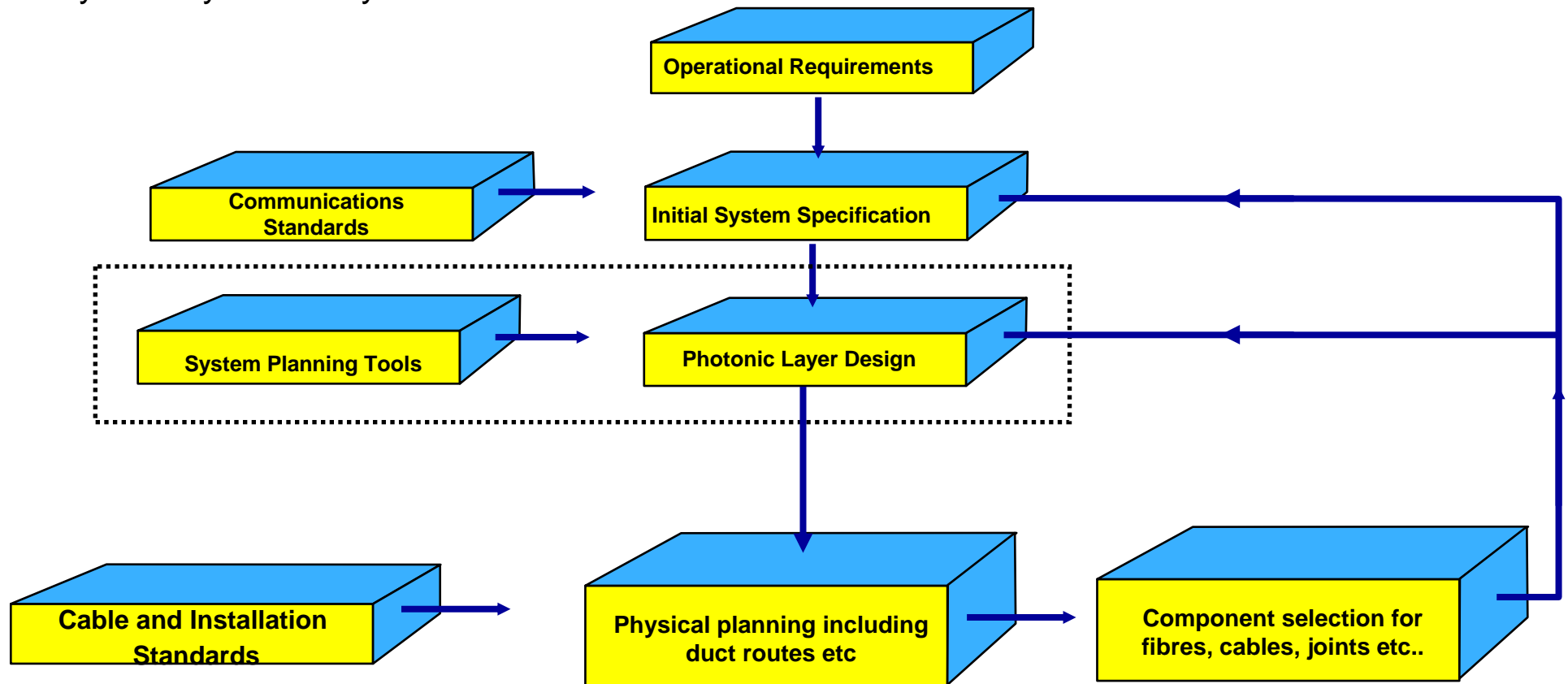


System Planning

- System design is an iterative process
- Will vary from system to system



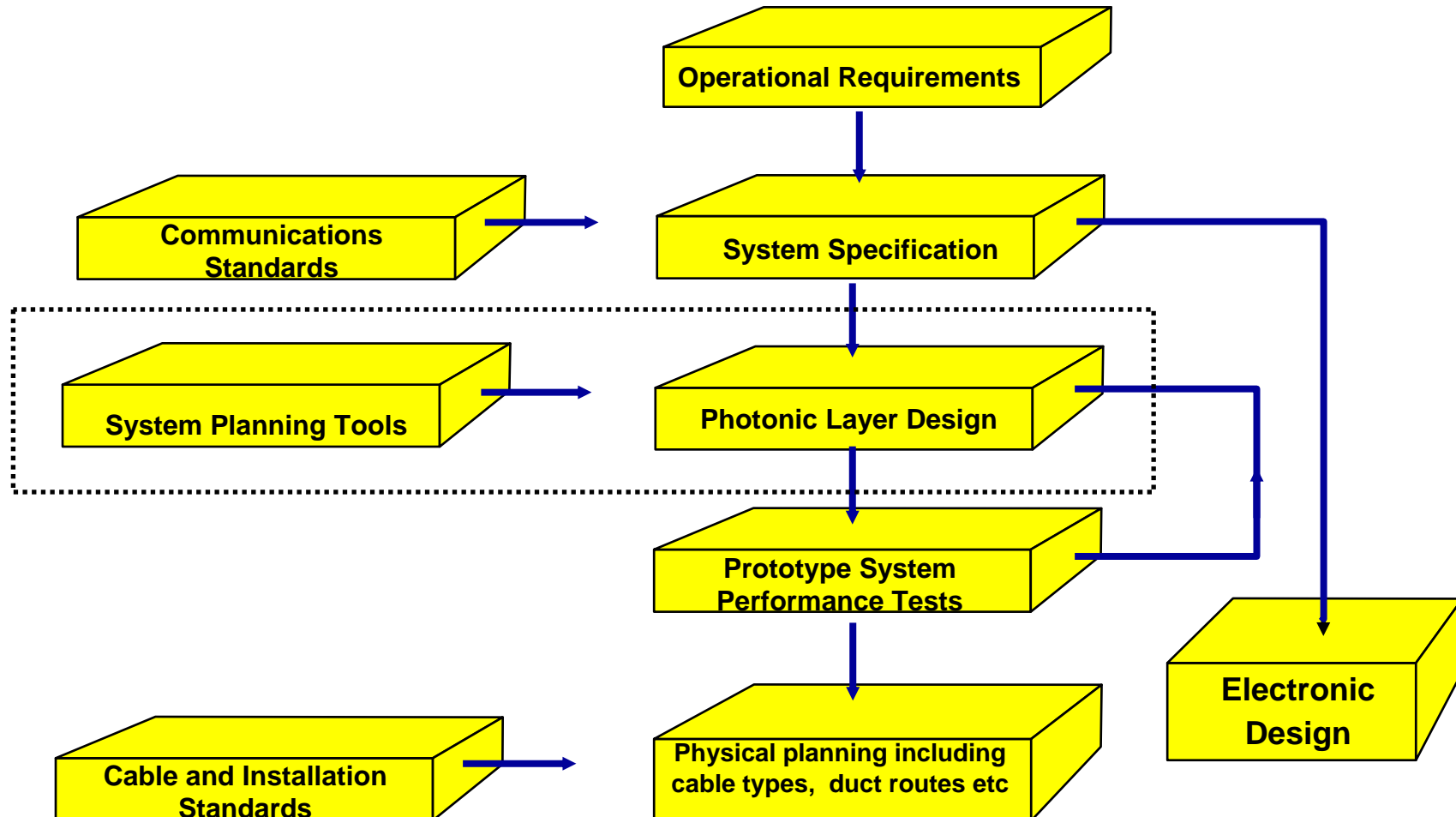


Design and Planning Issues

- **Network design and planning**
- **Individual link/route design**
- **Component selection**



System Design and Planning





System Specifications

- **Wide variety of specifications will emerge at an early stage:**
- **Relevant specifications will depend on whether you are the either the system specifier, equipment supplier, installation contractor, sub-contractor.**
 - **Physical:**
 - System topology, including cable location and/or cable routes
 - Existing cable protection, (none or building ducts or underground ducts)
 - Cable specifications based on standards, (fibre, moisture ingress etc..)
 - Number of fibres per cable, upgrade requirements
 - **Network issues**
 - Network application and proposed topology, network evolution plans
 - Transmission standards, bit rates, coding, multiplexing etc..
 - **Fibre**
 - MM or SM, core size, fibre NA, fibre attenuation, fibre dispersion, all with tolerances
 - Connector type, loss and reflection, tolerances
 - Splices, mechanical or fusion, loss and tolerances
 - Termination enclosures, access or patch panels etc..
 - **System**
 - Completed power and bandwidth budgets, source types: power and spectral width etc..
 - Civil works, delivery of fibre, trunking/conduit installation, splicing
 - System testing, acceptance tests, documentation etc..

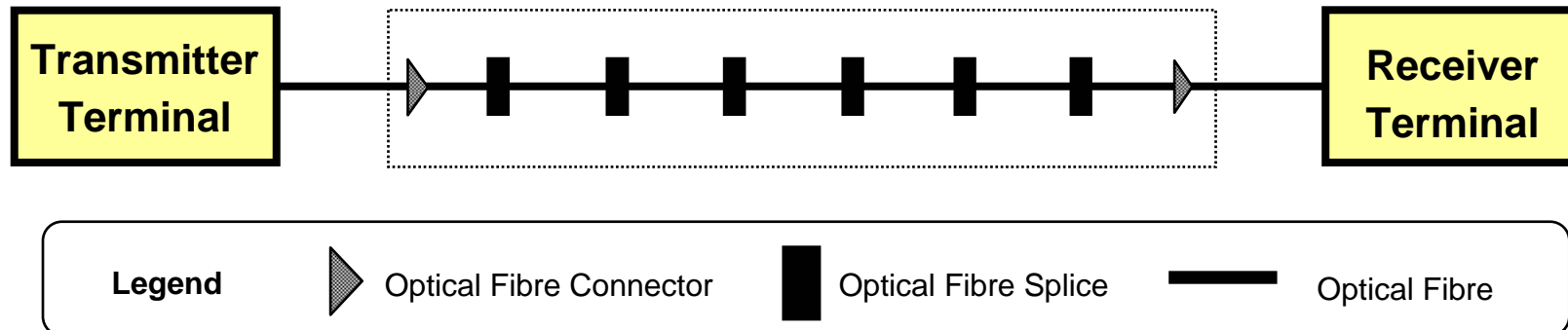


Tools for System Planning

- Link Bandwidth analysis
- Power Penalty evaluation
- Power Budget calculation

The purpose of so-called Photonic layer design process is to ensure that:

- The optical power reaching the receiver is adequate.
- The link bandwidth is adequate.





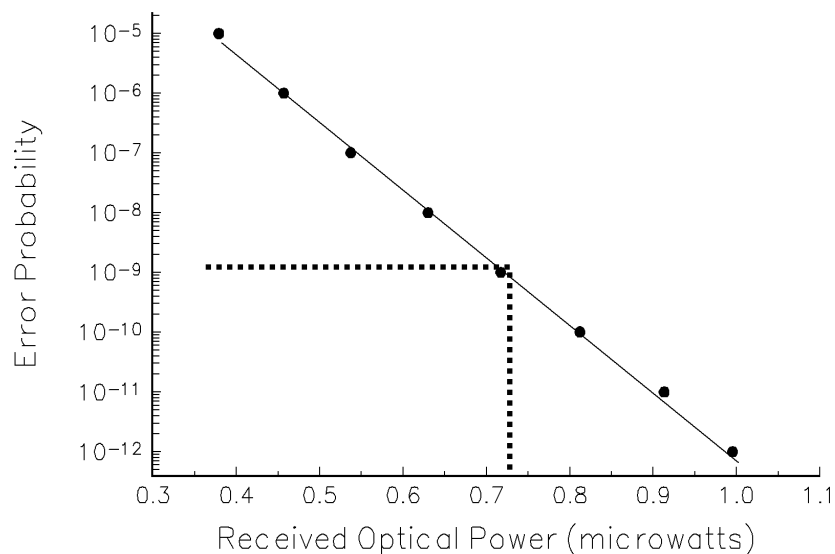
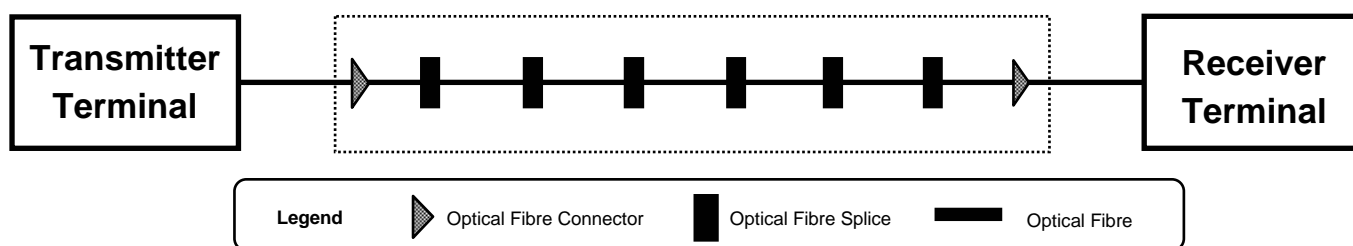
Power Budgeting



Power Budgeting

The purpose of power budgeting is to ensure that:

- The optical power reaching the receiver is adequate under all circumstances
- No component has an excessive loss



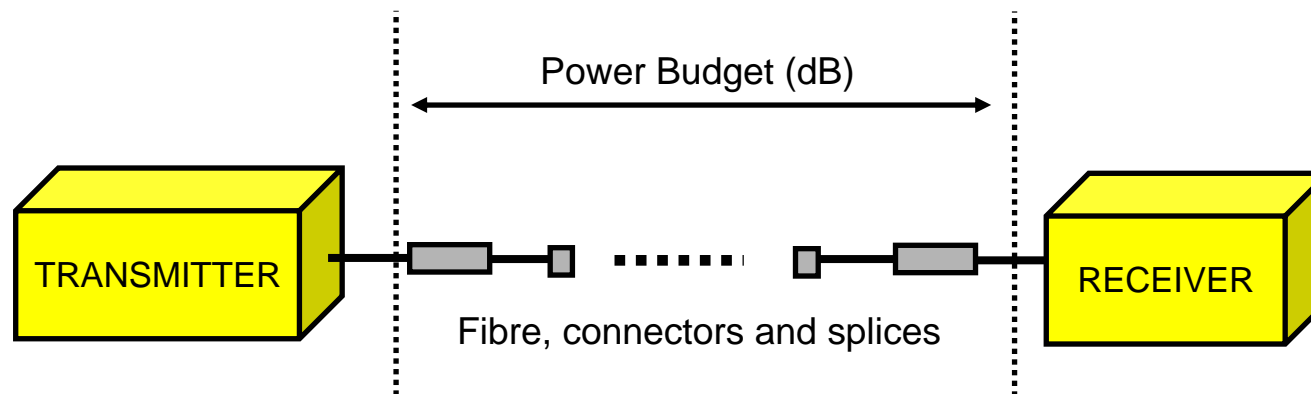
A receiver in an Optical System requires a minimum optical input power to operate with a specified error probability

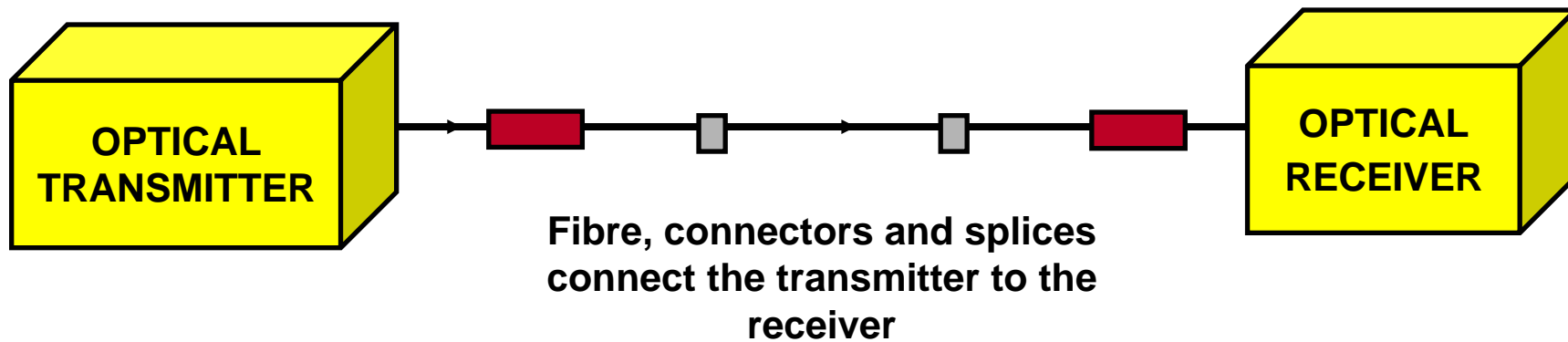
Graph shows error probability versus received power for a 622 Mbits/sec system



Power Budget Definition

- Power budget is the difference between:
 - The minimum (worst case) transmitter output power
 - The maximum (worst case) receiver input required
- Power budget value is normally taken as worst case.
- In practice a higher power budget will most likely exist but it cannot be relied upon
- Available power budget may be specified in advance, e.g for 62.5/125 fibre in FDDI the power budget is 11 dB between transmitter and receiver



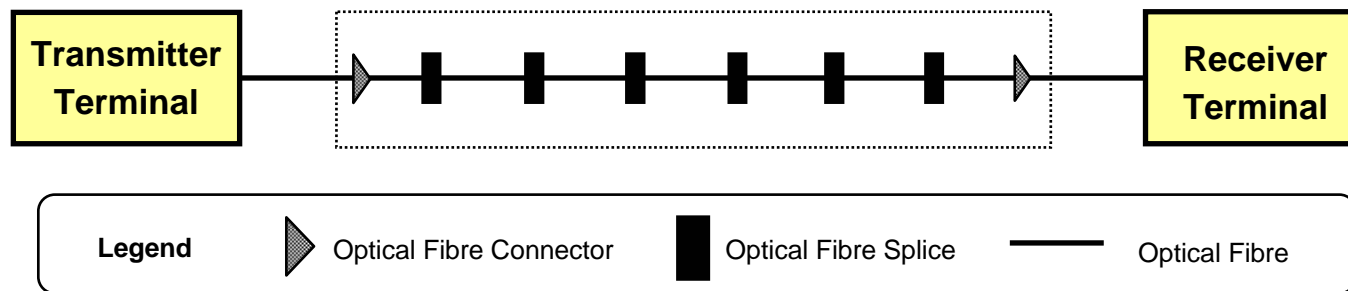




Photonic Layer Design Power Budgeting

The purpose of so-called Photonic layer design process is to ensure that:

- The optical power reaching the receiver is adequate under all circumstances
- The link bandwidth is adequate.



A receiver in an Optical System requires a minimum optical input power to operate as specified

- Photonic layer design involves:
 - Carrying out a power budget calculation
 - An evaluation of any power penalties
- Available power budget may be specified in advance, e.g for 62.5/125 fibre in FDDI the power budget is 11 dB between transmitter and receiver



Use of Power Budgets

Power budget calculations can produce a number of different results depending on how they are carried out.

- **To check if adequate receiver power will be available, under all conditions**
 - **Based on a knowledge of the receiver sensitivity to determine the maximum loss of some component.**
-

Simple example to find total fibre loss allowed:

Assume worst case transmitter output power is -10 dBm and the worst case receiver input power needed is -25 dBm

$$\begin{aligned}\text{Power budget} &= -10 \text{ dBm} - (-25 \text{ dBm}) \\ &= 15 \text{ dB}\end{aligned}$$

That is 15 dB of attenuation is possible over the link before failure occurs

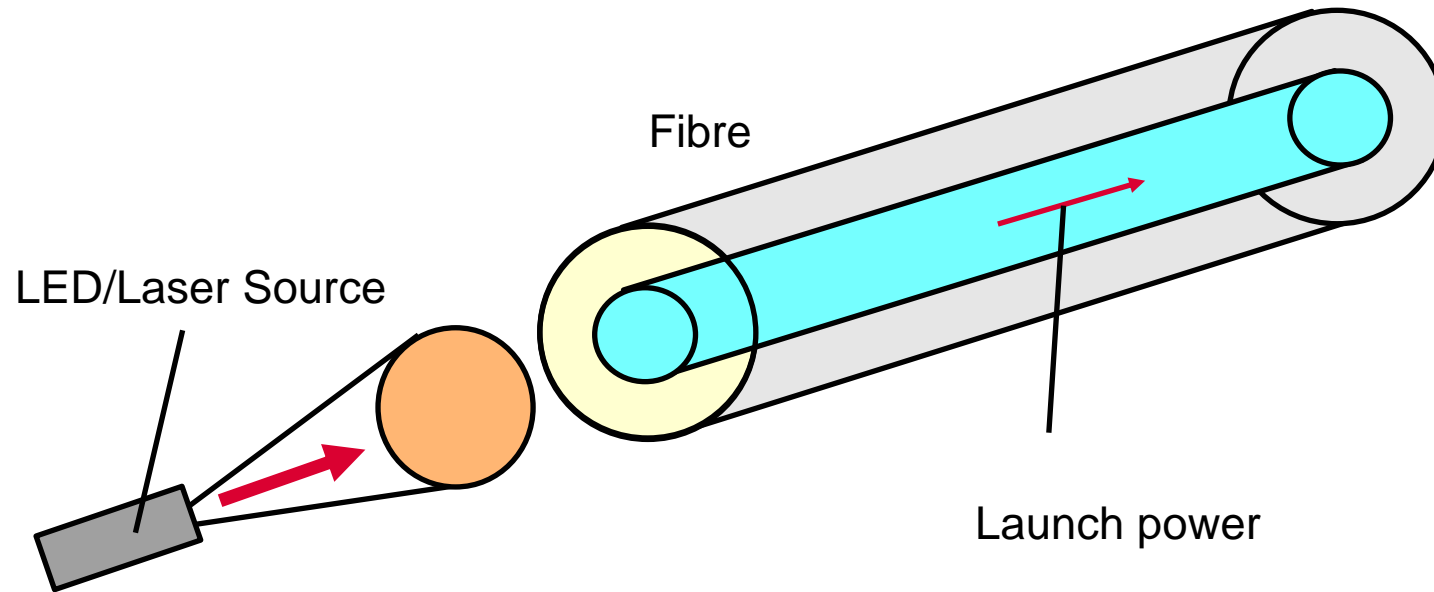
As a simple example to find the maximum fibre attenuation we eliminate from the 15 dB budget the loss due to connectors and splices

$$\begin{aligned}\text{Less:} \quad \text{Connector attenuation} &= 1 \text{ dB} \\ \text{Total splice attenuation} &= 1.2 \text{ dB}\end{aligned}$$

$$\text{So:} \quad \text{Total fibre attenuation allowed} = 15 - 1 - 1.2 = \mathbf{12.8 \text{ dB}}$$



Launch Power



- Transmitter output power quoted in specifications is by convention the launch power.
- Launch power is the optical power *coupled into the fibre*.
- Launch power is less than the LED/Laser output power.
- Calculation of launch power for a given LED/Laser and fibre is very complex.



Power Margin

- **Power margins are included for a number of reasons:**
 - **To allow for ageing of sources and other components.**
 - **To cater for extra splices, when cable repair is carried out.**
 - **To allow for extra fibre, if rerouting is needed in the future.**
 - **To allow for upgrades in the bit rate or advances in multiplexing.**
- **Remember that the typical operating lifetime of a communications transmission system may be as high as 20 to 30 years.**
- **No fixed rules exist, but a minimum for the power margin would be 2 dB, while values rarely exceed 8-10 dB. (depends on system)**



Sample Power Budget Calculation (Telecoms)

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Power budget calculation including power penalty used to calculate power margin

System: 70 km span, 0.8 km between splices

Transmitter o/p power (dBm)	0	
Number of Connectors	2	In most systems only two connectors are used, one at the transmitter and one the receiver terminal.
Connector loss per connector (dB)	0.5	
Total connector loss (dB)	1	
Fibre span (km)	70	
Fibre loss (dB/Km)	0.25	
Total fibre loss (dB)	17.5	
Splice interval (Km)	0.8	Fibre is normally only available in fixed lengths up to 2 km long, so fusion splices are required, to join lengths.
Number of splices	87	
Splice loss per splice (dB)	0.04	
Total splice loss (dB)	3.46	
Dispersion penalty estimate (dB)	1.5	In buildings fibre lengths will be much shorter
Receiver sensitivity (dBm)	-30	
Power margin (dB)	6.54	Answer



Sample Power Budget Calculation (FDDI System)

Power budget calculation used to calculate power margin

Transmitter o/p power (dBm)	-18.5 dBm min, -14.0dBm max
Receiver sensitivity (dBm)	-30 dBm min
Available power budget:	11.5 dB using worst case value (>FDDI standard)
Number of Connectors	6
Worst case Connector loss (dB)	0.71
Total connector loss (dB)	4.26
Fibre span (km)	2.0
Maximum Fibre loss (dB/Km)	1.5 dB at 1300 nm
Total fibre loss (dB)	3.0
Number of 3M Fibrlok mechanical splices	10
Worst case splice loss per splice (dB)	0.19
Total splice loss (dB)	1.9
Total loss:	9.16 dB
Power margin (dB)	2.34 — Answer



Sample Power Budget Exercise #1

- ✓ An optical fibre system is to operate at 622 Mbits/sec over a distance of 71 km without repeaters.
- ✓ Fibre with a worst case loss of 0.25 dB/km is available.
- ✓ The average distance between splices is approximately 1 km.
- ✓ There are two connectors and the worst case loss per connector is 0.4 dB.
- ✓ The power margin is to be at least 5 dB.
- ✓ The receiver sensitivity is -28 dBm and the transmitter output power is +1 dBm
- ✓ *Determine the maximum allowable attenuation per fusion splice*



Solution to Exercise #1

Transmitter output power	+1 dBm	Worst case (lowest) optical output power
Receiver sensitivity	-28 dBm	Minimum input optical power required
Power Budget	29 dB	Difference between transmitter and receiver levels.
Less power margin	5 db	Allowance for repair etc..
Less connector loss	0.8 dB	Two connectors at 0.4 dB max. each.
Less fibre loss	17.75 dB	71 km at 0.25 dB/km
Calculated total maximum splice loss	5.45 dB	eg. $29 - 5 - 0.8 - 17.75 \text{ dB} = 5.45 \text{ dB}$
Total number of splices	71	There are approximately 71 lengths of fibre in the link so there are approximately 71 splices
Answer: Maximum splice loss	0.076 dB	



More Advanced Power Budgets using Power Penalties



More Advanced Power Budgets: Power Penalties

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- **More sophisticated power budget calculations will include power penalties.**
- **A power penalty is defined as the increase in receiver power needed to eliminate the effect of some undesirable system noise or distortion**

Typically power penalties can result from:

- Dispersion.
 - Dependent on bit rate and fibre dispersion,
 - Typical dispersion penalty is 1.5 dB
- Reflection from passive components, such as connectors.
- Crosstalk in couplers.
- Modal noise in the fibre.
- Polarization sensitivity.
- Signal distortion at the transmitter (analog systems only).



Dispersion Penalty



Dispersion Penalty

- **Defined as:**

The increase in the receiver input power needed to eliminate the degradation in the BER caused by fibre dispersion

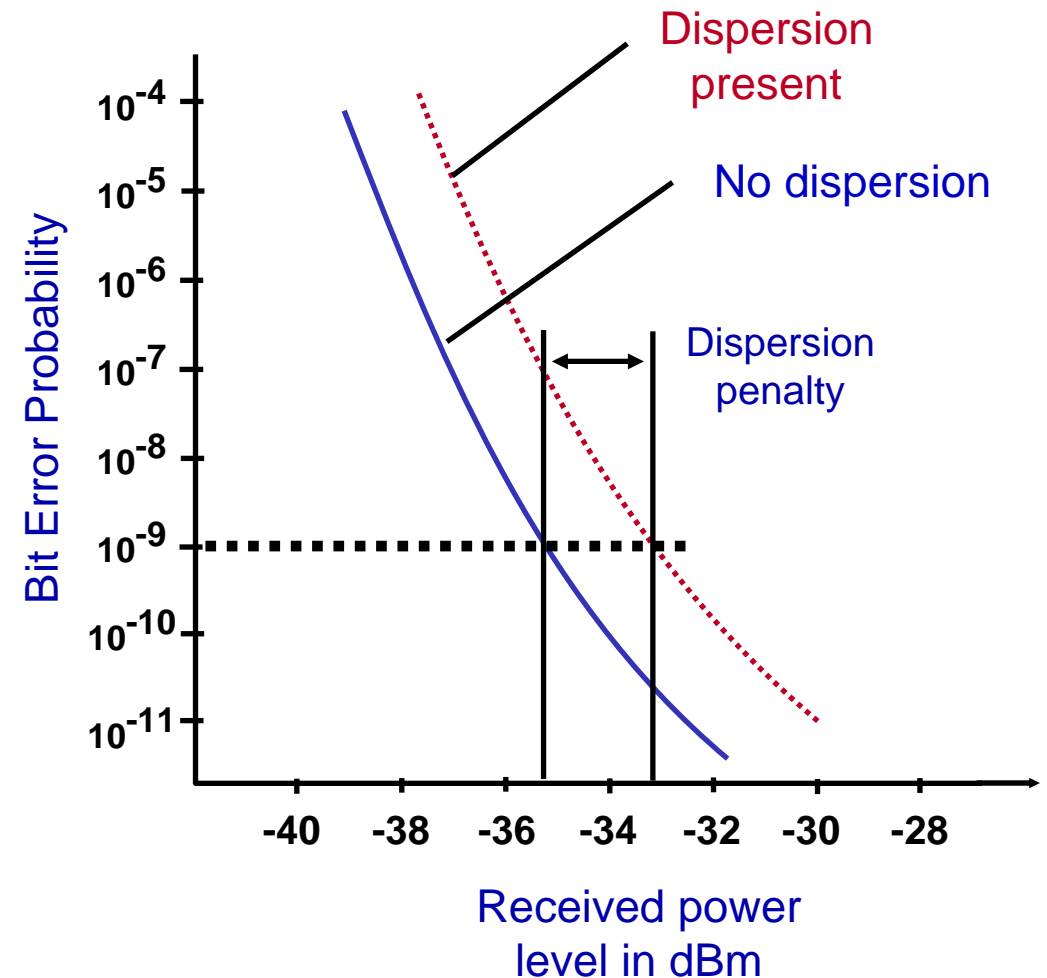
- **Typical value is about 1.5 dB.**
- **Several analytic rules exist:**
 - **Low pass filter approximation rule**
 - **Allowable pulse broadening (Bellcore) rule**



Dispersion Penalty Visualised

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- Defined as the increase in the receiver input power needed to eliminate the degradation caused by dispersion
- Defined at agreed Bit Error Probability, typically 1×10^{-9}
- In the sample shown the receiver power levels required at 1×10^{-9} with & without dispersion are -35.2 dBm & -33.1 dBm respectively
- The dispersion penalty is thus 2.1 dB



Bit Error Probability

10^{-4}
 10^{-5}
 10^{-6}
 10^{-7}
 10^{-8}
 10^{-9}
 10^{-10}
 10^{-11}

-40

-38

-36

-34

-32

-30

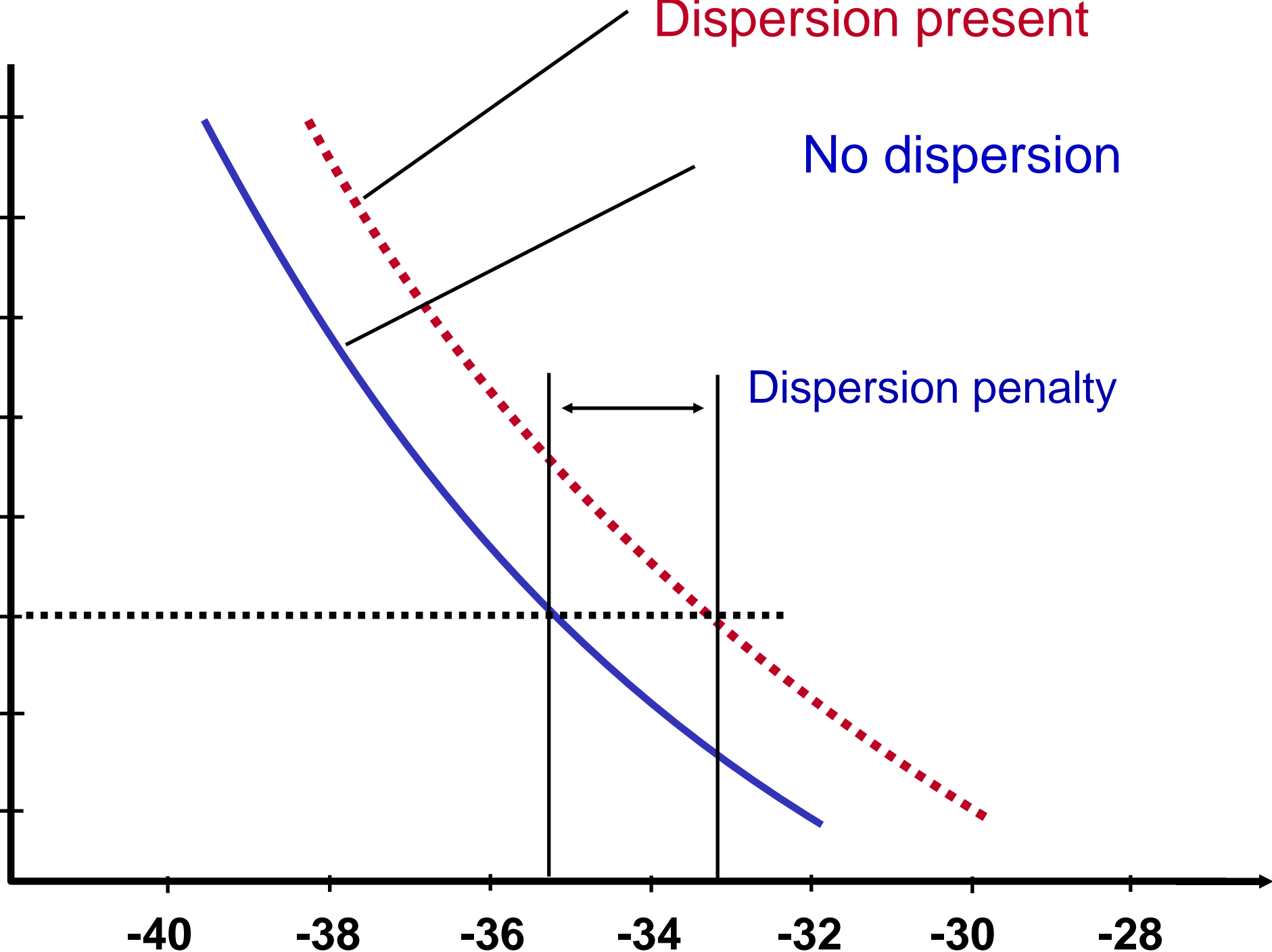
-28

Received power level in dBm

Dispersion present

No dispersion

Dispersion penalty

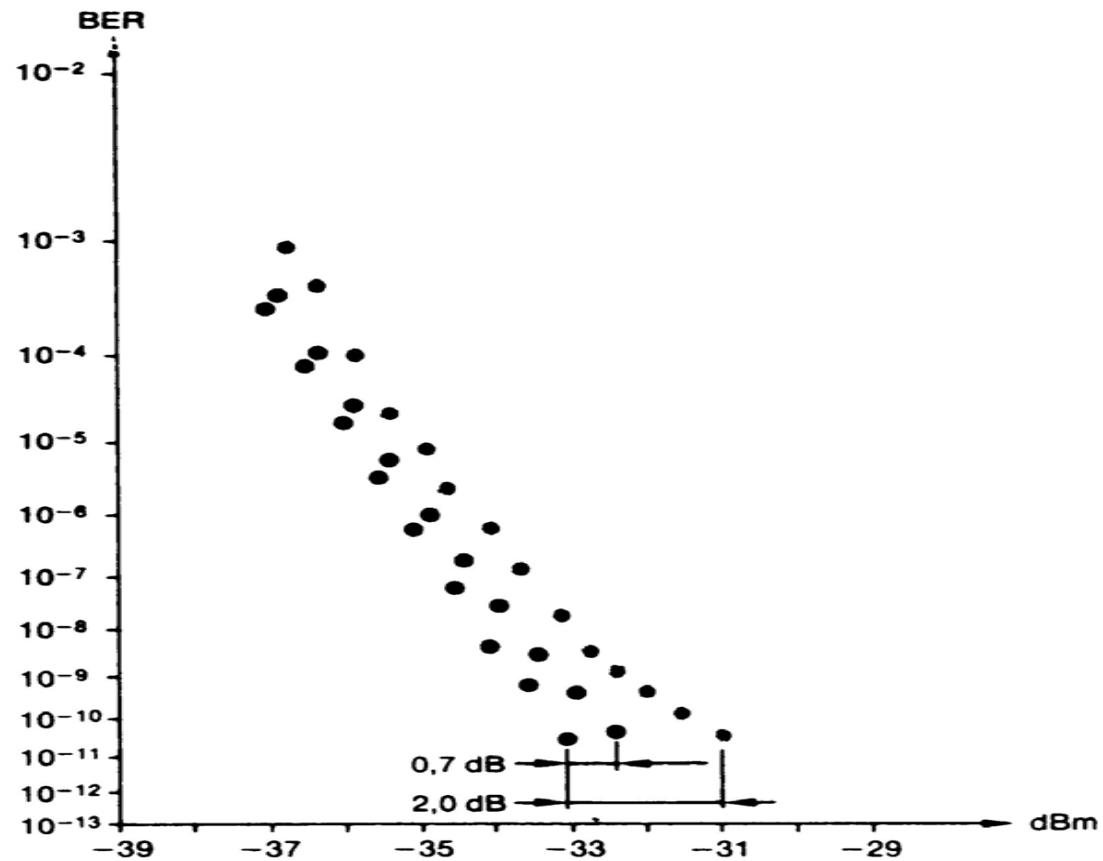




Dispersion Penalty Data

Fig. 4
Bit error rate, BER, as a function of the optical input power with dispersion as the parameter

- Dispersion = 0 ps/nm
- Dispersion = 119 ps/nm
- Dispersion = 157 ps/nm





Low pass filter approximation rule for the Dispersion Penalty



Dispersion Penalty

- Simple analytic rule of thumb for calculating the dispersion penalty P_d
- Based on two assumptions:
 - that dispersion can be approximated by a low pass filter response.
 - the data is the dotting 10101010 pattern.

$$P_d = -10 \log_{10} \left(1 - \frac{1}{2} (\pi B)^2 D_t^2 \right)$$

- B is the bit rate in bits/sec and D_t is the total r.m.s impulse spread caused by dispersion over the fibre.
- To keep $P_d < 1.5$ dB, the $B \cdot D_t$ product must be less than 0.25 approximately.



Low pass filter approximation Dispersion Penalty Analysis (I)

The transfer function for a fibre can be approximated by:

$$H(f) = A \left[1 - \frac{1}{2} (2\pi f)^2 D_t^2 \right]$$

A is the value of $H(f)$ at DC, effectively the fibre attenuation.

D_t is the RMS impulse broadening that occurs over the fibre.

- Assume that the transmitted pattern is very simple, e.g. the dotting pattern 10101010.....
- Also assume that most of the optical power in this pattern is contained in the component at $f = B/2$, where B is the bit rate and NRZ data is assumed.
- Finally for ease of analysis assume that A is 1.
- The extra attenuation caused by dispersion can be approximated by finding $H(B/2)$.
- Effectively this extra attenuation appears as the dispersion penalty



Low pass filter approximation Dispersion Penalty Analysis (II)

To compensate for this extra attenuation the transmitter output power must be increased by a factor:

$$\frac{1}{H\left(\frac{B}{2}\right)}$$

The dispersion penalty in dB is therefore:

$$P_d = 10 \text{ Log}_{10} \left[\frac{1}{H\left(\frac{B}{2}\right)} \right]$$

Rearrange thus:

$$P_d = -10 \text{ Log}_{10} \left[H\left(\frac{B}{2}\right) \right]$$

Substitute for $H(B/2)$ using the formula for $H(f)$ evaluated at $f = b/2$ to find P_d

$$P_d = -10 \log_{10} \left(1 - \frac{1}{2} (\pi B)^2 D_t^2 \right)$$



Allowable pulse broadening (Bellcore) rule for the Dispersion Penalty



Dispersion Penalty

- Approach used in Bellcore recommendations for SONET over singlemode fibre, so it can be used for SDH
- Sets defined values on dispersion penalty, 1 dB or 2 dB
- Based on defining ratio (ε) of allowable pulse broadening (total dispersion, D_t) to the bit interval T , for a given dispersion penalty
- Allows one to define maximum bit rate B_{\max} possible for a given dispersion penalty:

$$B_{\max} < \frac{\varepsilon}{10^{-6} \cdot D_t}$$

- Total dispersion, D_t is in picoseconds, ps, and the maximum bit rate B_{\max} is in Mbits/sec

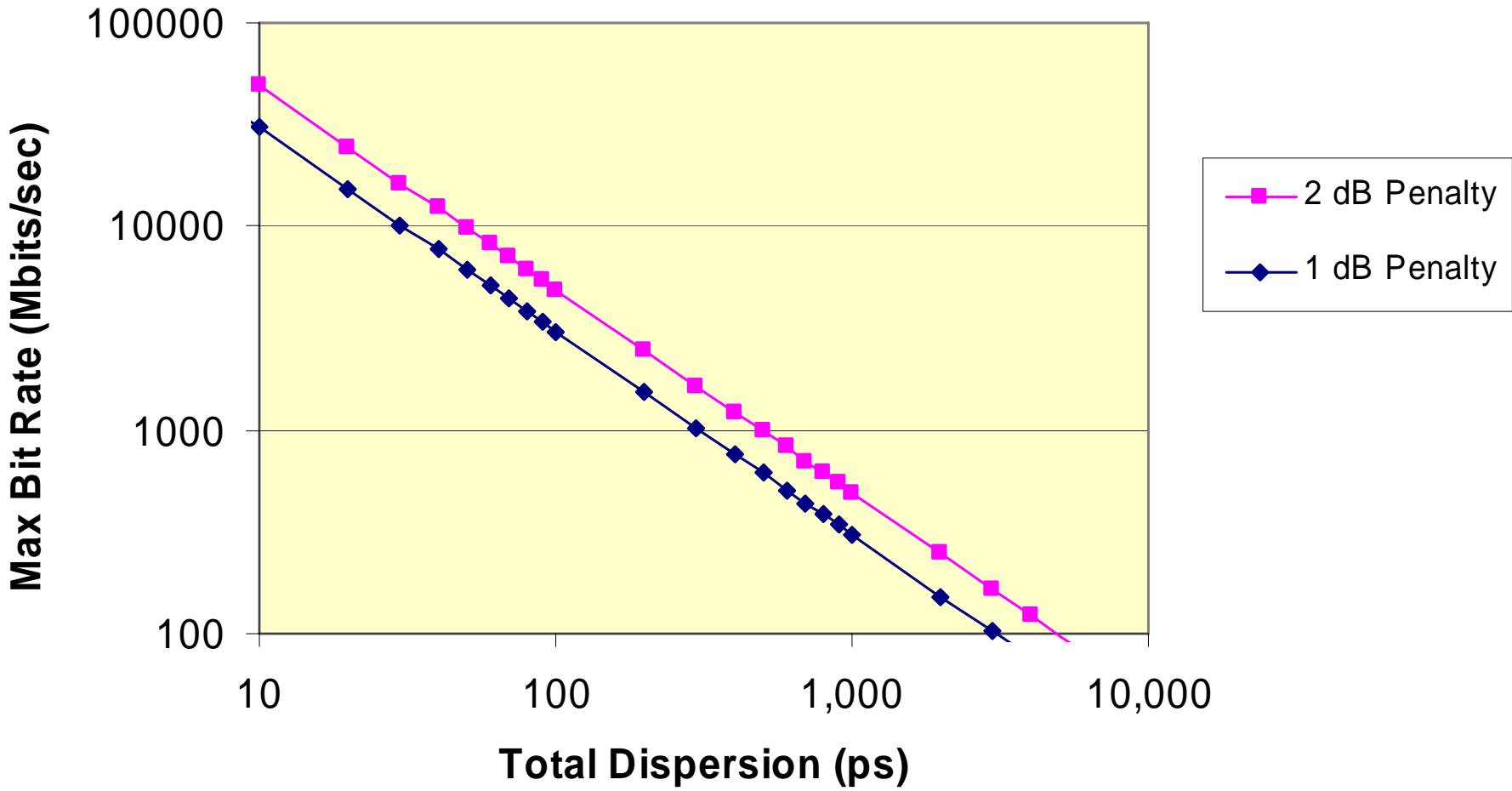
Values of allowable pulse broadening ratio ϵ

- Values shown for Lasers only - LEDs not used with singlemode fibre
- In practice multi-longitudinal mode lasers are an unlikely choice, most SDH transceivers use single-longitudinal mode lasers

Laser Type	Dispersion Penalty	ϵ value
Multi-longitudinal Mode	1 dB	0.115
	2 dB	0.182
Single-longitudinal Mode	1 dB	0.306
	2 dB	0.491

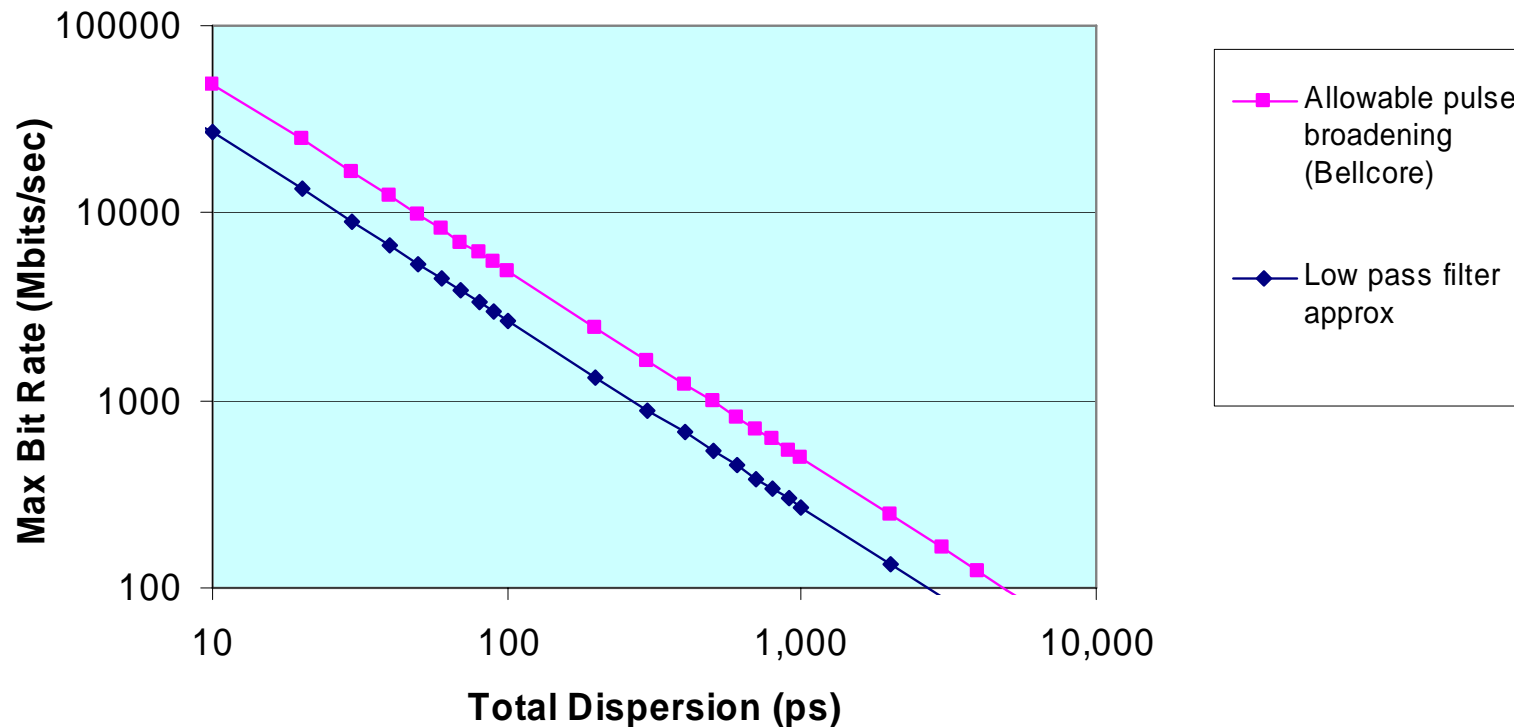


Maximum bit rate v Dispersion for different Penalties





Comparison of "Bellcore" and "low pass filter" rules



- Low pass filter approximation rule is more pessimistic than the allowable pulse broadening (Bellcore) rule
- For SDH/Sonet Bellcore rule is normally adopted



Calculating the Dispersion Penalty (Low pass filter approx rule)



Finding the Total Chromatic Dispersion

$$\text{Total Chromatic Dispersion, } D_t = D_C \times S \times L$$

where:

D_C is the dispersion coefficient for the fibre (ps/nm.km)

S is transmitter source spectral width (nm)

L is the total fibre span (km)

- Assuming singlemode fibre so there is no modal dispersion
- Does not include polarization mode dispersion
- Typically the dispersion coefficient will be known
- Eg. ITU-T Rec.G.652 for singlemode fibres circa 1550 nm states:
 - Attenuation < 0.25 dB/km
 - Dispersion coefficient is 18 ps/(nm.km)



Total Dispersion Example

- 50 km of singlemode fibre meeting ITU G.652
- 1550 nm DFB laser with a spectral width of 0.1 nm

$$\text{Total Dispersion, } D_t = D_c \times S \times L$$

$$= 18 \text{ ps/nm.km} \times 0.1 \text{ nm} \times 50 \text{ km}$$

$$= 90 \text{ ps total dispersion}$$



Dispersion Penalty Calculation

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- 50 km of singlemode fibre meeting ITU G.652
- 1550 nm DFB laser with a spectral width of 0.1 nm
- System operating at 2.5 Gbits/sec

Total Dispersion, $D_t = 90$ ps as before

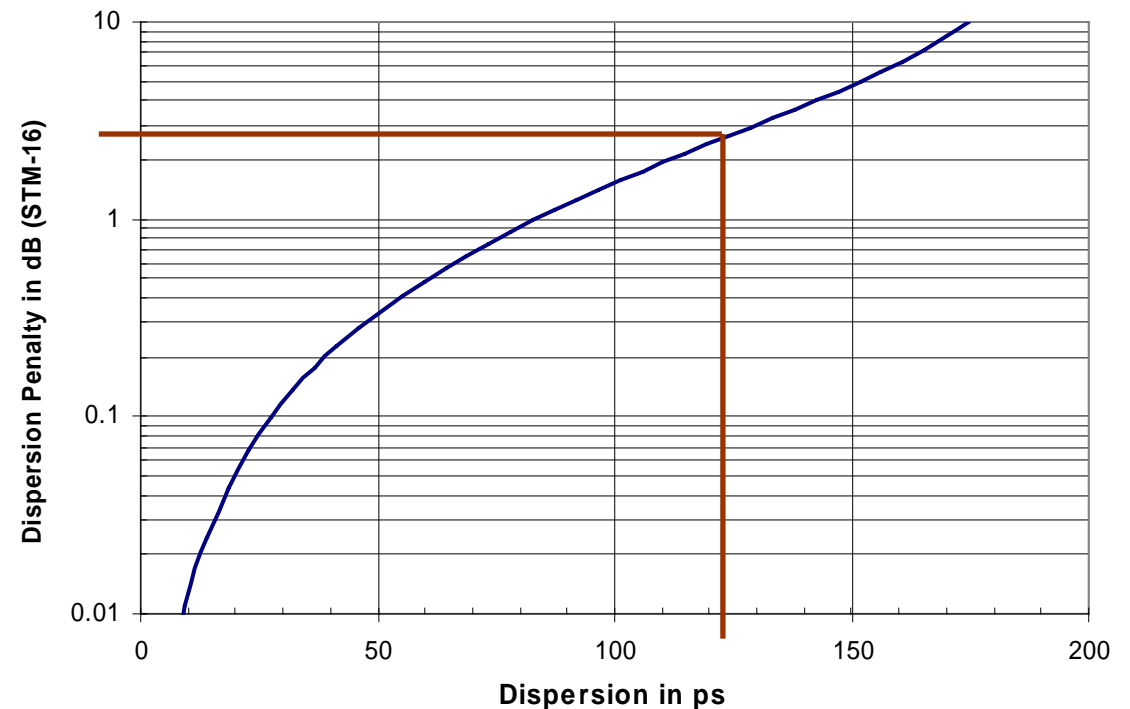
Dispersion Penalty: $P_d = -10 \log_{10} (1 - \frac{1}{2} (\pi B)^2 D_t^2)$

The Penalty is thus = 1.2 dB



Graphical Evaluation of the Dispersion Penalty

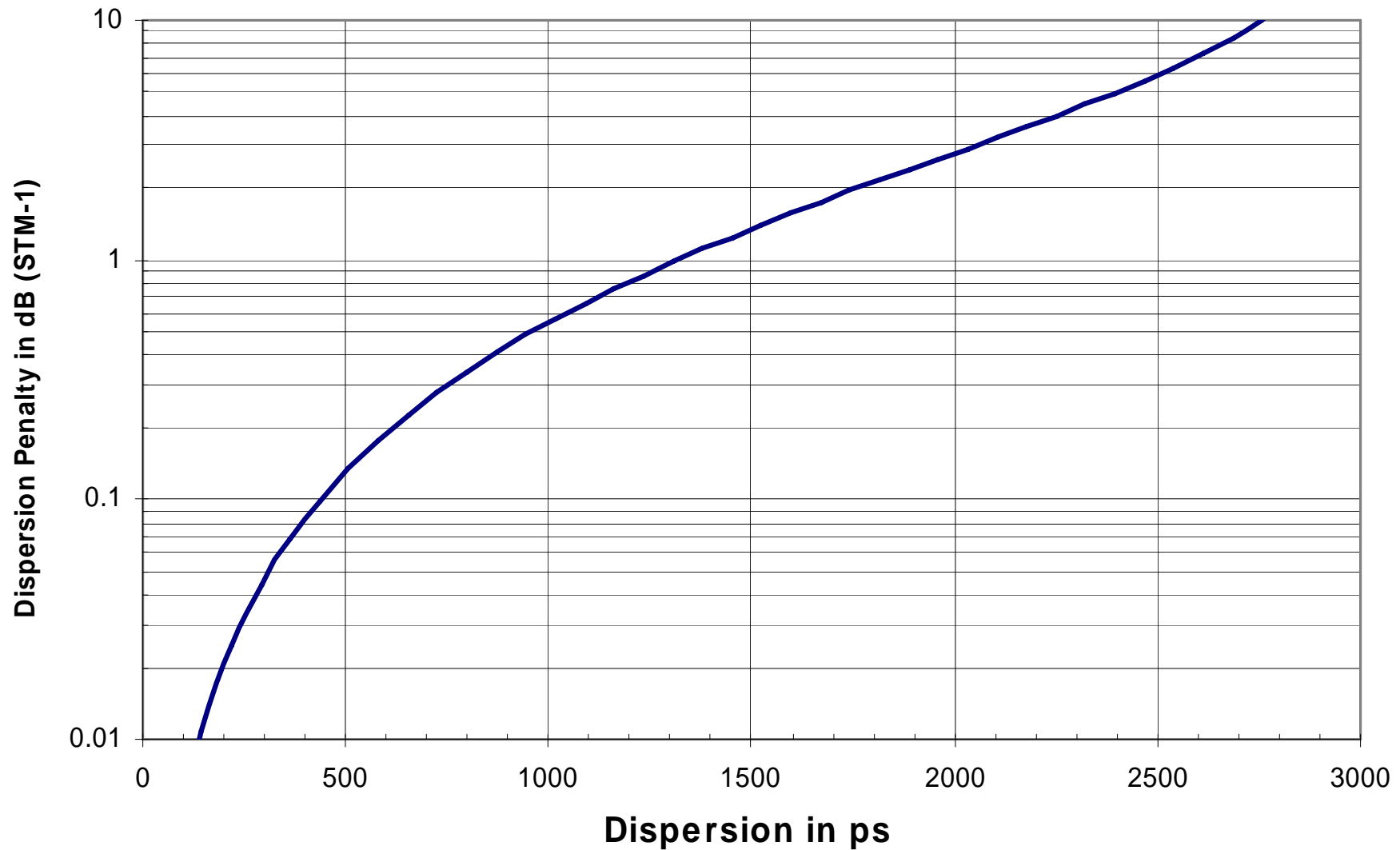
- Approximate dispersion penalty
- Draw line vertically from dispersion to meet curve
- Draw line horizontally to meet dispersion penalty axis
- Read off dispersion
- Example shown for STM-16
- 124 ps gives a penalty of 2.7 dB
- Exact calculated value is 2.64 dB



$$P_d = -10 \log_{10} (1 - \frac{1}{2} (\pi B)^2 \Delta^2)$$



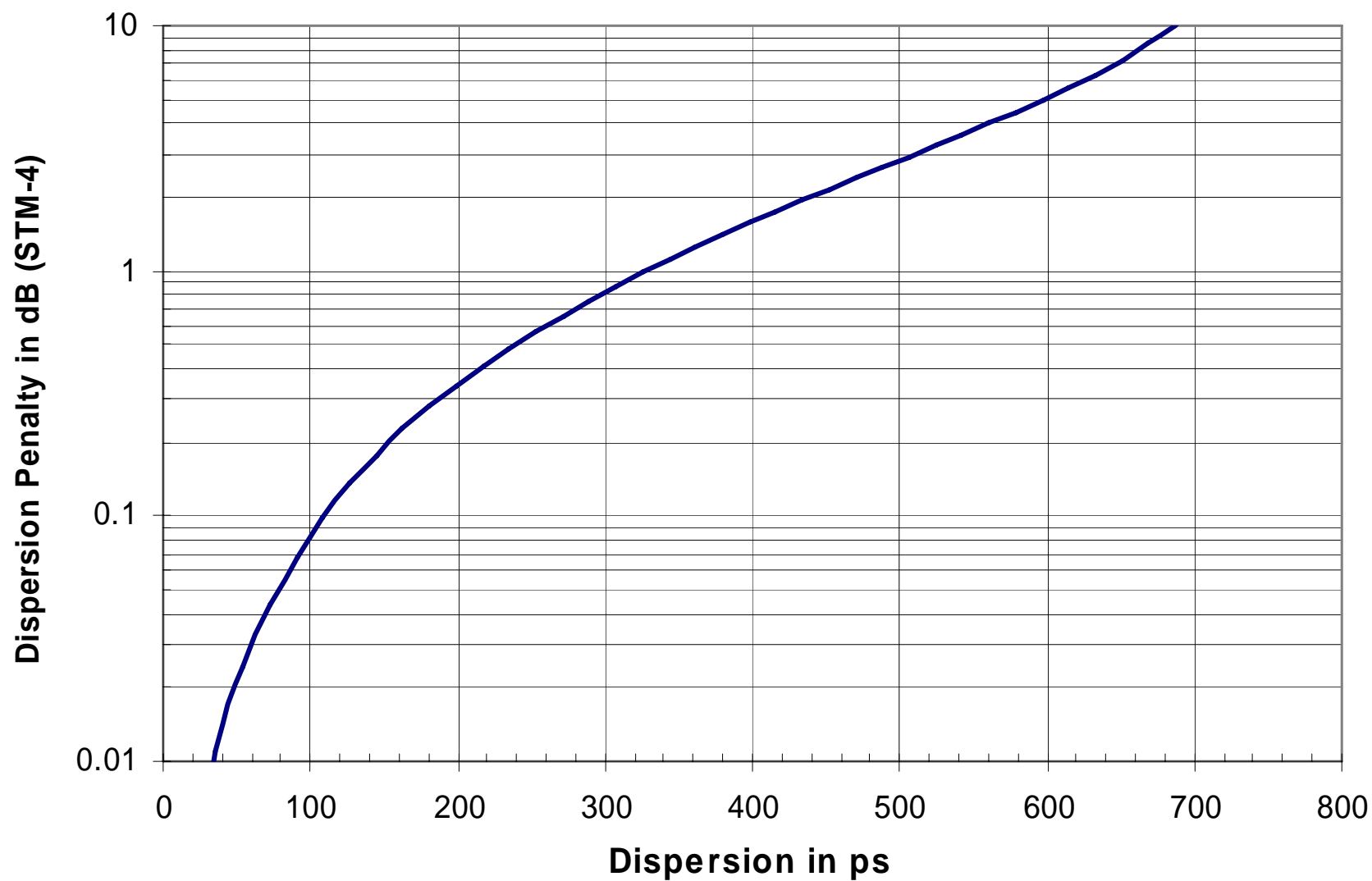
Dispersion Penalty for STM-1



$$P_d = -10\log_{10}\left(1 - \frac{1}{2}(\pi B)^2 \Delta^2\right)$$



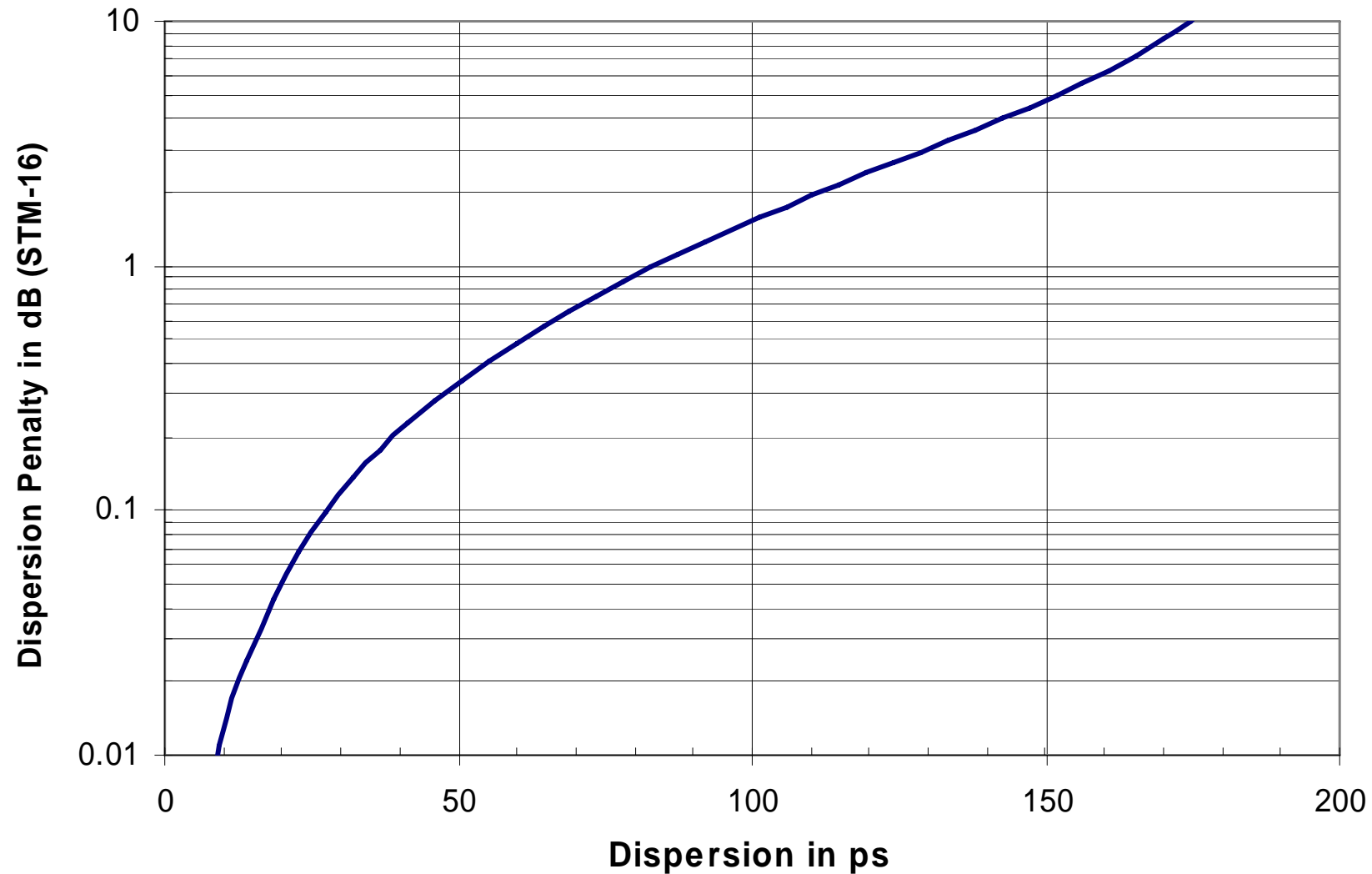
Dispersion Penalty for STM-4



$$P_d = -10\log_{10}\left(1 - \frac{1}{2}(\pi B)^2 \Delta^2\right)$$



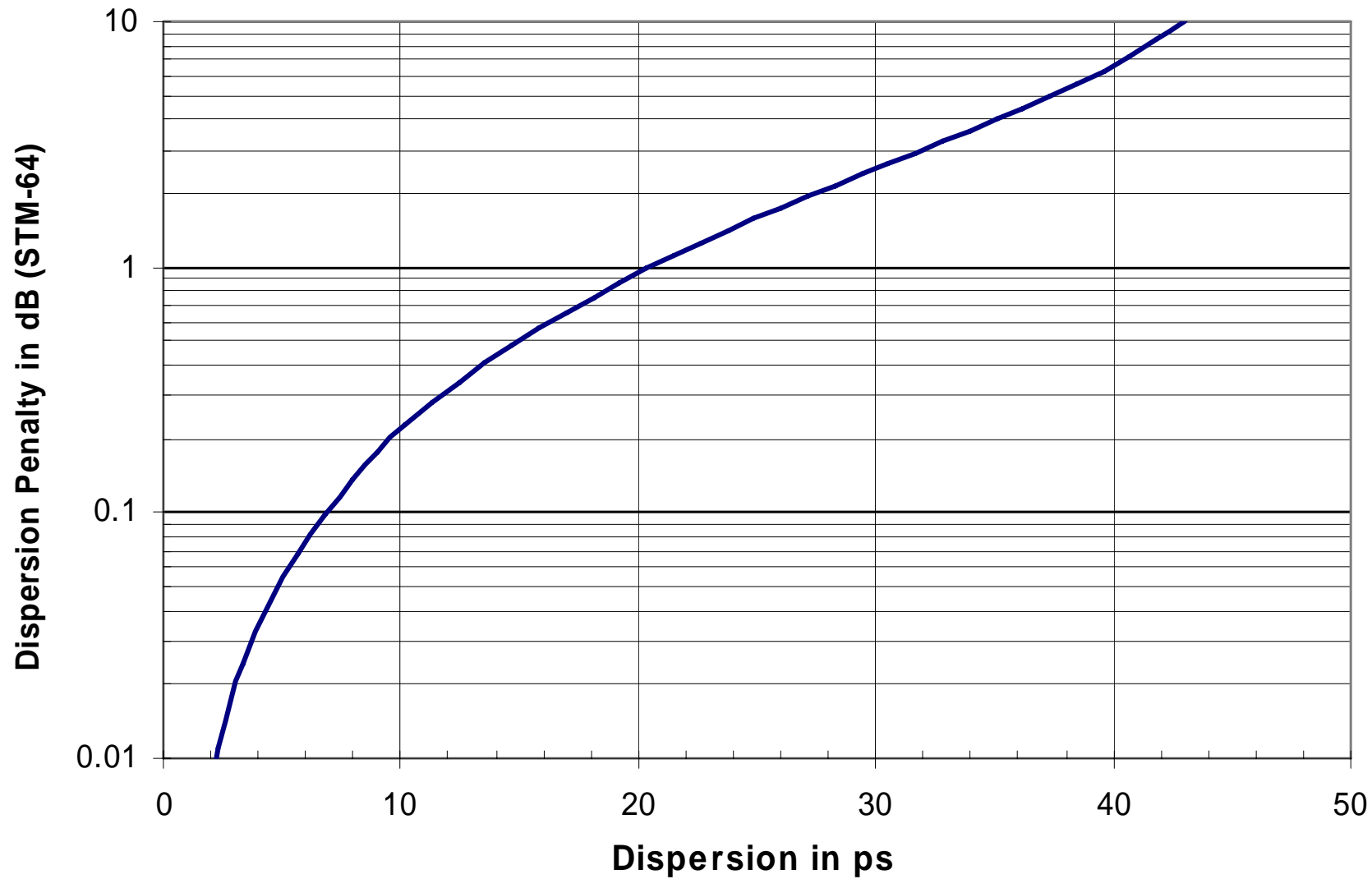
Dispersion Penalty for STM-16



$$P_d = -10 \log_{10} \left(1 - \frac{1}{2} (\pi B)^2 \Delta^2 \right)$$



Dispersion Penalty for STM-64



$$P_d = -10\log_{10}\left(1 - \frac{1}{2}(\pi B)^2 \Delta^2\right)$$



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Link Bandwidth Analysis

Link Bandwidth Analysis

- A link bandwidth analysis can answer the following questions:
 - The frequency response required for optical devices eg. source/detector/fibre.
 - The bandwidth of a particular electronic subsystem
 - The magnitude of bandwidth limiting, so that a power penalty can be calculated
-

Normal approach is carry out a worst case analysis using the risetimes of the various components.

Bandwidth can then be determined approximately from the expression:

$$\text{3 dB bandwidth} = \frac{0.35}{\text{Total risetime } tr}$$

or

$$\text{3 dB bandwidth (MHz)} = \frac{350}{\text{Total risetime } tr \text{ in ns}}$$



Evaluating Link Risetime

- If a system consists of n subsystems, each with an individual risetime then the total risetime t_r is given by:

$$t_r = 1.1 \sqrt{(t_{r1}^2 + t_{r2}^2 + \dots + t_{rn}^2)}$$

- From this formula t_r can be found OR if t_r is specified, then the subsystem risetime can be found by rearranging the formula.
- In an actual analysis the risetimes to be included are typically:
 - Source risetime.
 - Detector risetime.
 - Receiver electrical risetime = $0.35/(\text{rec BW})$.
 - Fibre modal dispersion, if present.
 - Fibre material dispersion.



Sample Problems involving a Dispersion Penalty



Sample Power Budget Exercise #2

- ✓ An optical fibre system operates at 1550 nm at a bit rate of 622 Mbits/sec over a distance of 71 km
- ✓ Fibre with a worst case loss of 0.25 dB/km is available.
- ✓ The average distance between splices is approximately 1 km.
- ✓ There are two connectors and the worst case loss per connector is 0.4 dB.
- ✓ The worst case fusion splice loss is 0.07 dB
- ✓ The receiver sensitivity is -28 dBm and the transmitter output power is +1 dBm
- ✓ The source spectral width is 0.12 nm and the fibre dispersion meets ITU recommendations at 1550 nm
- ✓ Use the **Low Pass Filter Approximation rule** - formula or graph
- ✓ *Determine worst case power margin, taking account of a power penalty*



Solution to Exercise #2

Step 1: Find the Dispersion Penalty

- 71 km of singlemode fibre meeting ITU G.652
- 1550 nm DFB laser with a spectral width of 0.12 nm
- System operating at 622 Mbits/sec

Total Dispersion = 153.6 ps

Dispersion Penalty from graph for STM-4 is 0.2 dB (why is it low?)



Solution to Exercise #2

Step 2: Develop the Power Budget and find the power margin

Transmitter output power	+1 dBm	Worst case (lowest) optical output power
Receiver sensitivity	-28 dBm	Minimum input optical power required
Power Budget	29 dB	Difference between transmitter and receiver levels.
Less dispersion penalty	0.2 db	From previous calculation
Less connector loss	0.8 dB	Two connectors at 0.4 dB max. each.
Less fibre loss	17.75 dB	71 km at 0.25 dB/km
Total number of splices	71	There are approximately 71 lengths of fibre in the link so there are approximately 71 splices
Less total maximum splice loss	4.97 dB	Assuming 0.07 dB per splice
Total attenuation and penalty	23.72 dB	Eg. $0.2 + 0.8 + 17.75 + 4.97$ dB
Answer: Power margin	5.28 dB	



Sample Power Budget Exercise #3

- ✓ The system described in Exercise #2 is to be upgraded to 2.5 Gbits/sec
- ✓ The span, fibre, connectors, splices are unchanged.
- ✓ The new transmitter output power and spectral width is the same
- ✓ The receiver sensitivity remains at -28 dB
- ✓ Again use the **Low Pass Filter Approximation rule** - formula or graph
- ✓ *Determine the new worst case power margin, taking account of a power penalty*



Solution to Exercise #3

Step 1: Find the Dispersion Penalty

- 71 km of singlemode fibre meeting ITU G.652
- 1550 nm DFB laser with a spectral width of 0.12 nm
- System operating at 2.5 Gbits/sec

Total Dispersion = 153.6 ps

Dispersion Penalty from the graph for STM-16 is about 5.5 dB

(The calculated penalty from the formula is 5.6 dB)



Solution to Exercise #3

Step 2: Develop the Power Budget and find the power margin

Transmitter output power	+1 dBm	Worst case (lowest) optical output power
Receiver sensitivity	-28 dBm	Minimum input optical power required
Power Budget	29 dB	Difference between transmitter and receiver levels.
Less dispersion penalty	5.5 db	From previous calculation
Less connector loss	0.8 dB	Two connectors at 0.4 dB max. each.
Less fibre loss	17.75 dB	71 km at 0.25 dB/km
Total number of splices	71	There are approximately 71 lengths of fibre in the link so there are approximately 71 splices
Less total maximum splice loss	4.97 dB	Assuming 0.07 dB per splice
Total attenuation and penalty	29.11 dB	Eg. 5.6 + 0.8 + 17.75 + 4.97 dB
Answer: Power margin	- 0.11 dB	Problem!



Options to Handle Poor Margin

- Clearly negative margin is a problem
- Could assume higher performance transmitter (higher o/p power) at higher bit rate but would be offset by lower receiver sensitivity, so probably no net gain
- Other options:
 - Given this is an upgrade scenario (fibre is installed), best approach is to measure actual attenuation and maybe dispersion, rather than use predicted values, probably will give acceptable margin.
 - Might also consider the use of a dispersion compensation module



More Advanced Power Budgets using a Statistical Approach

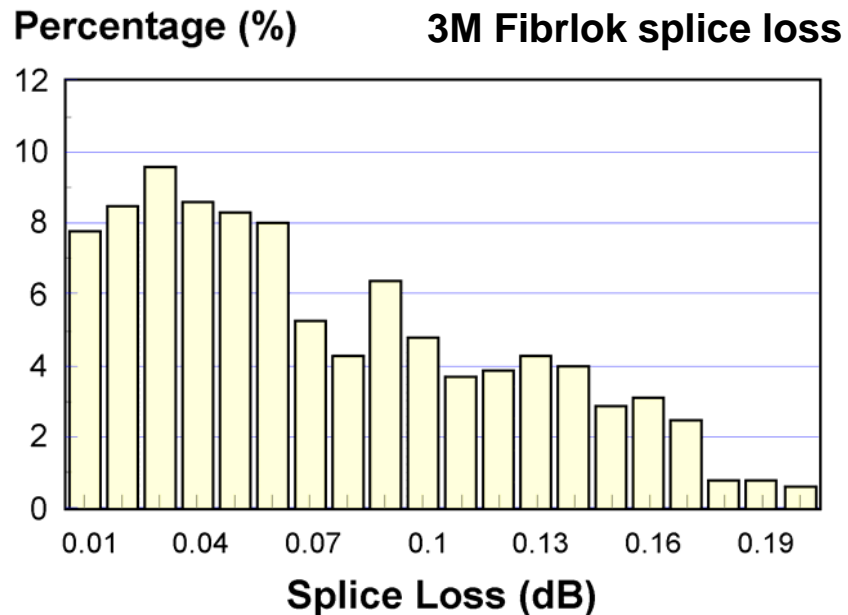


More Advanced Power Budgets: Statistical Analysis Approach

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- Ignoring the statistical nature of component performance by using worst case values in every case can create extremely overconservative designs.
 - Using average values only will give a more optimistic power budget but it may not be right every time
-

Example:



In finding the total loss caused by fusion splices, if the worst case loss for a fusion splice is simply multiplied by the number of splices involved, the result would be a figure for the total splice loss that would virtually never occur in practice.

3M Fibrlok average splice loss = 0.1 dB



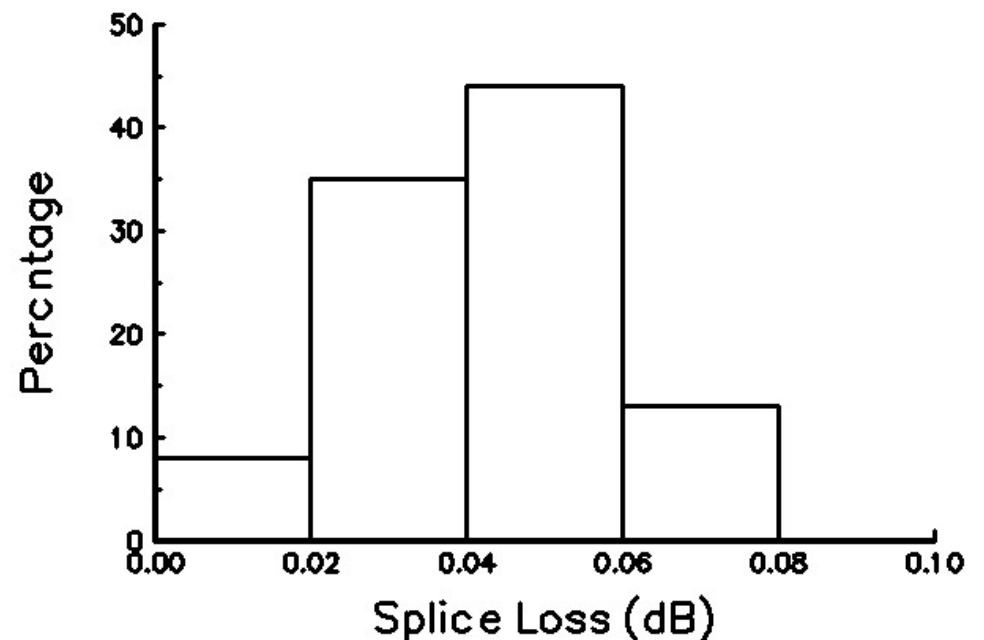
More advanced Power Budgets: Statistical Analysis Approach

- Ignoring the statistical nature of component performance by using worst case values, in every case, can create extremely overconservative designs.
 - If this approach continues into the installation, time will be wasted trying to solve "conditions" that do not really exist.
-

Example:

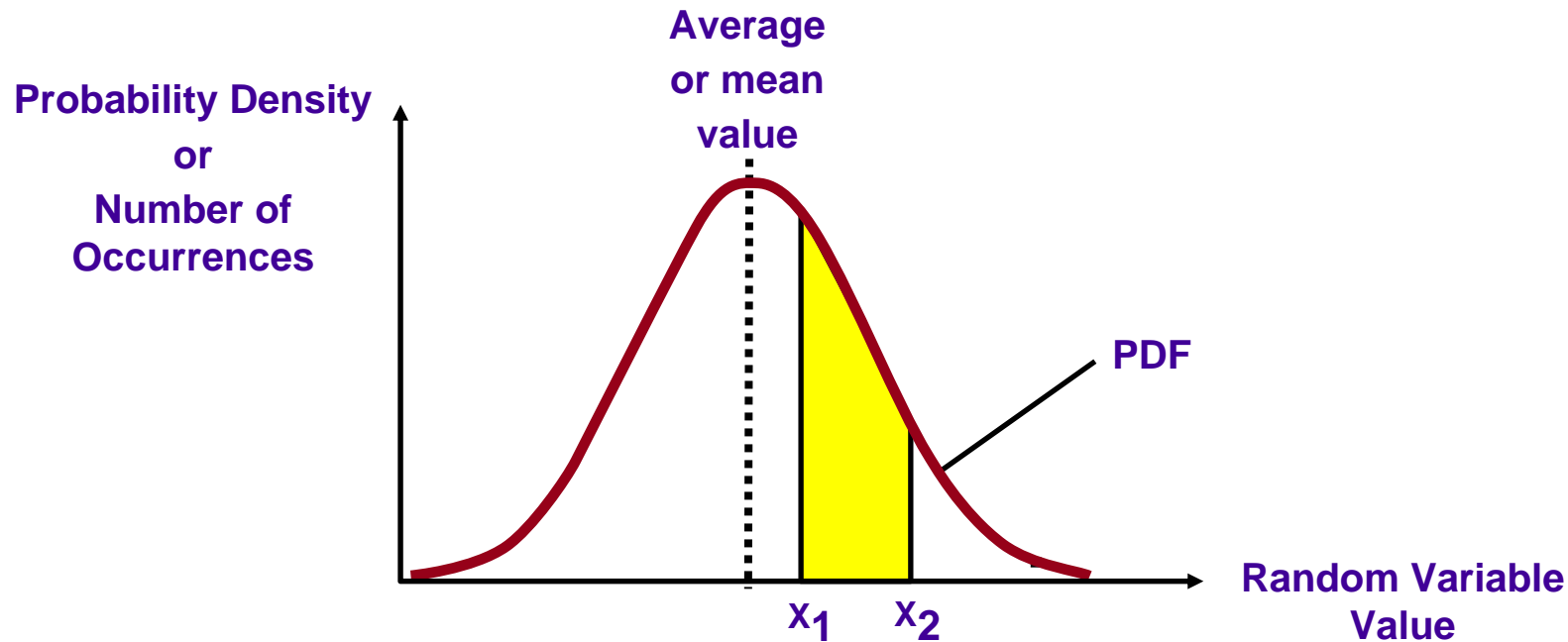
In finding the total loss caused by fusion splices, if the worst case loss for a fusion splice is simply multiplied by the number of splices involved, the result would be a figure for the total splice loss that would virtually never occur in practice.

Singlemode Fibre Fusion Splice Loss





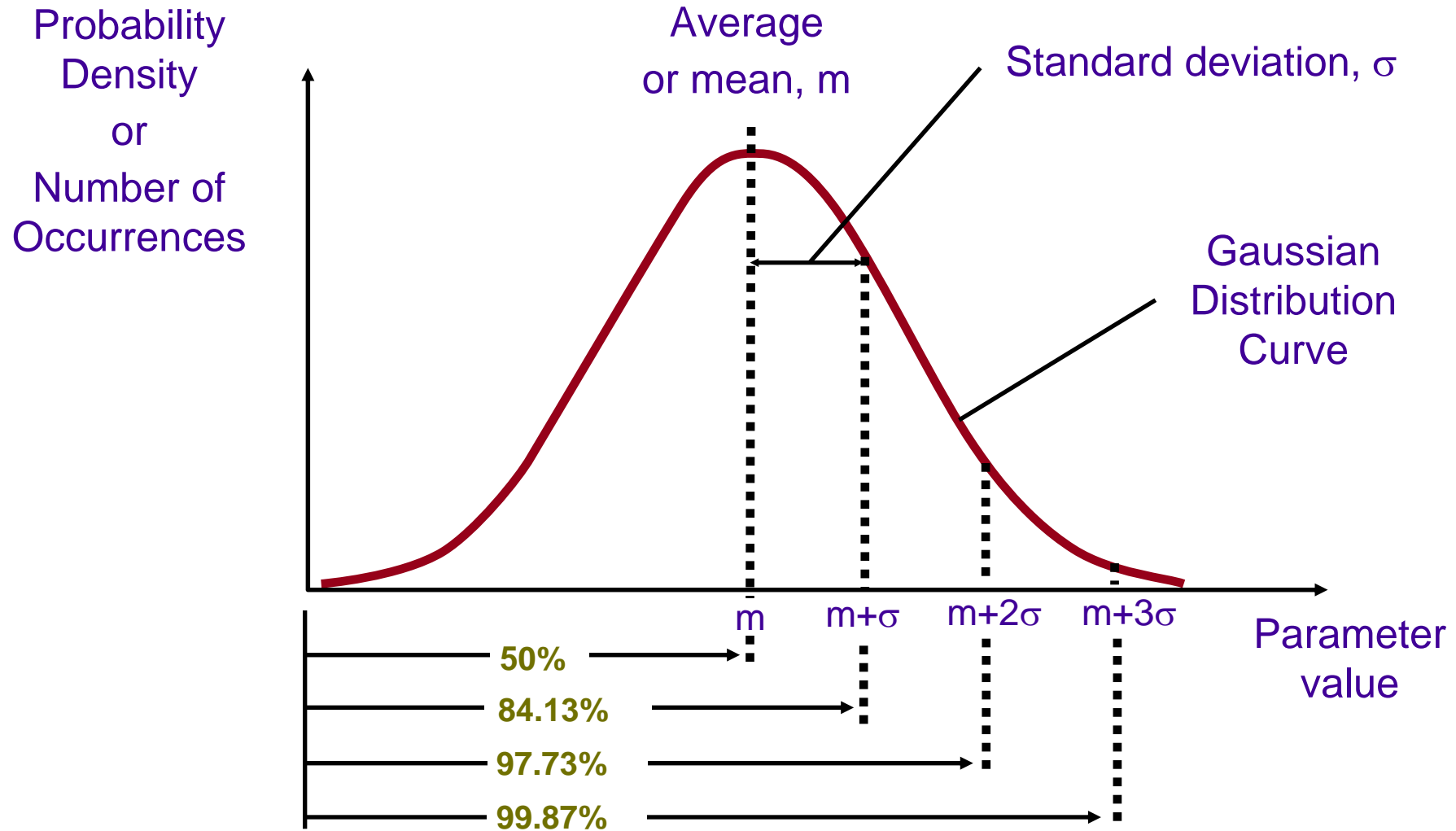
Probability Density Function Overview



- Area under probability density function (PDF) for a random variable X indicates probability that the random variable will take on a value within a specified range.
- For example above the probability that a random variable X lies between x_1 and x_2 is given by the area of the shaded portion under the PDF curve
- Variety of PDFs exist, Gaussian (or Normal) PDF is one of the most common

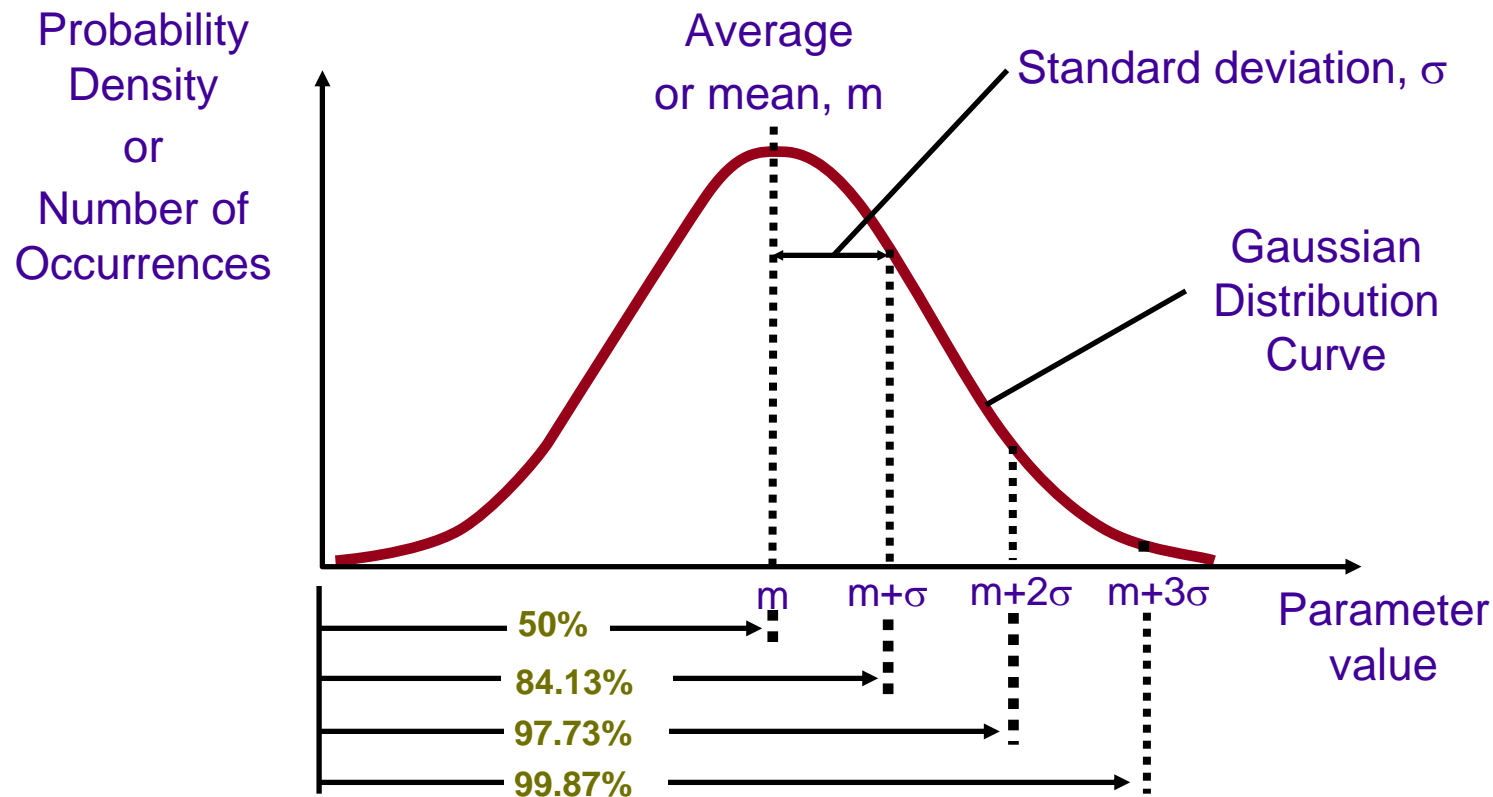


Gaussian Distribution





Statistical Confidence - Gaussian PDF



- 84.13% of the values contained within range zero and one standard deviation above average.
- 97.73% within range zero to two standard deviations above average.
- 99.87% within range zero to three standard deviations above average.



Using Statistical Component Losses

- Component loss tends to follow a Normal (Gaussian) statistical distribution.
- In a statistical approach the average value and the so-called standard deviation for component losses are found from the manufacturers data.
- The **statistical** loss value used in the power budget calculation is then found by adding together the average value and one or more standard deviations
- Statistically it is possible to predict how reliable the statistical loss value is:

Average + 1 Standard
Deviation

Statistical confidence level =
84.13 %

Average + 2 Standard
Deviations

Statistical confidence level =
97.73 %

Average + 3 Standard
Deviations

Statistical confidence level =
99.87%

- In power budget calculations, generally, the two standard deviation value is normally used.
- Difficulties can arise in getting statistical information on components. In this case use worst case for that component. Called a semi-statistical approach



Statistical Power Budget Example (I)

Power budget calculation to calculate power margin with worst case values

Transmitter o/p power (dBm)	-18.5 dBm min, -14.0dBm max
Receiver sensitivity (dBm)	-30 dBm min
Available power budget:	11.5 dB using worst case value
<hr/>	
Number of Connectors	6
Worst case Connector loss (dB)	0.71
Total connector loss (dB)	4.26
Fibre span (km)	2.0
Maximum Fibre loss (dB/Km)	1.5 dB at 1300 nm
Total fibre loss (dB)	3.0
Number of 3M Fibrlok mechanical splices	10
Worst case splice loss per splice (dB)	0.19
Total splice loss (dB)	1.9
Total loss:	9.16 dB
<hr/>	
Power margin (dB)	2.34 — Answer

Replace with
statistical data

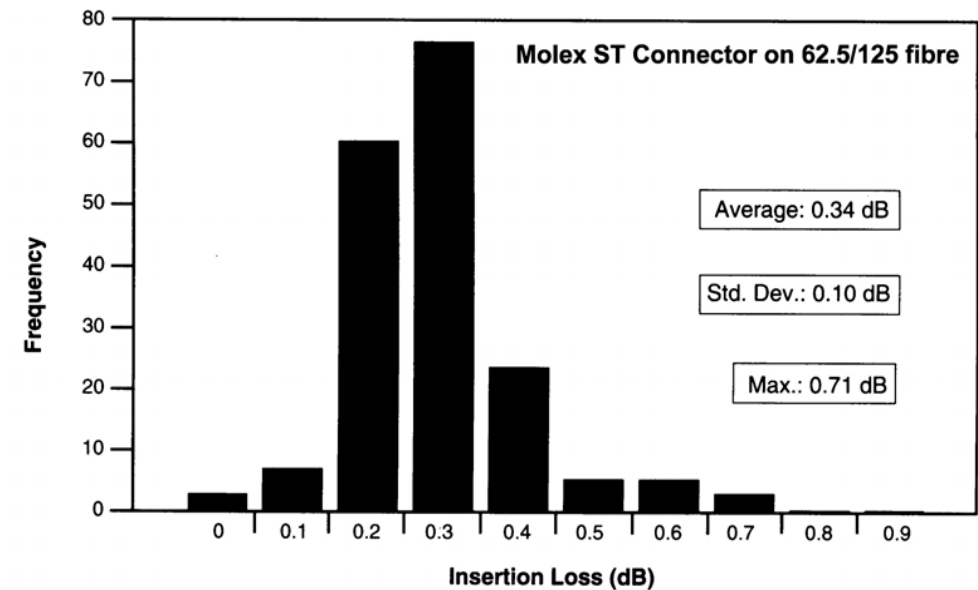


Statistical Power Budget Example (II): Component Data

Cable Attenuation:

Average at 1330 nm: 1.15 dB

Standard Deviation: 0.17 dB



Connector Loss

Mechanical Splice Attenuation:

Average: 0.1 dB Standard Deviation: 0.03 dB



Statistical Power Budget Example (III)

Repeat power budget calculation using average plus one standard deviation

Transmitter o/p power (dBm)	-18.5 dBm min, -14.0dBm max
Receiver sensitivity (dBm)	-30 dBm min
Available power budget:	11.5 dB using worst case value
<hr/>	
Number of Connectors	6
Connector loss (dB)	$0.34 + 0.1$
Total connector loss (dB)	2.64
Fibre span (km)	1.5
Fibre loss (dB/Km)	$1.15 + 0.17 \text{ dB at } 1300 \text{ nm}$
Total fibre loss (dB)	2.64
Number of 3M Fibrlok mechanical splices	10
Splice loss per splice (dB)	$0.1 + 0.03 \text{ dB}$
Total splice loss (dB)	1.3
Total loss:	6.58 dB
<hr/>	
Power margin (dB)	4.92 ——— Answer

Statistical data



Comparison of Results

	Total Connector Attenuation	Total Fibre Attenuation	Total Splice Attenuation	Available Power Margin
Average + 1 std dev	2.64 dB	2.64dB	1.3 dB	4.92 dB
Average + 2 std dev	3.24 dB	2.98 dB	1.6 dB	3.68 dB
Worst case	4.26 dB	3.0 dB	1.9 dB	2.34 dB



Sample Power Budget Exercise using a Statistical Approach



Sample Statistical Power Budget Exercise (Long-Haul)

A 622 Mb/s optical transmission system is to operate at a wavelength of 1550 nm over an unrepeated distance of 51 km. The transmitter available has a minimum fibre coupled output power of +4 dBm, while the receiver has a worst case sensitivity of -28 dBm.

Two types of fibre are available with different specifications as shown in Table 1 below. Two connectors are used in the system. The average distance between fusion splices is 700 m. The connector and fusion splice losses are shown in Table 2.

Calculate the dispersion penalty associated with the use of each fibre. By preparing a two standard deviation statistical power budget using each fibre type in turn decide whether fibre type A or B should be used and why. State clearly any assumptions made.



Sample Exercise Data

Fibre type	Total dispersion	Attenuation	Attenuation Standard Deviation
A	7 ps/km	0.36 dB/km	0.05 dB/km
B	9.5 ps/km	0.33 dB/km	0.04 dB/km

Table 1

Joint Type	Average attenuation	Attenuation Standard deviation
Fusion splice	0.03 dB	0.012 dB
Connector	0.25 dB	0.04 dB

Table 2



Sample Exercise Solution (I)

Step 1: Calculate the dispersion penalties for fibre type A and type B.

Find the total dispersion by multiplying the dispersion per km by the systems span of 51 km and then using the formula below to find the dispersion penalty:

$$P_d = -10 \log_{10} \left(1 - \frac{1}{2} (\pi B)^2 D_t^2 \right)$$

Fibre Type A: total dispersion 7 ps/km by 51 km = 357 ps, so the dispersion penalty is 1.21 dB

Fibre Type B: total dispersion 9.5 ps/km by 51 km = 484.5 ps, so the dispersion penalty is 2.58 dB

Fibre B has a higher penalty - but cannot make a decision on fibre choice yet!



Sample Exercise Solution (II)

Step 2: Calculate the attenuation values to be used:

Assuming a two standard deviation statistical power budget then the attenuation values to be used are:

Fibre A	0.36 dB/km	+	0.1 dB/km	=	0.46 dB/km
Fibre B	0.33 dB/km	+	0.08 dB/km	=	0.41 dB/km
Connector	0.25 dB	+	0.08 dB	=	0.33 dB
Fusion splice	0.03 dB	+	0.024	=	0.054 dB

Each attenuation value is the sum of the average plus two standard deviations

All other values such as transmitter output powers are available only as worst case and are used as such. Now proceed with comparative power budgets for fibre A and B



Sample Exercise: Power Budget Fibre A

Statistical Case, Fibre A				
Basic Information			Derived Information	
System Span in km	51.000			
Transmitter Output Power (dBm)	4.000			
Number of Connectors	2.000			
Connector Loss (dB)	0.330		Total Connector Loss (dB)	0.660
Fibre Attenuation	0.460		Total fibre attenuation (dB)	23.460
Maximum fibre length available (km)	0.700		No. of fibre lengths needed	72.857
Loss per splice (dB)	0.054		Total splice loss (dB)	3.880
Dispersion Penalties	1.211			
Receiver sensitivity (dBm)	-28.000		Available power margin (dB)	2.789



Sample Exercise: Power Budget Fibre B

Statistical Case, Fibre B				
Basic Infomation			Derived Information	
System Span in km	51.000			
Transmitter Output Power (dBm)	4.000			
Number of Connectors	2.000			
Connector Loss (dB)	0.330		Total Connector Loss (dB)	0.660
Fibre Attenuation	0.410		Total fibre attenuation (dB)	20.910
Maximum fibre length available (km)	0.700		No. of fibre lengths needed	72.857
Loss per splice (dB)	0.054		Total splice loss (dB)	3.880
Dispersion Penalties	2.583			
Receiver sensitivity (dBm)	-28.000		Available power margin (dB)	3.967



Sample Exercise Conclusions

Fibre type B is chosen as it offers a higher power margin for upgrades and repairs in the future

Extensions to the exercise:

1. Repeat the exercise using both a one and a three standard deviation approach -

- What are the power margins for each fibre in each case?
- What are your conclusions?

2. Estimate the bit rate for the two standard deviation case at which the power margin falls below 2 dB for fibre A and B, Discuss your result in the context of the dispersion performance of the different fibres

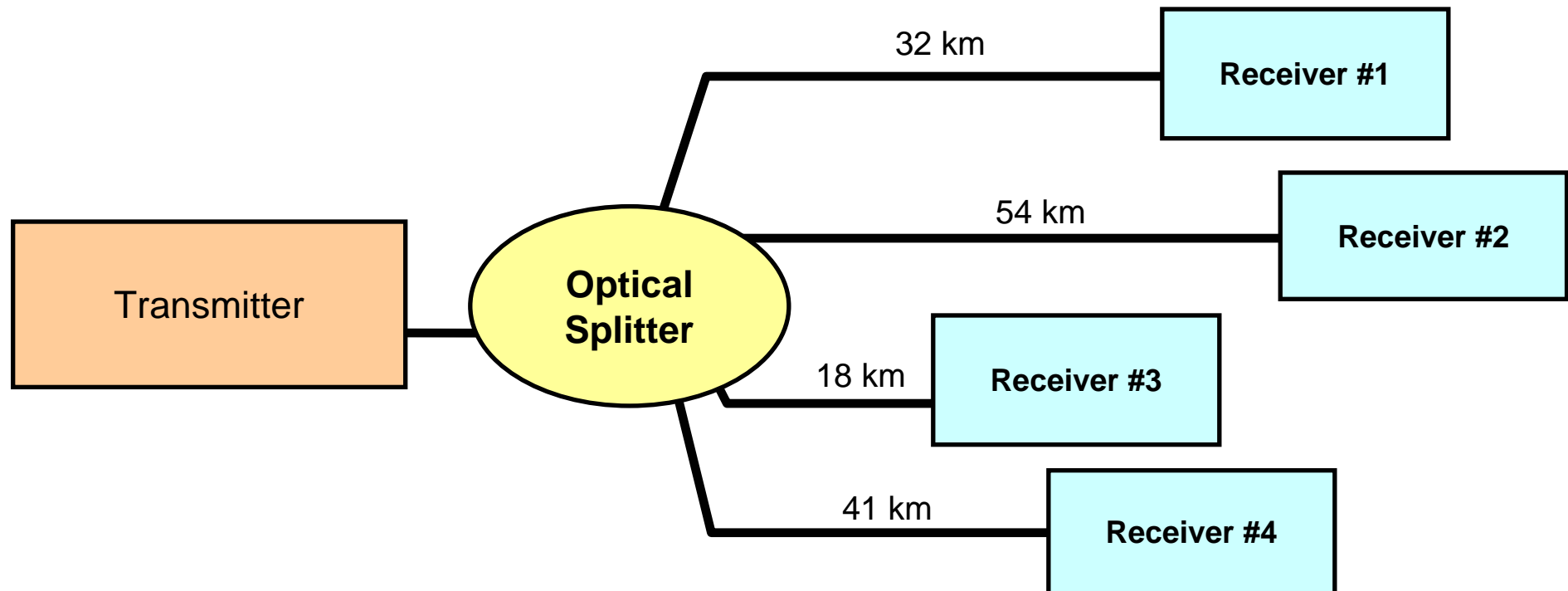


Power Budgeting in Distributed Systems



Overview

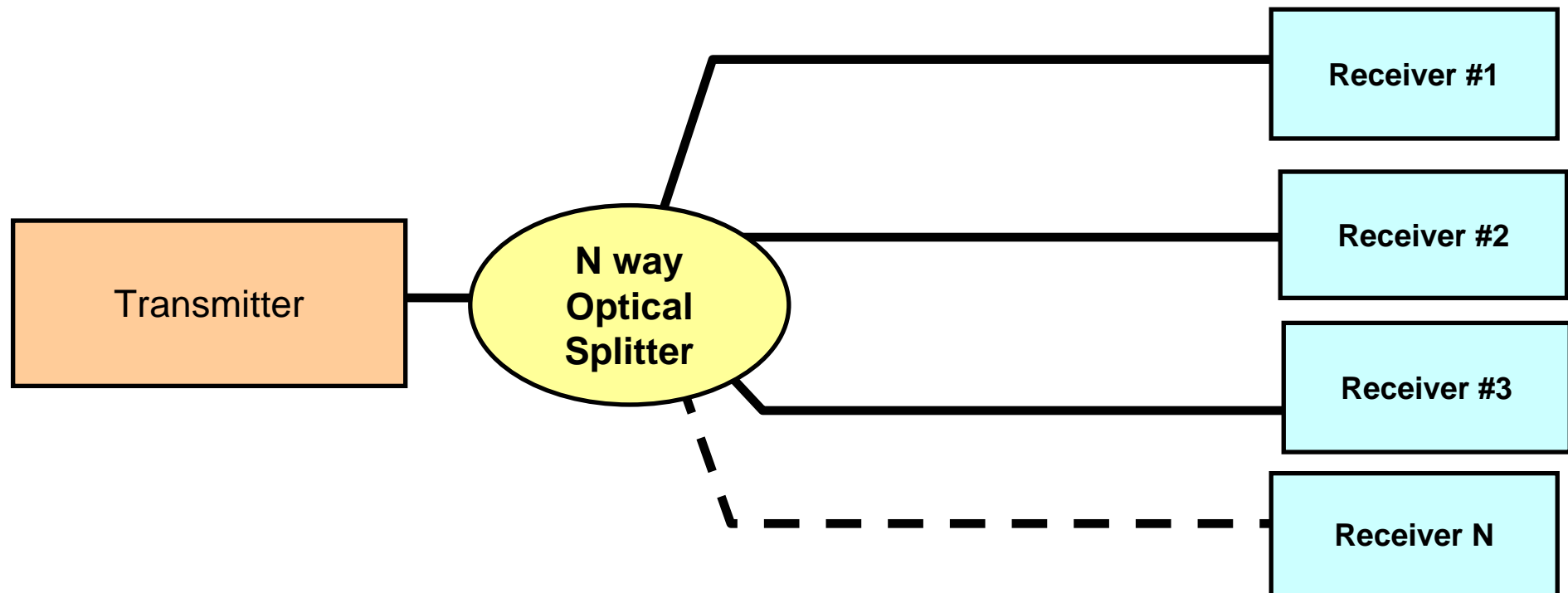
- Single transmitter signal distributed to two or more receivers via optical splitters





Equal power splitter

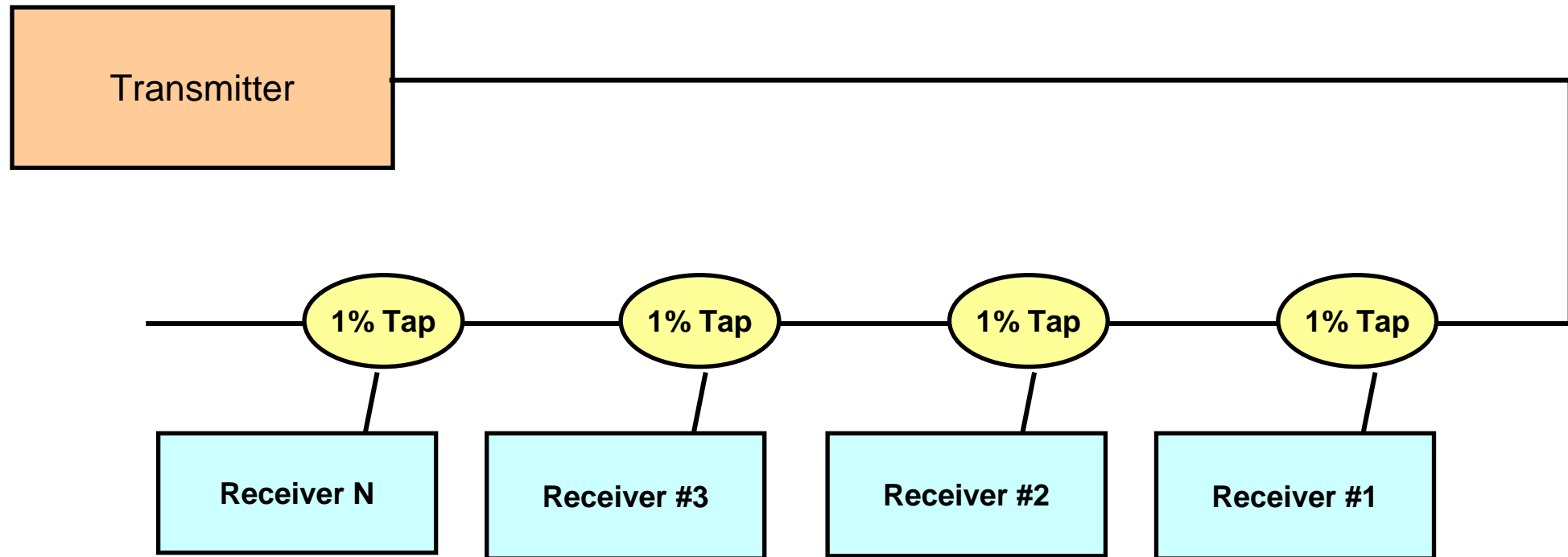
- Single transmitter signal distributed to N receivers
- Up to 32 ways
- Insertion loss of splitter main source of loss





1% tap splitter

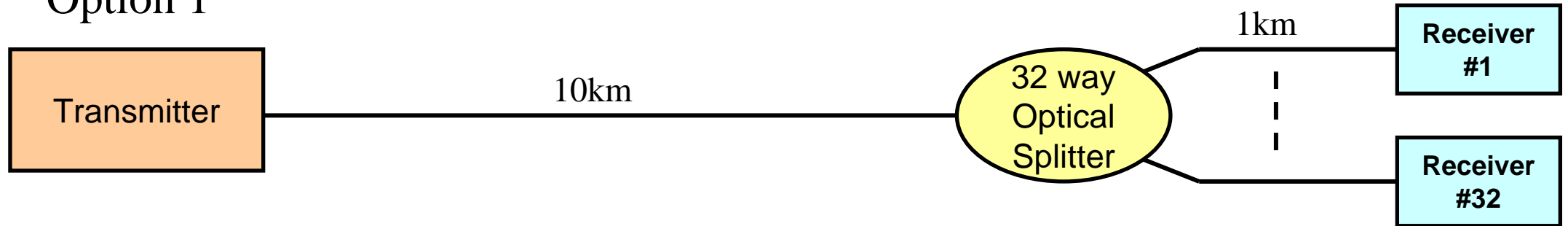
- Single transmitter signal distributed to N receiver
- Again insertion loss of splitter main source of loss





Exercise: Distributed systems

Option 1



Option 2



- Using only one transmitter we wish to distribute an optical video signal to 32 residential customers. Using the specifications and questions investigate both options.



Exercise: Distributed systems

APPLIED OPTOELECTRONICS CENTRE

- G.652 fibre – 0.2dB/km @ 1550 nm
 - Worst case splice loss 0.07dB per splice
 - Worst case connector loss 0.4dB
 - 32 way splitter
 - 4 of 1*8 splitter and 1 of 1*4 splitter
 - 1*4 splitter maximum insertion loss 7.2 dB
 - 1*8 splitter maximum insertion loss 10.8 dB
 - Splitters are spliced into network
 - 1% Tap
 - 1/99 split ratio, insertion loss 19-21 db / 0.2 dB
 - 50 m between taps
 - Tap is spliced into network
 - PON (passive optical network) typical Tx and Rx specs
 - Terminated with connectors
 - Transmitter output power 0 dBm
 - Receiver sensitivity -24 dBm
1. Determine the power margin for option one.
 2. Determine the power margin for the first receiver in option two.
 3. Investigate if any improvements can be made to option two by changing the splitter type.



Power Budgeting in SDH Systems



ITU Rec. G.957

**Optical Interfaces for Equipments
and Systems relating to the SDH**



ITU System Classification (I)

- SDH system interfaces are classified by an ITU coding scheme
- ITU Code is defined as: *Application Code* - *STM level*.*Suffix number*
 - **Application Code:**
I (intra-office), S (Short haul), L (Long haul), V (very long Haul)
 - **STM level:** 1, 4, 16, 64
 - **Suffix number:**
 - (blank) or 1 indicating nominal 1310 nm wavelength sources on G.652 fibre;
 - 2 indicating nominal 1550 nm wavelength sources on G.652 fibre for short-haul applications and either G.652 or G.654 fibre for long-haul applications;
 - 3 indicating nominal 1550 nm wavelength sources on G.653 fibre.



Application		Intra-office	Inter-office					
			Short-haul		Long-haul			
Source nominal wavelength (nm)		1310	1310	1550	1310	1550		
Type of fibre		Rec. G.652	Rec. G.652	Rec. G.652	Rec. G.652	Rec. G.652 Rec. G.654	Rec. G.653	
Distance (km) ^{a)}		≤ 2	~ 15		~ 40	~ 80		
STM level	STM-1	I-1	S-1.1	S-1.2	L-1.1	L-1.2		L-1.3
	STM-4	I-4	S-4.1	S-4.2	L-4.1	L-4.2		L-4.3
	STM-16	I-16	S-16.1	S-16.2	L-16.1	L-16.2		L-16.3
^{a)} These are target distances to be used for classification and not for specification.								

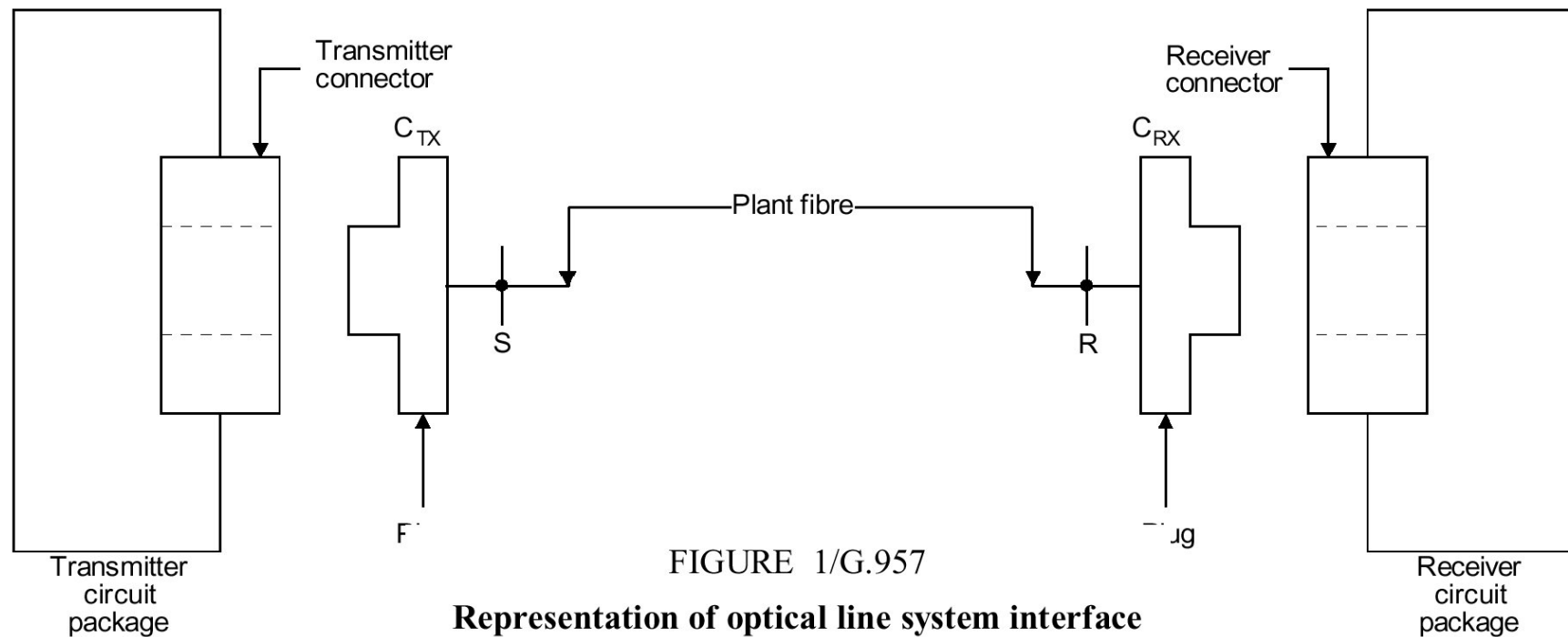


REC. G.957 Reference Points

APPLIED OPTOELECTRONICS CENTRE

G.957 is very specific about the optical path:

- The S reference point is just after the Transmitter optical connector C_{TX}
- The R reference point is just before the receiver optical connector C_{RX}
- Additional connectors on the Optical Distribution Frame (ODF) are considered to be part of the fibre plant





STM-16 Transmitter Specifications as per ITU G.957

APPLIED OPTOELECTRONICS CENTRE

	Unit	Values					
Digital signal Nominal bit rate	kbit/s	STM-16 according to Recommendations G.707 and G.958 2 488 320					
Application code (Table 1)		I-16	S-16.1	S-16.2	L-16.1	L-16.2	L-16.3
Operating wavelength range	nm	1266 ^a)-1360	1260 ^a)-1360	1430-1580	1280-1335	1500-1580	1500-1580
Transmitter at reference point S							
Source type		MLM	SLM	SLM	SLM	SLM	SLM
Spectral characteristics							
– maximum RMS width (σ)	nm	4	–	–	–	–	–
– maximum –20 dB width	nm	–	1	< 1 ^b)	1	< 1 ^b)	< 1 ^b)
– minimum side mode – suppression ratio	dB	–	30	30	30	30	30
Mean launched power							
– maximum	dBm	–3	0	0	+3	+3	+3
– minimum	dBm	–10	–5	–5	–2	–2	–2
Minimum extinction ratio	dB	8.2	8.2	8.2	8.2	8.2	8.2



STM-16 Receiver Specifications as per ITU G.957

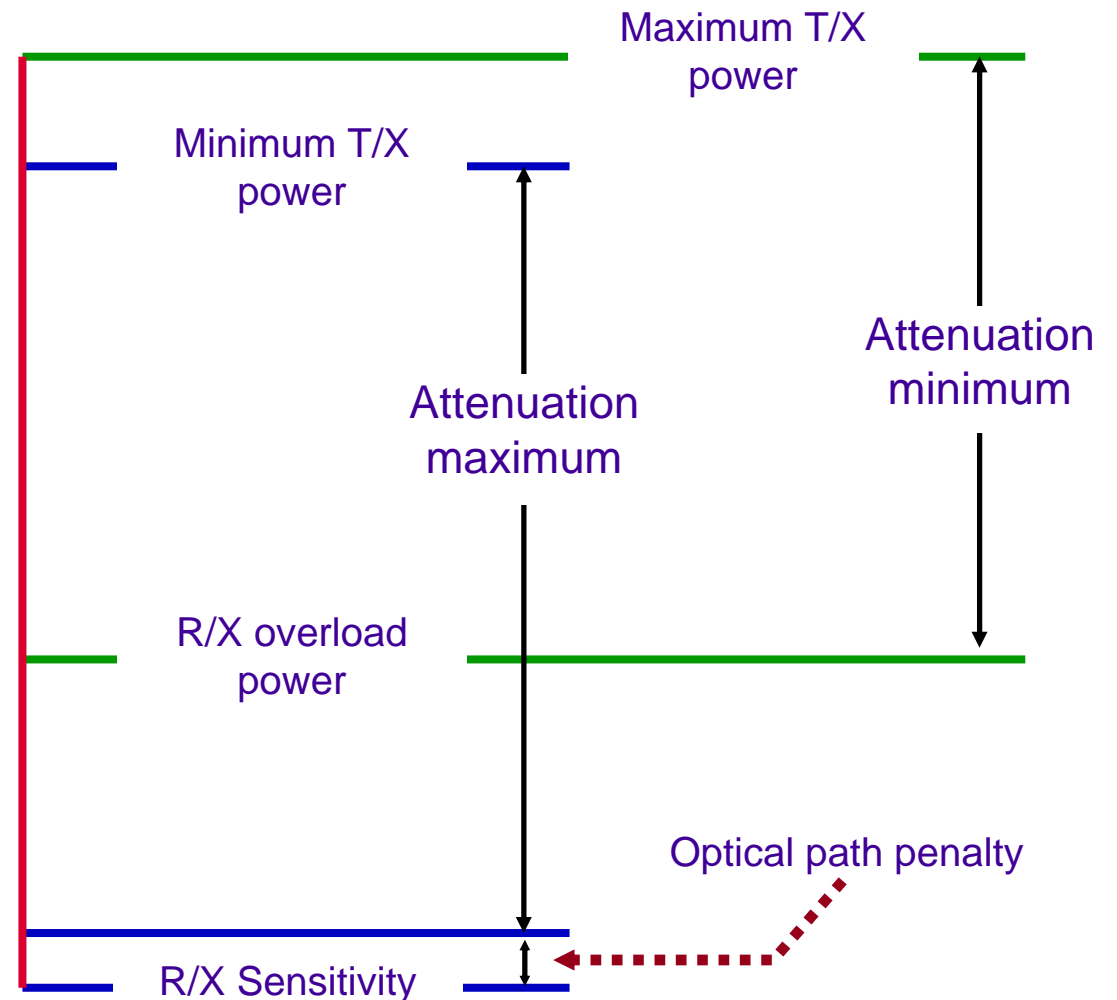
- The optical path penalty accounts for degradations due to reflections, intersymbol interference (caused by dispersion), mode partition noise and laser chirp.
- Overload is an important parameter on short range systems

	Unit	Values					
Digital signal Nominal bit rate	kbit/s	STM-16 according to Recommendations G.707 and G.958 2 488 320					
Application code (Table 1)		I-16	S-16.1	S-16.2	L-16.1	L-16.2	L-16.3
Operating wavelength range	nm	1266 ^a)-1360	1260 ^a)-1360	1430-1580	1280-1335	1500-1580	1500-1580
Receiver at reference point R							
Minimum sensitivity ^{c)}	dBm	-18	-18	-18	-27	-28	-27
Minimum overload	dBm	-3	0	0	-9	-9	-9
Maximum optical path penalty	dB	1	1	1	1	2	1
Maximum reflectance of receiver, measured at R	dB	-27	-27	-27	-27	-27	-27



REC. G.957 Design Approach

- The optical path penalty is effectively added to receiver sensitivity
- The maximum and minimum T/X powers are at the S reference point
- The receiver sensitivity is at the R reference point
- Worst case design and statistical design approaches used.
- Manufacturers data may exceed G.957 specs





STM-16 Optical Path Specifications as per ITU G.957

	Unit	Values					
Digital signal Nominal bit rate	kbit/s	STM-16 according to Recommendations G.707 and G.958 2 488 320					
Application code (Table 1)		I-16	S-16.1	S-16.2	L-16.1	L-16.2	L-16.3
Operating wavelength range	nm	1266 ^{a)} -1360	1260 ^{a)} -1360	1430-1580	1280-1335	1500-1580	1500-1580
Optical path between S and R							
Attenuation range ^{c)}	dB	0-7	0-12	0-12	10-24 ^{e)}	10-24 ^{e)}	10-24 ^{e)}
Maximum dispersion	ps/nm	12	NA	^{b)}	NA	1200-1600 ^{b),d)}	^{b)}
Minimum optical return loss of cable plant at S, including any connectors	dB	24	24	24	24	24	24
Maximum discrete reflectance between S and R	dB	-27	-27	-27	-27	-27	-27

Note: Dispersion limits are under study or cannot be agreed in some cases



Power Budgeting in DWDM Systems

Power Budgeting in DWDM Systems

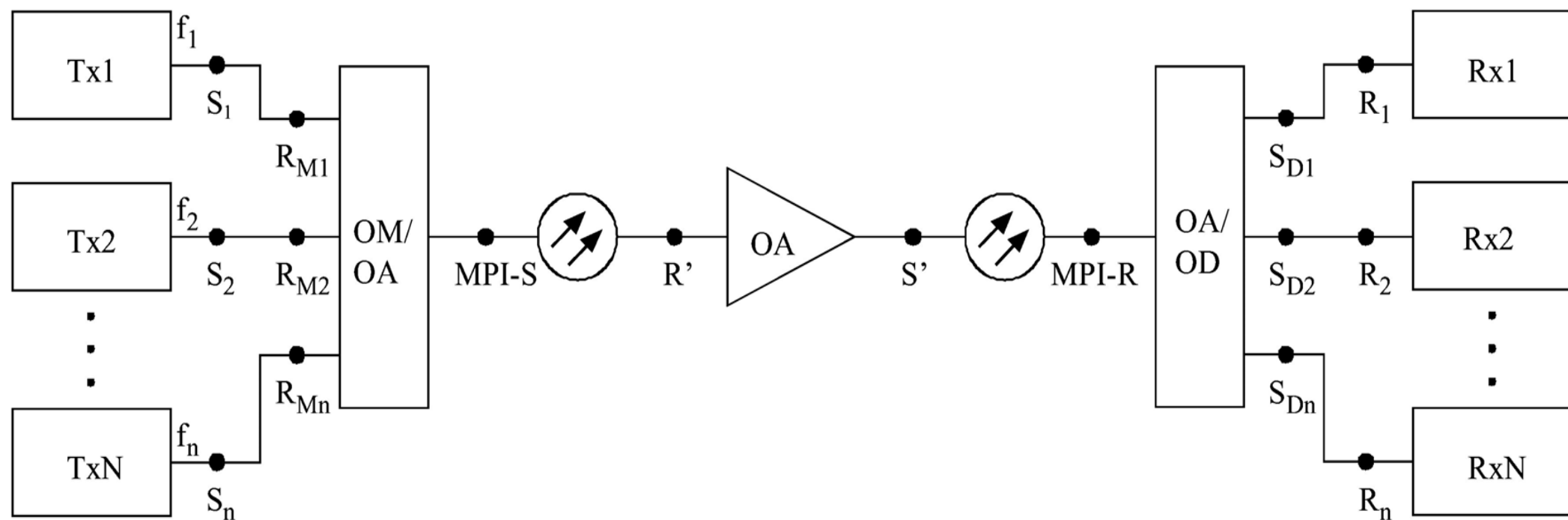
- **Power budgeting in DWDM is much more complex due to:**
 - Multiple channels
 - Limits on power caused by FWM and other effects
 - Presence of amplifiers, multiplexers and demultiplexers
- **Overall end-to-end budgets are typically a lot higher eg. 160 dB**
- **Most manufacturers comply with ITU-T standards G.692 and G.957 (single channel systems)**
- **As with SDH involves classifying the system by an ITU methodology**

Overview of the G.692 Standard

- **Recommendation deals with optical line systems that include the following features:**
 - Maximum number of channels: 4, 8, 16 , 32 or more;
 - Signal channel types: STM-4, STM-16, or STM-64;
 - Transmission over a single fibre: unidirectional or bi-directional.
- **As with G.957 the standard defines:**
 - A reference model for DWDM systems
 - Application codes with/without **LINE** optical amplifiers
- **G.692 draws heavily from G.957 for many parameter values, e.g.. transmitter output power etc.**



G.692 Reference Points



T1527240-97

Figure 1/G.692 – Representation of optical line system interfaces

S and R reference points refer to Transmitter outputs and receiver inputs at connectors as in G.957 (See next overhead)



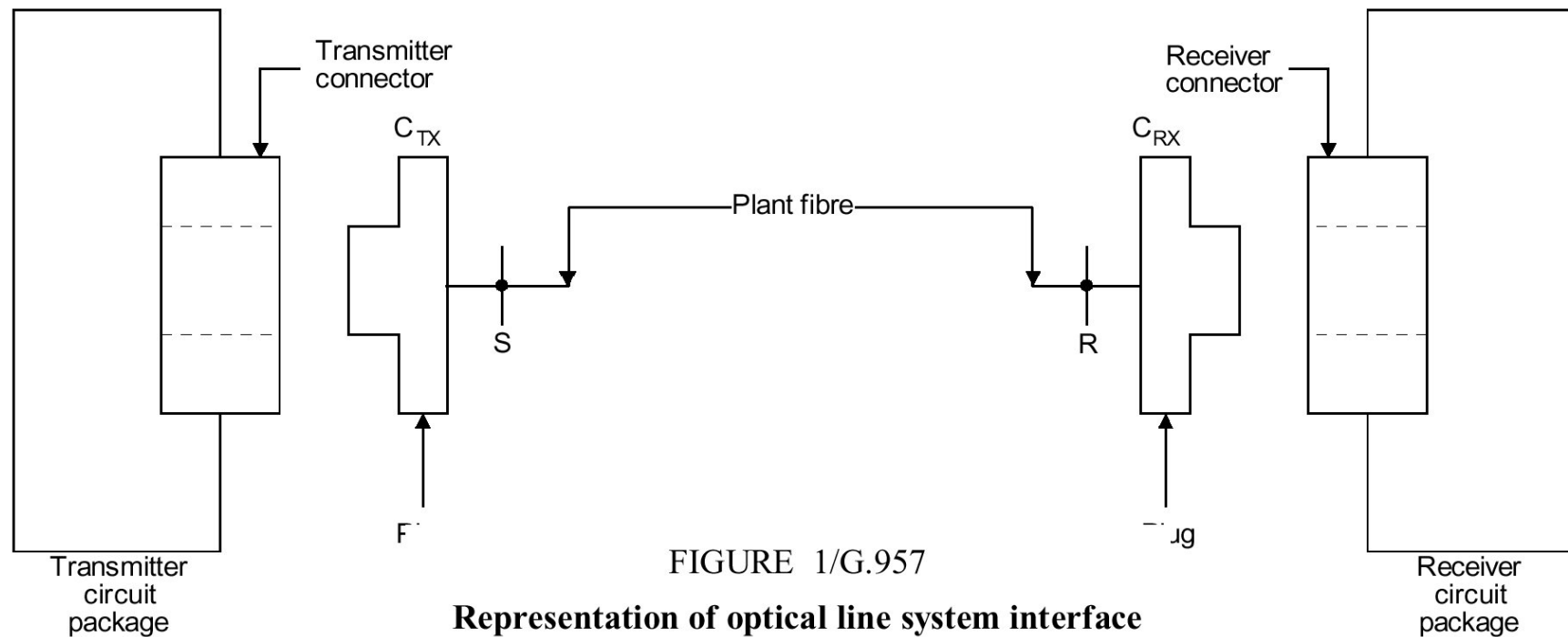


REC. G.957 Reference Points

APPLIED OPTOELECTRONICS CENTRE

G.957 is very specific about the optical path:

- The S reference point is just after the Transmitter optical connector C_{TX}
- The R reference point is just before the receiver optical connector C_{RX}
- Additional connectors on the Optical Distribution Frame (ODF) are considered to be part of the fibre plant





G.692 Application Codes without Line Amplifiers

Table 1/G.692 – Application codes for multichannel systems without line amplifiers

Application	Long-haul (target distance 80 km)	Very long-haul (target distance 120 km)	Ultra long-haul (target distance 160 km)
4-channel systems	4L-y.z	4V-y.z	4U-y.z
8-channel systems	8L-y.z	8V-y.z	8U-y.z
16-channel systems	16L-y.z	16V-y.z	16U-y.z ^{d)}
a) The target distances are to be used for classification only and not for specification. b) y = 4 or 16. c) z = 2, 3 or 5. d) The feasibility of this application is for further study.			

STM-4, STM-16 etc.

Fibre type: 2 = G.652, 3 = G.653, 5 = G.655



Attenuation Ranges without Line Amplifiers

Table 4/G.692 –Attenuation ranges for application codes without optical line-amplifiers

Application code	nL-y.z	nV-y.z	nU-y.z
Attenuation Range – maximum – minimum	22 dB For further study	33 dB For further study	44 dB For further study

per span target distance
up to 80 km

per span target
distance up to 120 km

per span target
distance up to 160 km



G.692 Application Codes with Line Amplifiers

Table 2/G.692 – Application codes for multichannel systems with line amplifiers

Application	Long-haul spans (per span target distance 80 km)		Very long-haul spans (per span target distance 120 km)	
	5	8	3	5
Number of spans	5	8	3	5
4-channel systems	4L5-y.z	4L8-y.z	4V3-y.z	4V5-y.z
8-channel systems	8L5-y.z	8L8-y.z	8V3-y.z	8V5-y.z ^{a)}
16-channel systems	16L5-y.z	16L8-y.z	16V3-y.z	16V5-y.z ^{a)}
a) The feasibility of this application code is for further study.				
b) The target distances are to be used for classification only and not for specification.				
c)	y = 4, or 16.			
d)	z = 2, 3, 5.			

STM-4, STM-16 etc.

Fibre type: 2 = G.652, 3 = G.653, 5 = G.655



Attenuation Ranges with Line Amplifiers

Table 5/G.692 – Attenuation ranges for application codes with optical line-amplifiers

Application code	nLx-y.z	nVx-y.z
Attenuation Range (between OAs) – maximum – minimum	22 dB For further study	33 dB For further study

per span target distance
up to 80 km

per span target distance up
to 120 km