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INSTITUTE OF SCIENCE

ELECTRICAL ELECTRONICS ENGINEERING DEPARTMENT

ELECTRICAL ELECTRONICS ENGINEERING

MASTER'S PROGRAMME

EEE530 - Assignment 3 – Optical Sources

NAME AND SURNAME

MEHMET ÇAĞATAY URVAYLIOĞLU

ALİ EKREM GÖKALP

MEHMET BURAK SALMAN

MOHAMMAD IBRAHIMI

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ABSTRACT

The performance and efficiency of optical communication systems are directly dependent on the characteristics of the light source used and the requirements of the application environment. In this study, Light Emitting Diodes (LEDs), Laser Diodes (LDs) and Super Luminescent Diodes (SLDs), which are the cornerstones of optical source technologies, were examined comparatively in terms of their emission mechanisms, spectral bandwidth, modulation speed and output power.

Within the scope of the study, a realistic link design was conceptualised based on a fibre optic communication scenario. Detailed link budget calculations were performed for the selected scenario; critical parameters such as path loss, scattering, and receiver sensitivity were analysed. In light of the numerical data obtained and theoretical comparisons, the most optimal optical source for the targeted system was determined. The report justifies the engineering suitability of the selected source in terms of reliability, cost and performance balance.

Keywords: Optical Sources, LED, Laser Diode, Link Budget, Optical Communication Design.

1.0 EXPECTED TASKS

1. Explain emission mechanisms of LED, LD, SLD.
2. Compare devices.
3. Choose one: fiber / FSO / underwater / QKD.
4. Perform link budget.
5. Select optimal source and justify.
6. Discuss reliability & engineering aspects.

2.0 OBJECTİVE

This study focuses on the comparative analysis of LED (Light Emitting Diode), LD (Laser Diode) and SLD (Super Luminescent Diode) technologies and their application to an engineering project. The main steps of the assignment are as follows:

Theoretical Background: First, we are expected to technically explain the emission mechanisms of these three devices (the differences between spontaneous and stimulated emission) and compare the devices based on their performance parameters.

Scenario-Based Design: We will work on single mode fibre optic communication scenario and design a real communication line.

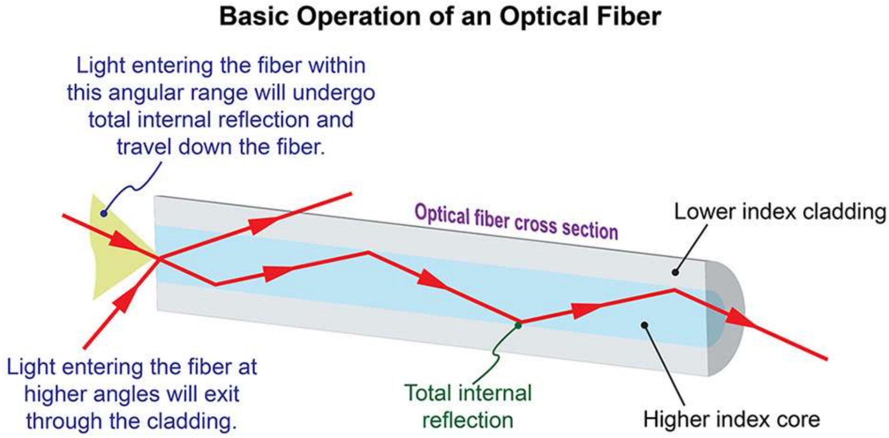
Engineering Calculations: We will determine the most suitable optical source our chosen scenario and mathematically prove that the system will work by performing a Link Budget calculation.

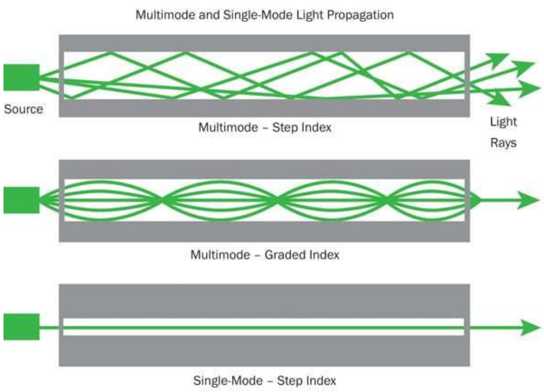
Evaluation: We will explain our choice in terms of reliability and engineering criteria.

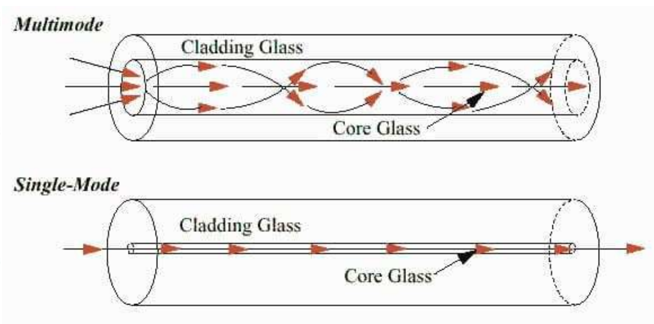
2.1 DEFINITION OF SINGLE MODE FIBER OPTIC AND OPTICAL SOURCES: EMISSION MECHANISMS & THEORY

2.1.1 DEFINITION OF SINGLE MODE FIBER OPTIC

Single-mode optical fiber is defined as a type of optical fiber designed to support broadband data communication, allowing the propagation of light with minimal dispersion over long distances.







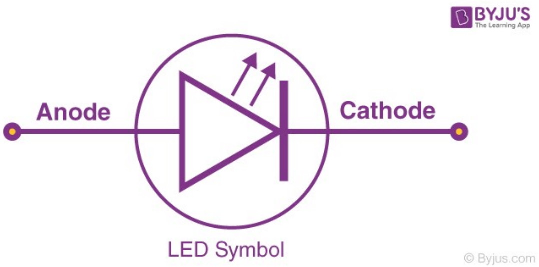
Fiber Optic Cable Type		Fiber Cable Distance						
		Fast Ethernet 100BA SE-FX	1Gb Ethernet 1000BASE-SX	1Gb Ethernet 1000BA SE-LX	10Gb Base SE-SR	25Gb Base SR-S	40Gb Base SR4	100Gb Base SR10
Single mode fiber	OS2	200m	5,000m	5,000m	10km	/	/	/
Multimode fiber	OM1	200m	275m	550m (mode conditioning patch cable required)	/	/	/	/
	OM2	200m	550m		/	/	/	/
	OM3	200m	550m		300m	70m	100m	100m
	OM4	200m	550m		400m	100m	150m	150m
	OM5	200m	550m		300m	100m	400m	400m

Single Mode vs Multimode Fiber Distance

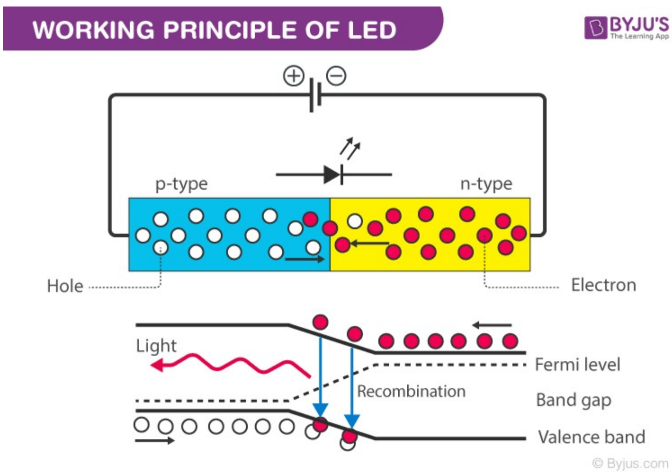
2.1.2 Spontaneous Emission (LED)

(The physics of spontaneous emission, incoherent light generation)

A light-emitting diode (LED) is a semiconductor device that emits light when an electric current flows through it. When current passes through an LED, the electrons recombine with holes emitting light in the process. LEDs allow the current to flow in the forward direction and blocks the current in the reverse direction.



LED (Spontaneous Emission): The emission of a photon by an electron in an unstable state, which randomly drops to a lower energy level without any external influence. There is no phase coherence.



Formula: Energy of the emitted photon

The Relationship between Energy (E), Frequency (υ), Wavelength (λ), and Planck's Constant (h)

$$\boxed{E = h\upsilon} \qquad \boxed{E = \frac{hc}{\lambda}}$$

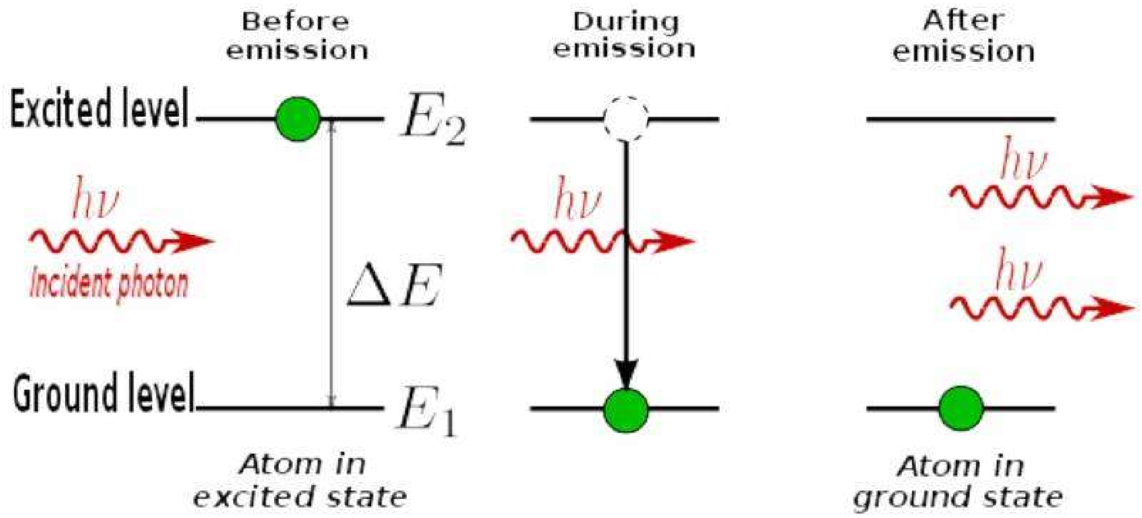
$$h = 6.626 \times 10^{-34}\ \text{J·s}$$

$$c = 3.0 \times 10^{8}\ \text{m/s}$$

2.1.2 Stimulated Emission (LD)

(Stimulated emission, population inversion, and optical gain)

It is the process whereby an incoming photon triggers an excited atom to emit a second photon in the same phase, at the same frequency, and in the same direction. Population inversion is a prerequisite.



$$E_2 - E_1 = \Delta E = h\nu$$

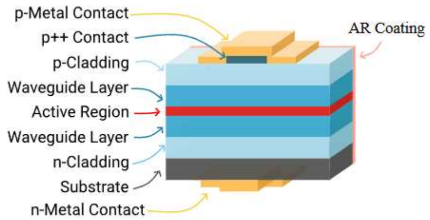
Properties of photons generated by spontaneous and stimulated emission are quite different. Spontaneous emission takes place without interaction with other photons, and the direction and phase are random. Stimulated emission takes place when the excited electron interacts with another photon. Both the direction and phase are “copied” from the other photon when stimulated emission takes place, and it is the most important phenomenon for creating a highly directional and highly coherent light source (e.g. laser diode, fiber laser, and fiber amplifier). The importance is quite evident from the fact that **LASER** is an abbreviation for **L**ight **A**mplification by “**S**timulated **E**mission” of **R**adiation.

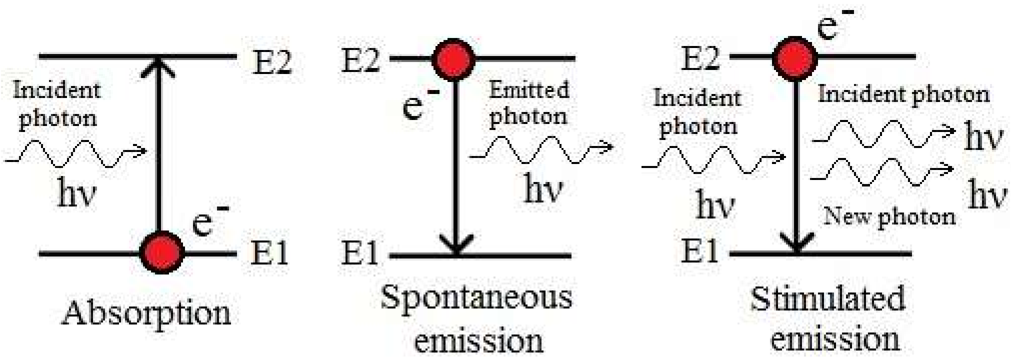
2.1.3 Super Luminescence (SLD)

(Hybrid structure between LED and LD, ASE (Amplified Spontaneous Emission))

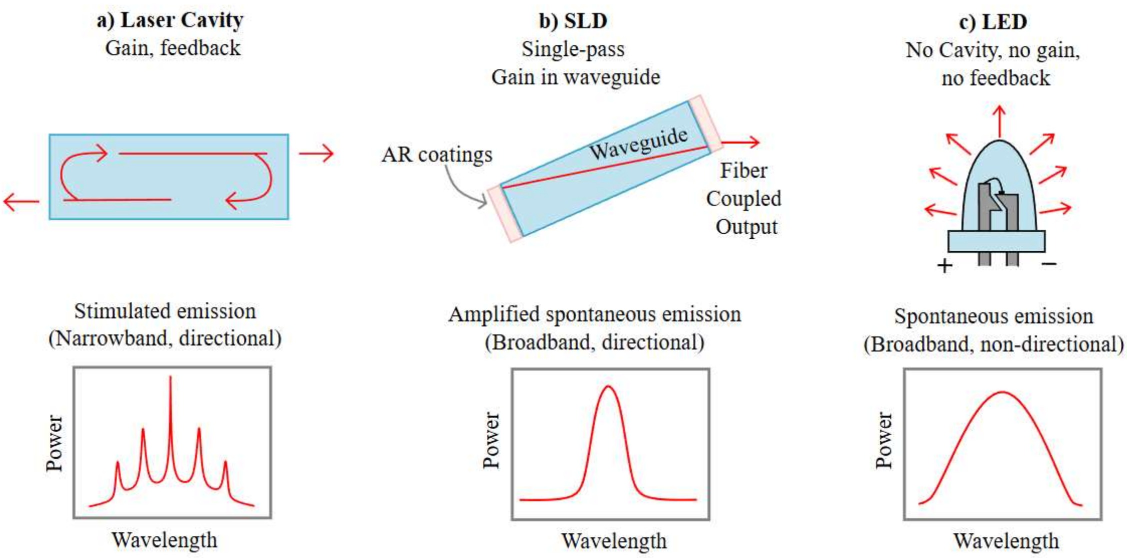
A superluminescent diode (SLD) is a high-power LED consisting of a PN junction embedded in an optical waveguide. When electrically biased in the forward direction, they exhibit optical gain and generate amplified spontaneous emission over a wide range of wavelengths. SLD light source has an output power similar to laser diode, the wide oscillation spectrum width of an LED (Light Emitting Diode), and low coherence. Superluminescent Diodes (SLDs) are broadband semiconductor devices that combine the advantages of LEDs and laser diodes. SLDs emit an optical spectrum that is broad in the wavelength, which translates to a low temporal coherence, as in LEDS.

Superluminescent Diode (SLD)





Laser, SLD & LED Cavity and Spectrum



2.1.4 Comparison of Optical Sources (in the SMF Focus)

Our working environment has been selected as SMF. The table shows and explains the separate comparisons of three different sources.

	SLDs	LEDs	Laser Diodes
Optical Spectrum	Broadband	Broadband	Narrowband
Temporal Coherence	Moderately Low (spectral linewidth <10 nm)	Low (spectral linewidth of tens of nm)	High (spectral linewidth below 1 nm)
Speckle Noise Generation	Moderately Low	Low (below human perception)	High
Directionality	High	Low	High
Modulation Bandwidth	Hundreds of MHz	10s of MHz (Hundreds MHz for micro-LED)	Beyond GHz
Polarization	High	High	Low
Spatial Coherence	High	Low	High
Coupling into Single-Mode Fibers	Efficient	Poor	Efficient
Polarization State	Linear	Random	Linear
Beam Divergence	Low	High	Low
Total optical power output	Medium	Medium	High

PARAMETER	LED	LASER DIODE (LD)	SLD
Output Power (into fiber)	Low (-15 to -10 dBm)	**High (0 to +10 dBm)**	Medium (-5 to +5 dBm)
Spectral Width (FWHM)	Broad (30-100 nm)	**Narrow (< 1 nm)**	Broad (20-50 nm)
Modulation Bandwidth	Low (< 200 MHz)	**Very High (> 10 GHz)**	Medium (~500 MHz)
Fiber Coupling	Poor (Lambertian)	**Excellent (Directional)**	Good (Directional)
Cost & Complexity	Low	High (Temp control needed)	Medium/High

Critical Explanation (Coupling Loss): The mathematical proof of why LEDs are not suitable for Single Mode Fibre is as follows:

$$\eta_{coupling} \approx \left(\frac{NA_{fiber}}{NA_{source}}\right)^2$$

The Numerical Aperture (NA) value of the SMF is very low (~0.1). The NA value of the LED is high. This ratio creates a large loss proportional to its square (~15-20 dB loss).

2.2 SYSTEM SCENARIO DESIGN for Link Budget Calculation

In this section, we must fix the design parameters.

- Scenario: Single Mode Fibre (Long-Haul Communication).
- Fibre Type: ITU-T G.652 Standard SMF.
- Wavelength: 1550 nm (Fibre's minimum attenuation window).
- Distance: 50 km.
- Target Speed: 2.5 Gbps.

2.2.1 TECHNİCAL JUSTİFİCATİON

The selection of system parameters has been balanced between cost, performance, and physical limitations (attenuation and dispersion):

2.2.1.1. Why Single Mode Fibre (SMF - G.652)?

- **Reason:** Multi-Mode Fibre (MMF) cannot be used for the targeted 50 km distance. In MMF, different modes of light follow different paths, causing 'Modal Dispersion' and signal degradation after a few kilometres.

- **Engineering Explanation:** SMF allows light to propagate only in the fundamental mode due to its narrow core diameter of approximately 9 µm. This completely eliminates modal dispersion, theoretically approaching the bandwidth-distance product towards infinity.

2.2.1.2 Why 1550 nm Wavelength?

- **Reason:** The window with the lowest signal loss (attenuation) in fibre optic cables is the 1550 nm region.
- **Engineering Explanation:** At 1310 nm, the loss is approximately 0.35 dB/km, while at 1550 nm, the loss is approximately 0.20 dB/km. If 1310 nm is used on a 50 km line, the total cable loss is 50 x 0.35 = 17.5 dB,
whereas at 1550 nm this loss is 50 x 0.20 = 10 dB. The 7.5 dB power gain allows the system to consume less power and eliminates the cost of an additional amplifier.

2.2.1.3 Why 2.5 Gbps Data Rate?

- **Reason:** This speed is the threshold where the difference between LED and Laser (LD) is most clearly visible.
- **Engineering Explanation:** The modulation bandwidth of LEDs is typically limited to 100-200 MHz. At speeds of the gigabit order, such as 2.5 Gbps, the LED's 'on-off' time (Rise Time / Fall Time) is insufficient, causing 'Inter-Symbol Interference (ISI)'. The use of a Laser Diode (LD) is mandatory for transmitting data at this speed.

2.2.1.4 Intended Output & Design Goal

The fundamental engineering objectives of this design are as follows:

- Power Budget Compliance: The system must deliver the signal with a power level above the minimum sensitivity value (e.g., -28 dBm) required on the receiver side. A system margin of at least 3 dB is maintained to prevent line failure even in cases of connector contamination or cable ageing.
- Dispersion Management: To prevent the signal from spreading and interfering with itself (ISI) over 50 km, the effect of chromatic dispersion is minimised by using a Laser Diode with a very narrow spectral width (< 1 nm).
- Reliability: Minimising maintenance costs and failure probability by creating a 'Passive Point-to-Point Link' that does not require a repeater or optical amplifier (EDFA).

2.3.LINK BUDGET ANALYSIS

The Optical Link Budget (Power Budget) is the calculation of whether the optical power emitted from the transmitter (Tx) is still at a sufficient level when it reaches the receiver (Rx), after accounting for losses incurred as it passes through the fibre optic cable, connectors, and splice points.

The primary objective of this analysis is to ensure 'Continuity and Reliability'. The calculation must satisfy the following fundamental inequality:

$$P_{TX} - \text{Total Loss} - \text{System Margin} \geq \text{Receiver Sensitivity}$$

2.3.1 DESIGN PARAMETERS & REAL-WORLD CONSTRAINTS

The parameters and industry standard values used for our selected Single Mode Fibre (SMF) G.652 scenario are as follows:

1. **Optical Transmitter Power (P_TX):**
   - Selection: Laser Diode (LD)).
   - Value: 0 dBm (1mW)
   - Reason: Standard long-distance SFP (Small Form-factor Pluggable) modules typically provide output between 0 and +5 dBm. For the safe side (worst-case) in the calculation, 0 dBm has been taken.
2. **Fiber Attenuation (α_fiber):**
   - Selection: G.652 SMF at 1550 nm wavelength..
   - Value: 0.2 dB/km.
   - Real-Life Note: Cable manufacturers typically provide a value of 0.18-0.19 dB/km in a laboratory environment, but in the field (bends, temperature differences), this value should be calculated as 0.20-0.22 dB/km.

3. **Connector Loss (L_conn):**
   - Value: 0.5 dB/unit
   - Scenario: There are at least 2 connectors (patch cord connection) at the beginning (Tx side) and end (Rx side) of the line. For SMF.
4. **Splice Loss (L_splice):**
   - Value: 0.1 dB/splice.
   - Real-Life Application: Fibre cables are typically sold in reels of 2km or 4km. When laying a 50km line, you cannot find the cable without interruptions. At the end of each reel, a splice is made using a 'Fusion Splicer' device..
   - Calculation: Assuming an average of one splice every 10 km, there will be approximately 4 or 5 splice points for 50 km.
5. **Receiver Sensitivity (P_sens):**
   - Value: -28 dBm (for 2.5 Gbps speed)
   - Meaning: The receiver requires at least this much power to decode the signal without errors (BER 10^{-9}).
6. **System Margin (M_sys):**
   - Value: 3 dB.
   - Why is it necessary? Over time, the laser diode ages and its power decreases (Aging). Connectors become dusty. If there is a break in the line in the future (e.g., due to excavation), a mandatory splice must be inserted there. Leaving a 'safety margin' of 3-6 dB for these extra losses is an engineering rule.

2.3.2 STEP-BY-STEP CALCULATION FOR LİNK BUDGET

Formula:

$$P_{RX} = P_{TX} - (\alpha \cdot L) - (N_{conn} \cdot L_{conn}) - (N_{splice} \cdot L_{splice}) - M_{sys}$$

Known Data:

- P_{TX} = 0 dBm
- Distance (L) = 50 km
- α_fiber (1550nm) = 0.2 dB/km
- Connectors (N_{conn}) = 2 piece (0.5 dB for each)
- Splices (N_{splice}) = 4 piece (0.1 dB each - 10km intervals)
- System Margin (M_{sys}) = 3 dB

Link Parameter /Component	Calculation / Details	Value / Loss
Transmitter Power P_{tx})	**Laser Diode Output (0 dBm)**	**0.0 dBm**
Fiber Attenuation	50 km x -0.2 dB/km	-10.0 dB
Connector Loss	2 connectors x 0.5 dB	-1.0 dB
Splice Loss	4 splices x 0.1 dB	-0.4 dB
System Margin (Safety)	Engineering Safety Allowance	-3.0 dB
Total Link Loss		**-14.4 \dB**
Received Power (P_{rx})	P_{tx} - Total Link Loss	**-14.4 dBm**
Receiver Sensitivity (S_{rx})	Minimum required power for BER 10^{-9}	**-28.0 dBm**
Net Power Margin	P_{rx} - S_{rx} = (-14.4 - (-28.0))	**+13.6 dB**
Result	**P_{rx} > S_{rx}**	**LINK FUNCTIONAL**

2.4. VERDICT & ENGINEERING ANALYSIS

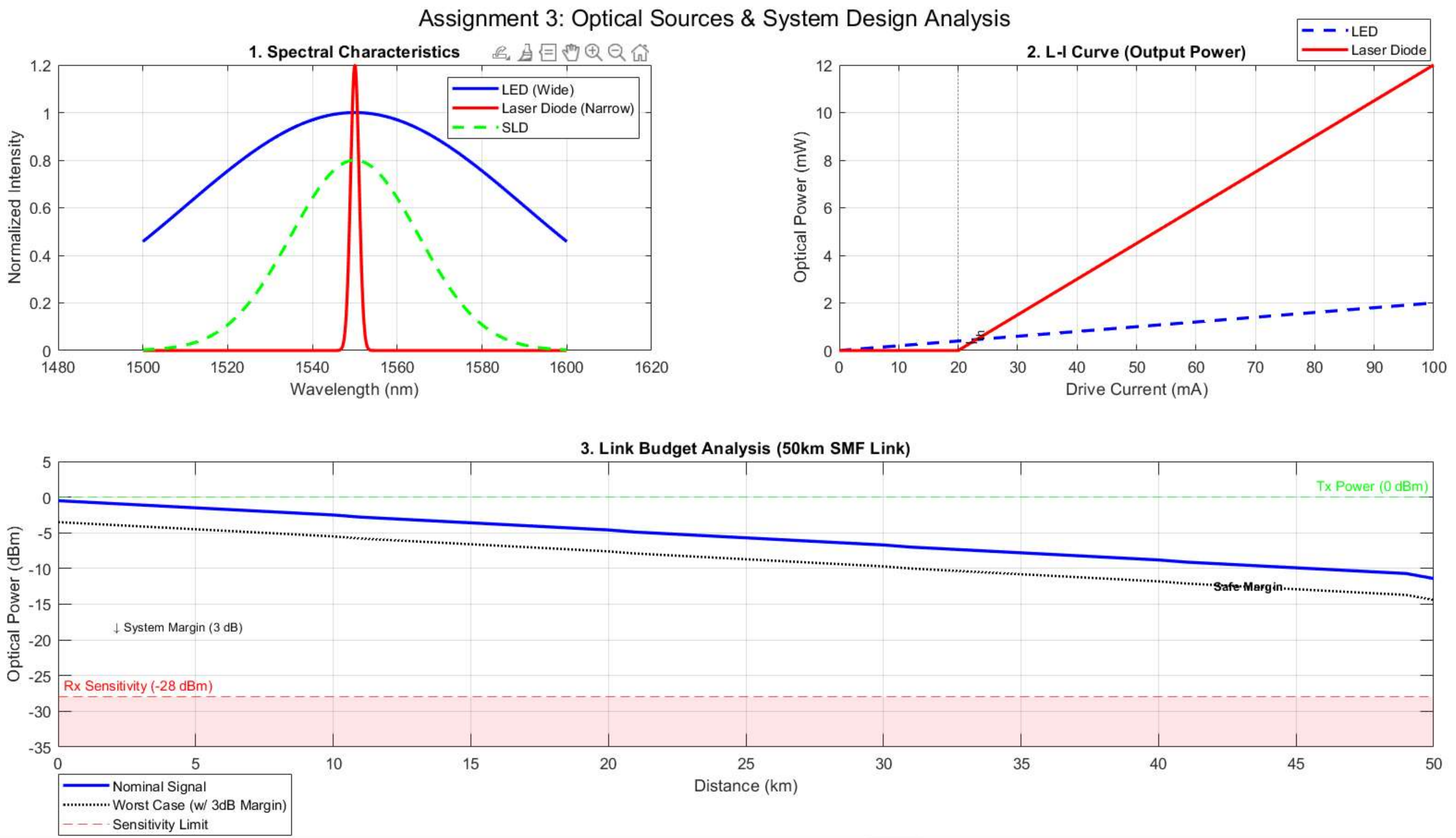
The data obtained from this calculation should be interpreted as follows:

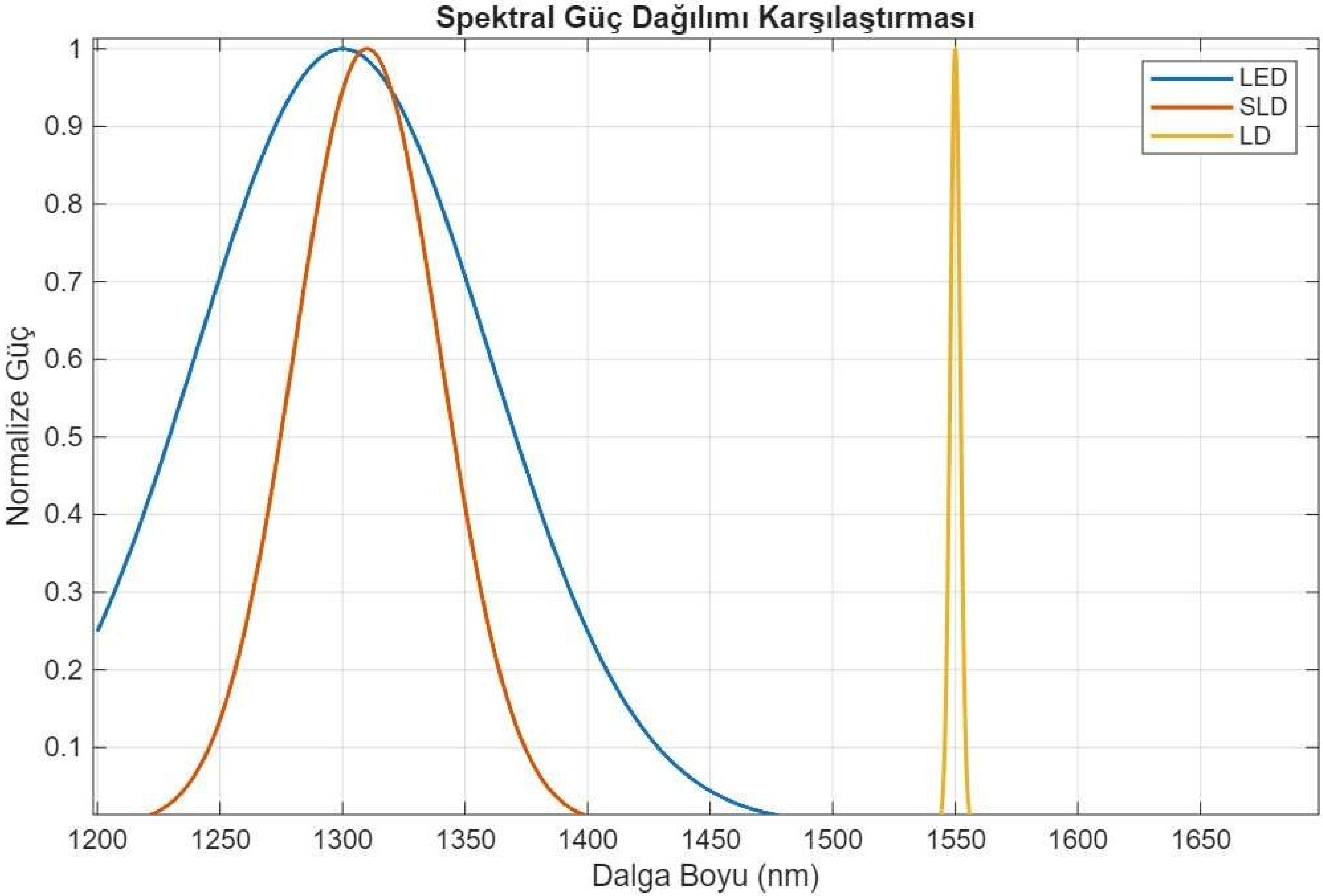
1. Power Level Check:
   - Power reaching the receiver (P_{RX}): -14.4 dBm
   - Receiver Sensitivity (Sensitivity): -28.0 dBm
   - Result: -14.4 > -28.0 the system works successfully.
2. Excess Power (Power Penalty) Analysis:
   - The difference between them: | -14.4 - (-28) | = 13.6 dB
   - This demonstrates that the system is highly secure. Even if the line distance is increased to 80-90 km in the future (an additional 40 km × 0.2 = 8 dB loss), the system will continue to operate.
3. Proof of Why LED Was Not Chosen:
   - If an LED had been selected as the source, approximately 20 dB of loss would have occurred when injecting light into the Single Mode Fibre (Coupling Loss). Furthermore, the LED's broad spectrum (due to chromatic dispersion) would distort the signal at a distance of 50 kilometres.
   - n this case, the calculation is:
     P_{RX} = -20 (Coupling) - 14.4 (Link) = -34.4 dBm.
   - Result: -34.4 dBm, which is well below the receiver sensitivity (-28 dBm) so this link cannot be established with an LED.

In addition to the concluding statements:

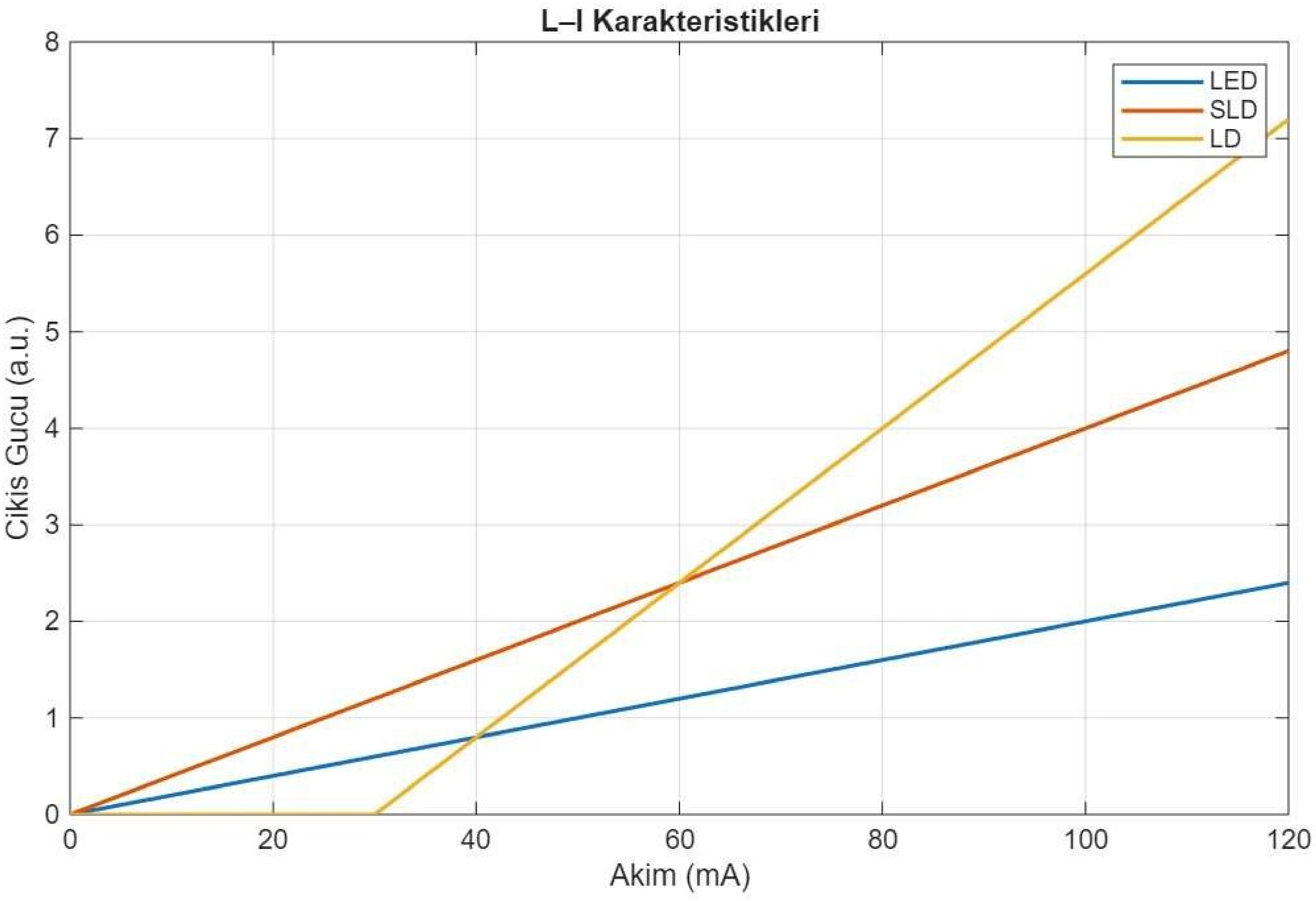
In the visual provided in Section 2.5 MATLAB FIGURES, "Even in the “Worst-Case” scenario shown by the black dashed line in Figure 3 (when the 3 dB system margin is reduced), the signal level received at the end of 50 km remains above the receiver sensitivity limit of -28 dBm (red zone), guaranteeing uninterrupted communication. "

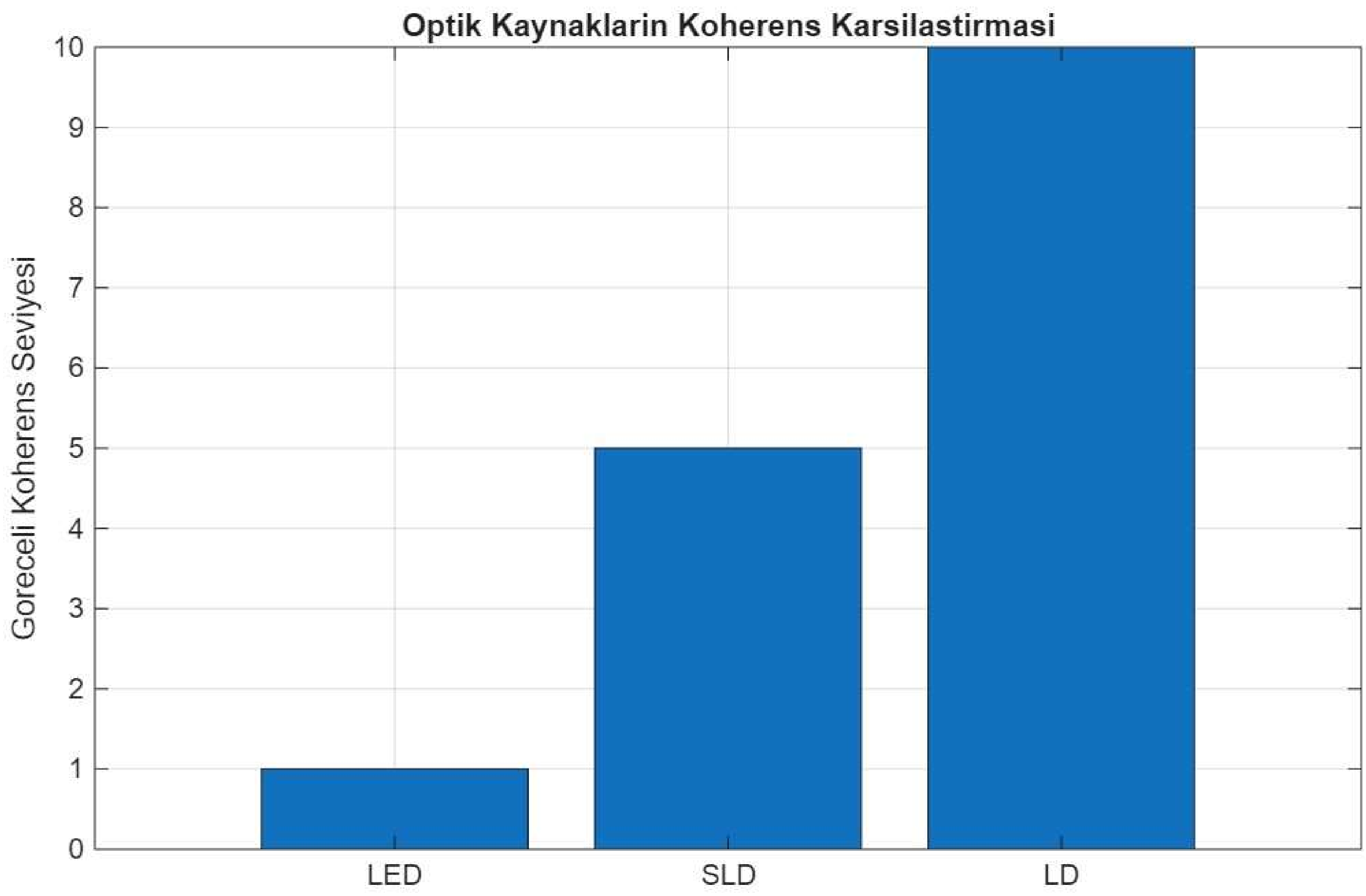
2.5 MATLAB FIGURES

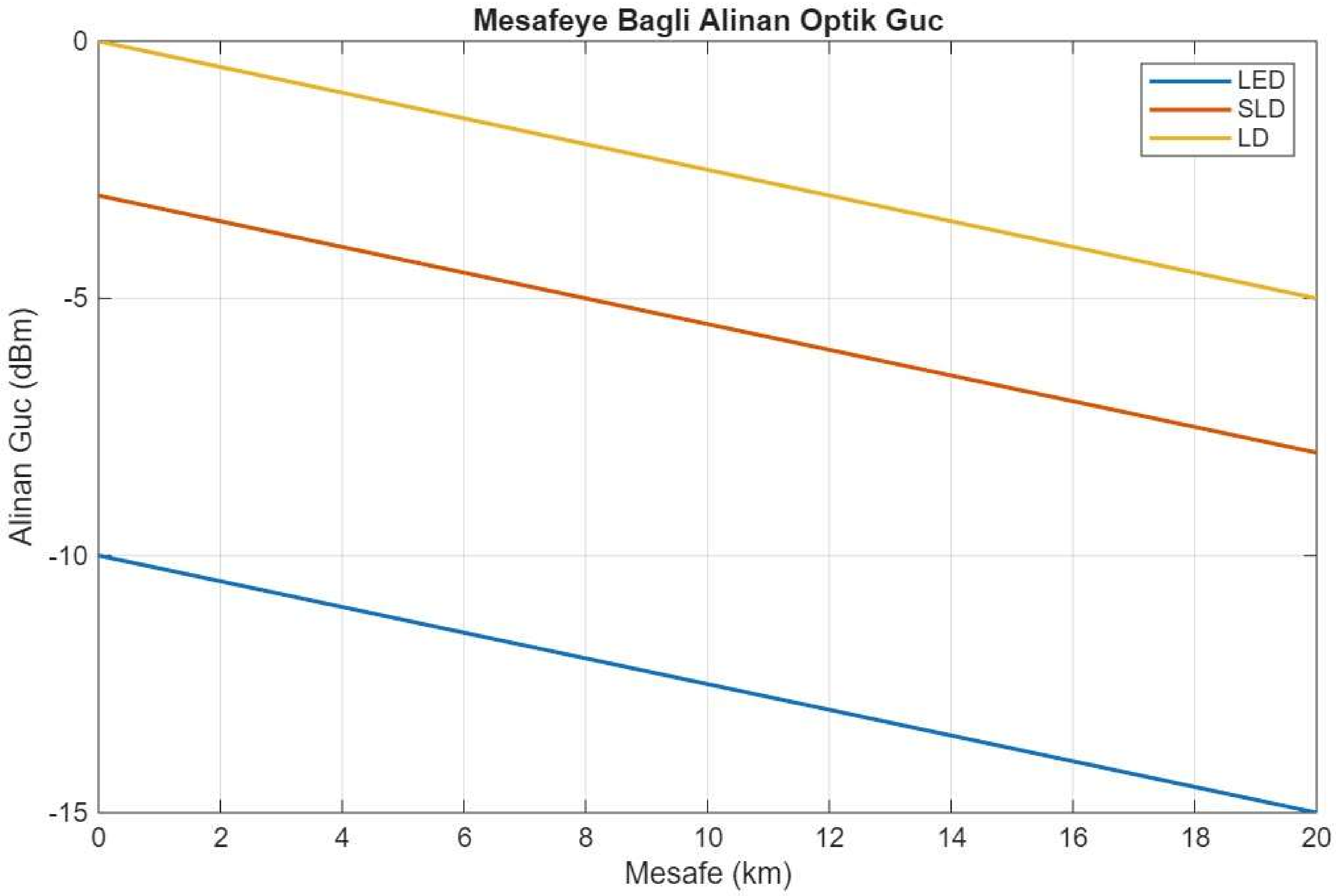


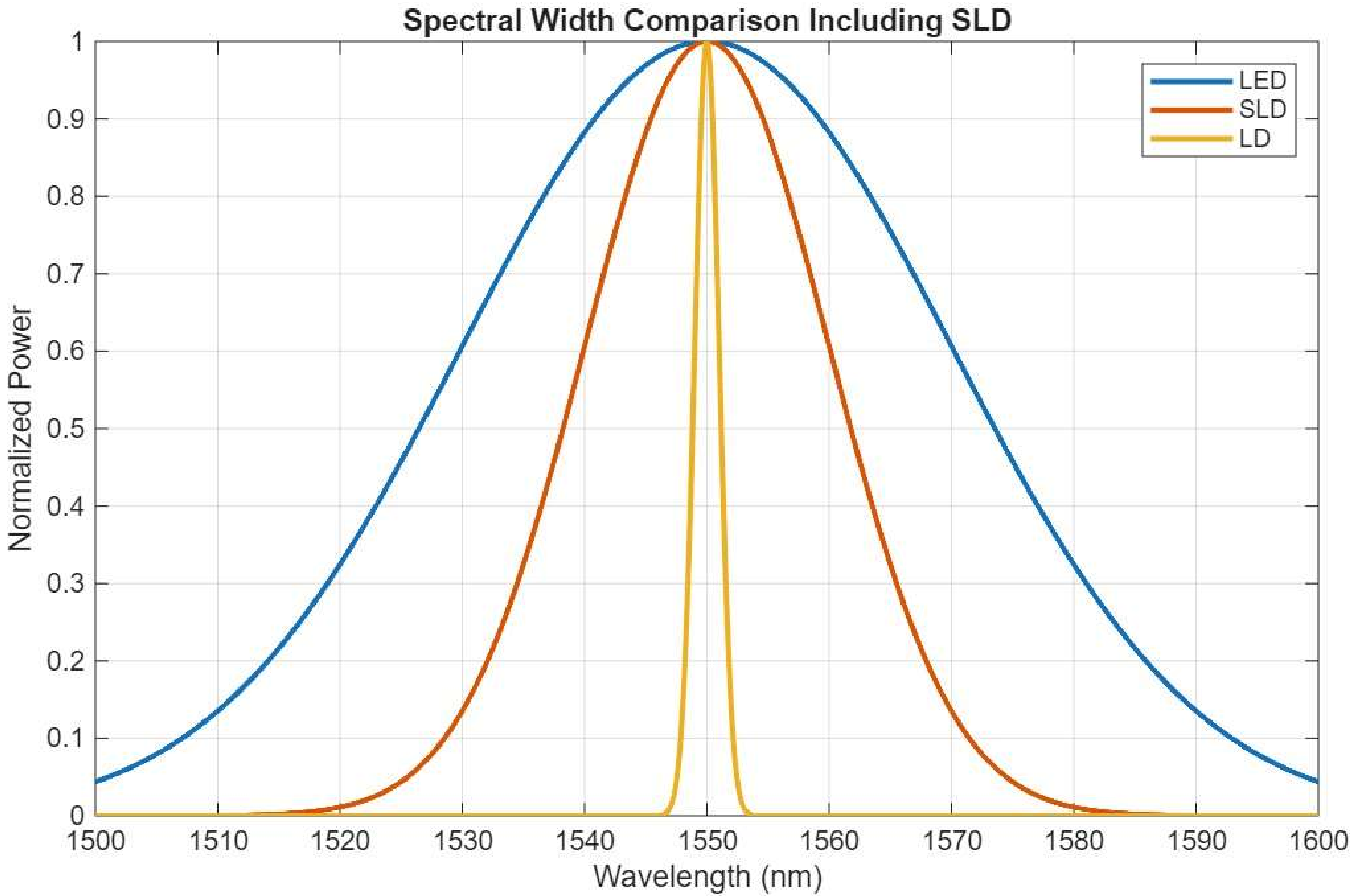


Spektral Güç Dağılımı Karşılaştırması
LED
SLD
LD
Normalize Güç
Dalga Boyu (nm)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
1200
1250
1300
1350
1400
1450
1500
1550
1600
1650


L–I Karakteristikleri
LED
SLD
LD
Cikis Gucu (a.u.)
Akim (mA)
0
1
2
3
4
5
6
7
8
0
20
40
60
80
100
120


Optik Kaynaklarin Koherens Karsilastirmasi
Goreceli Koherens Seviyesi
0
1
2
3
4
5
6
7
8
9
10
LED
SLD
LD


Mesafeye Bagli Alinan Optik Guc
LED
SLD
LD
Alinan Guc (dBm)
0
-5
-10
-15
0
2
4
6
8
10
12
14
16
18
20
Mesafe (km)


Spectral Width Comparison Including SLD
LED
SLD
LD
Normalized Power
Wavelength (nm)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1500
1510
1520
1530
1540
1550
1560
1570
1580
1590
1600

2.5.1 THE MEANINGS OF THE LINES ON THE LINK BUDGET GRAPH

Blue Line (Signal Power):

- Start (0. km): Does not start at 0 dBm. Since we wrote (P_tx - Conn_Loss) at calculation, it starts after deducting the first connector loss (approximately -0.5 dBm).
- Slope: The downward shift of the line represents the fibre attenuation of 0.2 dB/km.).
- Small Steps: The small sudden drops you will see at 10, 20, 30, and 40 kilometres on the graph are the Splice losses at those points. (The 4 x 0.1 dB part in the report).
- End (50th km): The sudden drop at the very end of the line is the final connector loss on the receiver side.

Red Dotted Line (Receiver Sensitivity):

- It is at the -28 dBm level. Below this limit is the 'dead zone' (communication breaks down). In the graph, your signal (Blue) ends well above this red line.

System Margin:

- The gap between where the blue line ends (-14.4 dBm) and the red line (-28 dBm) is your system margin (approximately 13.6 dB).

In the output of the third graph:

- Blue Line: Current calculated signal strength.
- Black Dotted Line (New): Signal strength with a 3 dB safety margin deducted (worst-case scenario).
- Red Area: The 'Blind Zone' where the signal should never fall below.

2.8 RESOURCES

https://www.sciencedirect.com/topics/physics-and-astronomy/single-mode-optical-fiber#:~:text=Single%2Dmode%20optical%20fiber%20is,minimal%20dispersion%20over%20long%20distances.

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