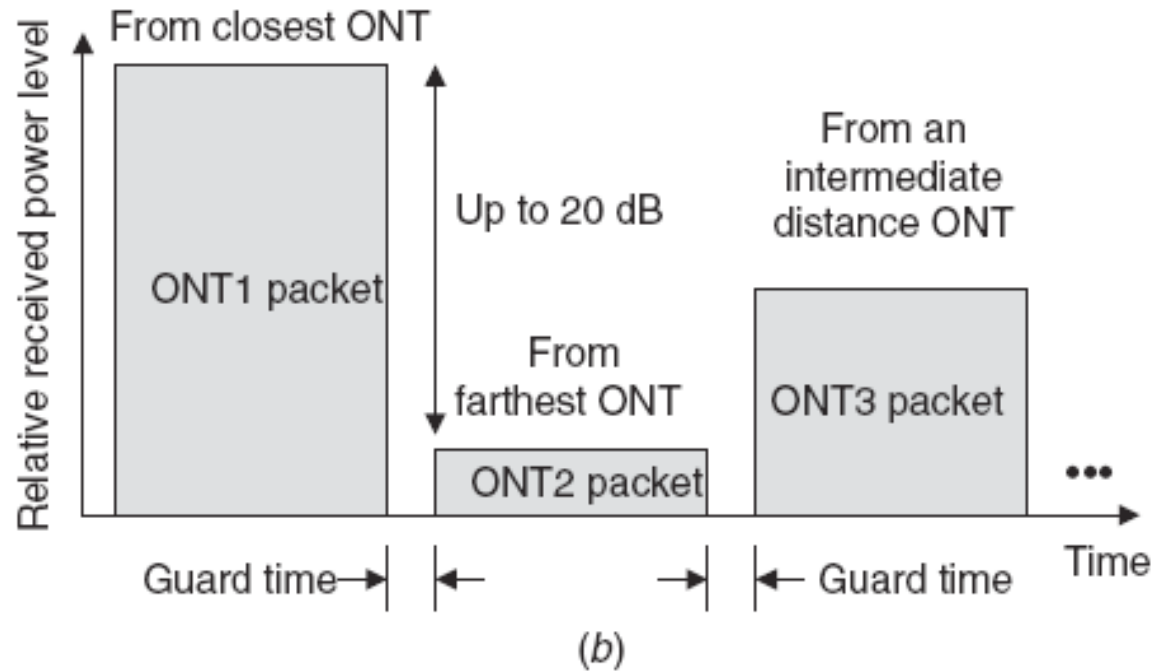
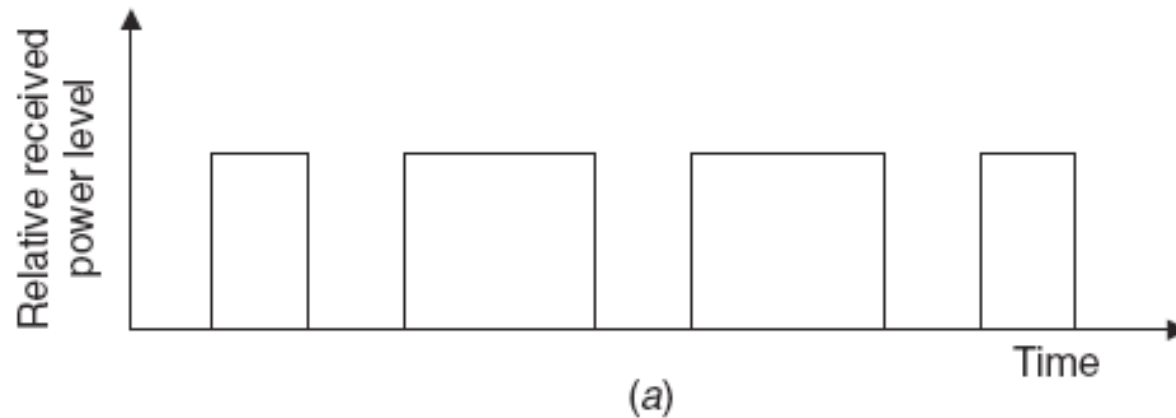
This methodology results in a receiver sensitivity **power penalty of up to 3 dB.**

The key requirements of a burst-mode receiver are:

- 1. High sensitivity**
- 2. Wide dynamic range**
- 3. Fast response time**



Large distance variations of customers from the central office result in different signal power losses across the PON.



(a) Typical received data pattern in conventional point-to-point links; (b) Optical signal level variations in pulses that may arrive at an OLT