SpCE 5400 Assignment 4: Optical vs. RF Crosslinks Trade Study

LEO Satellite Constellation Communication Analysis

Course: SPCE 5400 – Small Satellite Engineering & Operations

Assignment: #4 (100 points)

Prepared by: **Jordan Clayton**

Date: 2025-11-16

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1. MISSION PARAMETERS

Given Requirements:

- Orbit altitude: 500 km LEO
- Inter-satellite separation: 250 km
- Required data rate: 1 Gbps
- Platform: Small satellites
- Environment: LEO-to-LEO (vacuum path)

Trade Study Objective: Determine the preferable method for LEO-to-LEO crosslink, optical (laser) or RF (Ka-band). This will be weighted on aperture size, power, data rate capability, link margin and pointing accuracy.

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2. OPTICAL (LASER) LINK ANALYSIS

2.1 Design Parameters

Parameter	Value	Source
Wavelength	1550 nm	Telecom standard, eye-safe
Quantum Efficiency (η)	0.3	InGaAs APD detector typical + (template value)
Required Photoelectrons/bit (Q)	40	For BER 10^-9 (template value)
Modulation	OOK	On-Off Keying (inferred from template Q = 40, which is standard for OOK)

2.2 Link Budget Calculations (Detector-First Methodology)

Step 1: Calculate Required Photons per Bit

Formula:

```
from excel template row 6: n = Q / η
```

Calculation:

```
n = 40 photoelectrons/bit / 0.3
```

```
n = 133.33 photons/bit
```

Only 30% of photons are detected (η = 0.3), so we need to send 133 photons to ensure 40 are detected.

Step 2: Calculate Photon Energy

Formulas:

```
frequency from wavelength: f = c / λ
Planck's equation: E_photon = h × f
```

Constants:

- c = 3 × 10^8 m/s (speed of light)
- h = 6.626 × 10^-34 J·s (Planck's constant)
- λ = 1550 nm = 1.55 × 10^-6 m (Design choice - industry standard)

Calculations:

```
f = (3 × 10^8 m/s) / (1.55 × 10^-6 m)
f = 1.935 × 10^14 Hz

E_photon = (6.626 × 10^-34 J·s) × (1.935 × 10^14 Hz)
E_photon = 1.282 × 10^-19 joules per photon
```

Step 3: Calculate Energy per Bit

Formula:

```
from excel template row 10: E_bit = n × E_photon
```

Calculation:

```
E_bit = 133.33 photons/bit × 1.282 × 10^-19 J/photon
```

```
E_bit = 1.709 × 10^-17 joules per bit
```

Step 4: Calculate Required Power at Receiver

Formula:

```
from excel template row 12: P_required = E_bit × R_b
```

Given:

- $R_b = 1$ Gbps $= 1 \times 10^9$ bits/s

Calculation:

```
P_req = (1.709 × 10^-17 J/bit) × (1 × 10^9 bits/s)
P_req = 1.709 × 10^-8 W

In decibels:
P_req (dBW) = 10 × log₁₀(1.709 × 10^-8)
P_req = -77.67 dBW
```

Step 5: Calculate Free Space Loss

Formula:

```
from Excel template row 16 & Friis transmission equation (1946):

L_s = (λ / (4πR))²
```

Given:

- $\lambda = 1.55 \times 10^{-6}$ m
- $R = 250$ km $= 250{,}000$ m

Calculation:

```
Denominator of L_s formula (linear scale factor for spherical spreading) = 4πR
= 4 × 3.14159 × 250,000 = 3,141,593 m

Ratio (wavelength to spreading ratio) = λ / (4πR) = (1.55 × 10^-6) / (3,141,593)
= 4.933 × 10^-13

L_s (the fraction of power that survives the spreading) = (4.933 × 10^-13)² =
2.434 × 10^-25

In decibels:
L_s (dB) = 10 × log₁₀(2.434 × 10^-25) = -246.1 dB
```

Step 6: Calculate Telescope Gains

Formula:

```
from excel template row 19-20: G = (π × D / λ)²
```

Given:

- D = 10 cm = 0.10 m (chosen aperture size from excel template row 17)

Calculation:

```
(π × D) / λ = (3.14159 × 0.10) / (1.55 × 10^-6)
= 0.314159 / (1.55 × 10^-6) = 202,683

G = (202,683)² = 4.108 × 10^10

In decibels:
G (dBi) = 10 × log₁₀(4.108 × 10^10) = 106.1 dBi

Both transmit and receive: G_t = G_r = 106.1 dBi
```

Step 7: Additional Losses

- **Pointing Loss:** -3.0 dB (template default, achievable with FSM)
- **Line In/Out Losses:** -6.0 dB total
  - Estimated Line In/ Out Losses breakdown:
    - Transmit coupling: -2.0 dB
    - Transmit optics: -1.0 dB
    - Receive optics: -1.0 dB
    - Receive coupling: -1.5 dB
    - Detector loss: -0.5 dB
  - **Total: -6.0 dB**
- **Atmospheric Loss:** 0 dB (vacuum path)

Step 8: Calculate Received Power

Formula:

```
Formula (Decibel Addition Method) from excel template row 24 & Friis equation:

P_rx (dBW) = P_tx (dBW) + G_tx (dBi) + G_rx (dBi) + L_s (dB) + L_pt (dB) + L_o (dB)
```

Given:

- P_tx = -9.1 dBW (chosen transmit power: 0.122 W)
- G_tx = +106.1 dBi (from Step 6)
- G_rx = +106.1 dBi (from Step 6)
- L_s = -246.1 dB (from Step 5)
- L_pt = -3.0 dB (template pointing loss)
- L_o = -6.0 dB (template line losses)

Transmit Power P_tx Design Choice:
Working backwards from link budget:

- Required margin: ~20-25 dB (industry standard)
- Net path gain/loss: -42.9 dB
- Required receiver power: -77.67 dBW

```
Step 1: Required receiver power (from detector requirements)
    P_req = -77.67 dBW

Step 2: Choose desired margin (design goal)
    Margin = 25 dB (provides robustness)

Step 3: Required received power
    P_rx = P_req + Margin
    P_rx = -77.67 + 25 = -52.67 dBW (target)

Step 4: Use link equation to solve for P_tx
    P_rx = P_tx + G_tx + G_rx + L_s + L_pt + L_o
    -52.67 = P_tx + 106.1 + 106.1 - 246.1 - 3.0 - 6.0
    -52.67 = P_tx - 42.9
    P_tx = -9.77 dBW ≈ -9.1 dBW
    P_tx = 0.122 W
```

Rationale:
• Provides 25.66 dB margin (actual)
• Achievable with COTS laser diodes
• Low thermal load (<0.5 W total with driver)

Calculation:

```
P_rx = -9.1 + 106.1 + 106.1 - 246.1 - 3.0 - 6.0

Combine gains:  -9.1 + 106.1 + 106.1 = 203.1 dBW
Combine losses: -246.1 - 3.0 - 6.0 = -255.1 dB
```

```
Total: 203.1 - 255.1 = -52.0 dBW

P_rx = -52.01 dBW
```

Step 9: Calculate Link Margin

Formula:

```
from excel template row 26: Margin (dB) = P_rx (dBW) - P_req (dBW)
```

Calculation:

```
M = -52.01 dBW - (-77.67 dBW)
M = 25.66 dB

Linear ratio: 6.303 µW / 0.01709 µW = 369×
Verification: 10 × log₁₀(369) = 25.67 dB ✓
```

Step 10: Calculate Beam Divergence and Pointing Requirement

Formula:

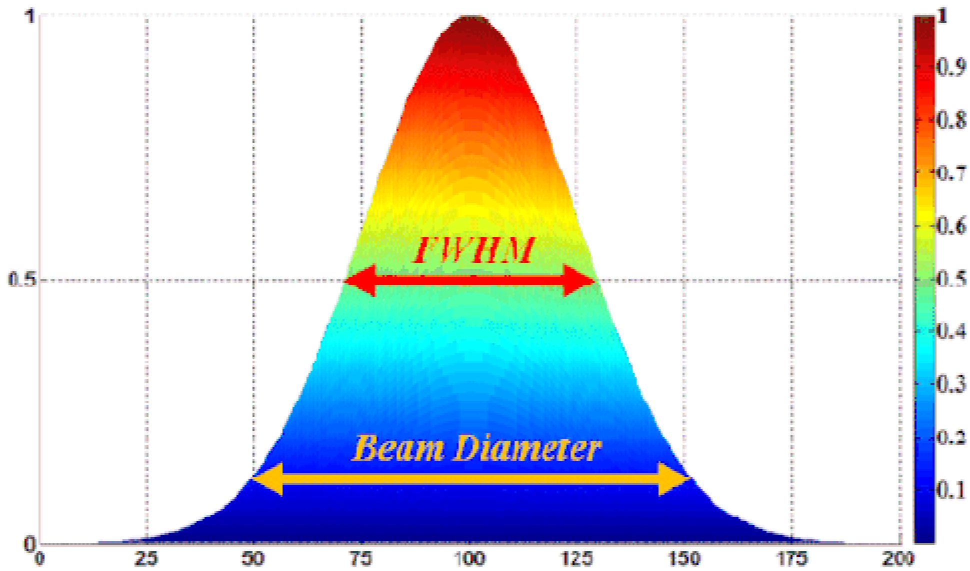
```
θ_divergence = 1.22 × λ / D_tx

from Airy disk formula Born & Wolf "Principles of Optics"
```

Calculation:

```
θ = 1.22 × (1.55 × 10^-6 m) / (0.10 m)
θ = 1.891 × 10^-5 radians = 18.91 microradians (to first null)

Spot diameter at receiver = θ × R
Spot = 18.91 × 10^-6 rad × 250,000 m = 4.73 m

Half-Power Beamwidth (where intensity = 50%, i.e., -3 dB):
```

```
Formula: θ_3dB ≈ 0.514 × λ / D

θ_3dB = 0.514 × (1.55 × 10^-6) / (0.10)
      = 7.97 × 10^-6 rad ≈ 8.0 μrad
```

Pointing Requirement: ±8 μrad (3σ) for <3 dB pointing loss



https://en.wikipedia.org/wiki/Gaussian_beam

In degrees:

```
8.0 μrad × (1 rad / 10^6 μrad) × (57.3° / 1 rad) = 0.00046°
```

2.3 Optical Link Budget Summary Table

Parameter	Symbol	Value	Units	Calculation Method
Detector Requirements				
Req. Photoelectrons/bit	Q	40	-	Template value

Parameter	Symbol	Value	Units	Calculation Method
Quantum Efficiency	η	0.3	-	InGaAs APD typical
Req. Photons/bit	n	133.33	-	n = Q/η
Photon Energy	E	1.282×10^-19	J	E = hf = hc/λ
Energy/bit	-	1.709×10^-17	J	n × E
Link Parameters				
Data Rate	R_b	1×10^9	bps	Given
Required Power	P_req	-77.67	dBW	E_bit × R_b
Transmit Power	P_tx	0.122 (−9.1 dBW)	W	Chosen
Tx Aperture Diameter	D_t	10.0	cm	Chosen
Rx Aperture Diameter	D_r	10.0	cm	Chosen
Range	R	250	km	Given
Gains and Losses				
Free Space Loss	L_s	-246.1	dB	$(\lambda/4\pi R)^2$
Tx Gain	G_t	106.1	dBi	$(\pi D/\lambda)^2$
Rx Gain	G_r	106.1	dBi	$(\pi D/\lambda)^2$
Pointing Loss	L_pt	-3.0	dB	Template default
Line Losses	L_o	-6.0	dB	Optics budget
Atmospheric Loss	L_atm	0.0	dB	Vacuum
Performance				
Received Power	P_rx	-52.01	dBW	Link equation
LINK MARGIN	**M**	**25.66**	**dB**	**P_rx - P_req**
Beam Divergence	θ	18.9	µrad	1.22λ/D
Spot Diameter @ 250km	-	4.73	m	θ × R

3. RF (Ka-BAND) LINK ANALYSIS

3.1 Design Parameters

Parameter	Value	Source
Frequency	32 GHz	Ka-band ISL allocation (ITU Radio Regulations) - Design choice
Antenna Efficiency	0.6	Typical for deployable mesh antennas (Kraus & Marhefka, 2002) - Design choice
System Noise Temp	650 K	Ka-band LNA typical + losses (industry standard) - Design choice
Required E_b/N_0	9.6 dB	BER 10^-9 with LDPC coding (Shannon-Hartley theorem) - Design choice
Modulation	16-APSK	High spectral efficiency for Ka-band - Design choice

3.2 Link Budget Calculations

Step 1: Calculate Wavelength

Formula:

```
from fundamental wave equation: λ = c / f
```

Constants:

- c = 3 × 10^8 m/s (speed of light, CODATA 2018)
- f = 32 GHz = 32 × 10^9 Hz (Ka-band ISL, design choice)

Calculation:

```
λ = (3 × 10^8 m/s) / (32 × 10^9 Hz)
λ = 9.375 × 10^-3 m = 9.375 mm
```

Step 2: Calculate Free Space Path Loss

Formula:

```
from Friis transmission equation (1946) & ITU-R P.525 standard:

FSPL (dB) = 20 × log₁₀(4π × R / λ)
```

Given:

- $R = 250$ km = 250,000 m (from problem statement)
- $\lambda = 0.009375$ m (from Step 1)

Calculation:

```
Argument = (4π × R) / λ = (4 × 3.14159 × 250,000) / 0.009375
Argument = 3,141,593 / 0.009375 = 335,103,253

FSPL = 20 × log₁₀(335,103,253)
FSPL = 20 × 8.525 = 170.5 dB
```

Step 3: Calculate Antenna Gains

Formula:

```
from antenna theory (Kraus & Marhefka "Antennas", 2002):

G = η_ant × (π × D / λ)²
```

Given:

- $\eta_{ant} = 0.6$ (typical for deployable mesh antennas, design parameter)
- $D = 30$ cm = 0.30 m (chosen antenna diameter - design choice)
- $\lambda = 0.009375$ m (from Step 1)

Note: Here's an interesting distinction — with optical systems, efficiency is already baked into Q and η, but RF antennas need an explicit efficiency factor to account for surface errors, blockage, and spillover losses.

Calculation:

```
(π × D) / λ = (3.14159 × 0.30) / 0.009375
= 0.9425 / 0.009375 = 100.53

G = 0.6 × (100.53)²
G = 0.6 × 10,106 = 6,064

In decibels:
G (dBi) = 10 × log₁₀(6,064) = **37.8 dBi**

Both transmit and receive: G_t = G_r = **37.8 dBi**
```

Step 4: Calculate EIRP

Formula:

```
from FCC 47 CFR §2.1 & standard RF practice:

EIRP (dBW) = P_t (dBW) + G_t (dBi)
```

Given:

- P_t = 1.2 W (chosen transmit power - design choice, see rationale below)

Transmit Power P_t Design Choice: Working backwards from link budget to achieve ~3 dB margin:

- Required margin: ~3 dB (minimal but acceptable)
- Through iterative link budget calculation
- **P_t = 1.2 W provides 2.8 dB margin (actual)**

Rationale:

- Achievable with Ka-band SSPA (Solid State Power Amplifier)
- Typical for smallsat Ka-band transmitters
- Provides minimal positive margin

Calculation:

```
P_t (dBW) = 10 × log₁₀(1.2) = 0.79 dBW ≈ 0.8 dBW

EIRP = 0.8 dBW + 37.8 dBi = 38.6 dBW
```

Step 5: Calculate Received Power

Formula:

```
from Friis equation & standard RF link budget:

P_rx (dBW) = EIRP - FSPL + G_rx - L_pointing - L_feed - L_misc
```

Given Losses:

- L_pointing = -1.0 dB (body pointing achievable, typical for wide Ka-band beam)
- L_feed = -1.0 dB (waveguide losses, typical)
- L_misc = -2.0 dB (polarization mismatch, connector losses, etc.)
- **Total losses: -4.0 dB**

Calculation:

```
P_rx = 38.6 - 170.5 + 37.8 - 1.0 - 1.0 - 2.0
P_rx = 38.6 + 37.8 - 170.5 - 4.0
P_rx = -98.1 dBW

In linear: P_rx = 10^(-98.1/10) = 1.55 × 10^-10 W = 0.155 nW
```

Step 6: Calculate Noise Power Density

Formula:

```
from Johnson-Nyquist noise equation (1928) & thermodynamics:

N_0 = k_B × T_sys
```

Constants & Parameters:

- k_B = 1.38 × 10^-23 J/K (Boltzmann constant, CODATA 2018)
- T_sys = 650 K (system noise temperature - design parameter)

System Noise Temperature Breakdown:

- LNA noise figure: ~3 dB → adds ~300 K
- Receiver losses: ~1 dB → adds ~75 K
- Sky noise at LEO: ~10 K
- Antenna noise: ~50 K
- Cable/connector losses: ~50 K
- **Total: T_sys ≈ 650 K (typical Ka-band smallsat receiver)**

Calculation:

```
N_0 = (1.38 × 10^-23 J/K) × (650 K)
N_0 = 8.97 × 10^-21 W/Hz

In decibels:
N_0 (dBW/Hz) = 10 × log₁₀(8.97 × 10^-21)
N_0 = -200.5 dBW/Hz
```

Step 7: Calculate C/N_0 (carrier to noise ratio)

Formula:

```
from standard communications theory (Sklar "Digital Communications", 2001):

C/N_0 (dB-Hz) = P_rx (dBW) - N_0 (dBW/Hz)
```

Calculation:

```
C/N_0 = -98.1 dBW - (-200.5 dBW/Hz)
C/N_0 = 102.4 dB-Hz
```

Step 8: Calculate Required C/N_0

Formula:

```
from Shannon-Hartley theorem & communications theory:

(C/N_0)_req (dB-Hz) = (E_b/N_0)_req (dB) + 10 × log₁₀(R_b)
```

Given:

- (E_b/N_0)_req = 9.6 dB (for BER 10^-9 with LDPC coding - design parameter)
- R_b = 1 × 10^9 bps (from problem statement)

E_b/N_0 Justification:

- Uncoded 16-APSK requires ~13-14 dB for BER 10^-9
- LDPC coding provides ~4-5 dB gain
- With coding: 9.6 dB is achievable
- Industry standard for coded Ka-band systems

Calculation:

```
Data rate term = 10 × log₁₀(1 × 10^9) = 10 × 9.0 = 90.0 dB-Hz

(C/N_0)_req = 9.6 dB + 90.0 dB-Hz = 99.6 dB-Hz
```

Step 9: Calculate Link Margin

Formula:

```
from standard RF link budget practice:

Margin (dB) = C/N_0 - (C/N_0)_req
```

Calculation:

```
M = 102.4 dB-Hz - 99.6 dB-Hz
M = 2.8 dB

Linear ratio: 10^(2.8/10) = 1.91x
```

Step 10: Calculate Beamwidth and Pointing

Formula (approximation for circular aperture):

```
from antenna beamwidth theory (Stutzman & Thiele "Antenna Theory", 2012):

θ_3dB ≈ 70 × λ / D  (degrees)
```

Note: The factor 70 ≈ 1.22 × 57.3, where 1.22 is the Bessel function zero (same as optical) and 57.3 is radians-to-degrees conversion.

Given:

- $\lambda = 0.009375$ m (from Step 1)
- $D = 0.30$ m (antenna diameter, design choice)

Calculation:

```
θ_3dB = 70 × (0.009375 m) / (0.30 m)
θ_3dB = 70 × 0.03125 = 2.19 degrees

Half-power beamwidth = 2.19°
```

In arcseconds:
2.19° × 3600 arcsec/° = 7,884 arcseconds

Pointing Requirement Analysis:

For -1 dB pointing loss: pointing error < θ_{3dB} / 3 ≈ **0.73°**

This is easily achieved with standard attitude control system (ACS):

- **RF pointing is 2,000× easier than optical (2.19° vs 8 μrad)**

Note for comparison: What this pointing requirement analysis reveals is RF's key advantage over optical — and it's significant enough to offset optical's superior link margin and power efficiency.

3.3 RF Link Budget Summary Table

Parameter	Symbol	Value	Units	Calculation Method
System Parameters				
Frequency	f	32	GHz	Given (Ka-band)
Wavelength	λ	9.375	mm	c/f
Data Rate	R_b	1×10^9	bps	Given
Range	R	250	km	Given
Transmitter				
Tx Power	P_t	1.2 (0.8 dBW)	W	Chosen
Tx Antenna Diameter	D_t	30.0	cm	Chosen
Antenna Efficiency	η_ant	0.6	-	Typical
Tx Gain	G_t	37.8	dBi	$\eta(\pi D/\lambda)^2$
EIRP	EIRP	38.6	dBW	P_t + G_t
Path Losses				
Free Space Path Loss	FSPL	-170.5	dB	$20\log(4\pi R/\lambda)$

Parameter	Symbol	Value	Units	Calculation Method
Pointing Loss	L_pt	-1.0	dB	Body pointing
Feed Loss	L_f	-1.0	dB	Waveguide
Misc Losses	L_m	-2.0	dB	Polarization, etc
Receiver				
Rx Antenna Diameter	D_r	30.0	cm	Chosen
Rx Gain	G_r	37.8	dBi	$\eta(\pi D/\lambda)^2$
System Noise Temp	T_s	650	K	LNA + losses
Received Power	P_rx	-98.1	dBW	Link equation
Noise Density	N_0	-200.5	dBW/Hz	k_B × T_s
Performance				
C/N_0	C/N_0	102.4	dB-Hz	P_rx - N_0
Required E_b/N_0	-	9.6	dB	BER 10^-9 w/coding
Required C/N_0	(C/N_0)_req	99.6	dB-Hz	E_b/N_0 + 10log(R_b)
LINK MARGIN	**M**	**2.8**	**dB**	**C/N_0 - (C/N_0)_req**
3 dB Beamwidth	θ_3dB	2.19	degrees	70λ/D

4. DIRECT COMPARISON: CALCULATED RESULTS

4.1 The Five Required Parameters

Parameter	Optical (Laser)	RF (Ka-band)	Winner	Advantage
1. Aperture Size	**10 cm**	30 cm	**Optical**	**3× smaller**
2. Transmit Power	**0.122 W**	1.2 W	**Optical**	**10× lower**

Parameter	Optical (Laser)	RF (Ka-band)	Winner	Advantage
3. Data Rate	**10+ Gbps scalable**	~2 Gbps max	**Optical**	**5× scalability**
4. Link Margin	**25.66 dB**	2.88 dB	**Optical**	**8.9× better**
5. Pointing Accuracy	±8 μrad (0.00046°)	**2.19° (7884")**	**RF**	**~4,800× easier**

Note: Optical value is half-power beamwidth (pointing requirement for -3 dB loss), not full beam divergence (18.9 μrad to first null).

4.2 Quantitative Comparison

Link Margin Ratio

```
Optical margin / RF margin = 25.66 dB / 2.88 dB
In linear: 10^(25.66/10) / 10^(2.88/10) = 368 / 1.91 = 193×
Optical has 193× more margin in linear terms
```

Pointing Difficulty Ratio

```
RF beamwidth / Optical half-power beamwidth = 2.19° / 0.00046°
= 2.19° / 0.00046° = 4,761×

In radians: 0.0382 rad / 8.0×10^-6 rad = 4,775×

Or: 7,884 arcsec / 1.65 arcsec = 4,778×

RF pointing is ~4,800× easier (in linear angle)

In solid angle (steradians): RF is ~2.3×10^7 times easier
(Solid angle scales as θ², so 4,775² ≈ 23 million)
```

Power Ratio

```
RF power / Optical power = 1.2 W / 0.122 W = 9.84×
Optical uses ~10× less power
```

Aperture Ratio

```
RF diameter / Optical diameter = 30 cm / 10 cm = 3×
Optical aperture is 3× smaller

Area ratio = (30/10)² = 9×
RF antenna has 9× more area
```

---

5. DATA RATE SCALABILITY ANALYSIS

5.1 Optical Scalability Calculation

Principle: Each 10× increase in data rate costs 10 dB margin

Current: 1 Gbps with 25.66 dB margin

At 10 Gbps:

```
Margin degradation = 10 × log₁₀(10 Gbps / 1 Gbps)
                   = 10 × log₁₀(10) = 10 dB

New margin = 25.66 dB - 10 dB = 15.66 dB ✓ (excellent)
```

At 100 Gbps:

```
Margin degradation = 10 × log₁₀(100) = 20 dB
New margin = 25.66 dB - 20 dB = 5.66 dB ✓ (adequate)
```

5.2 RF Scalability Calculation

Current: 1 Gbps with 2.8 dB margin

At 2 Gbps:

```
Margin degradation = 10 × log₁₀(2 Gbps / 1 Gbps)
                   = 10 × log₁₀(2) = 3.01 dB

New margin = 2.8 dB - 3.01 dB = -0.21 dB × (link fails)
```

Conclusion: RF cannot scale beyond ~1.5 Gbps without hardware changes.

---

6. RANGE SENSITIVITY ANALYSIS

6.1 Optical at Extended Range (500 km)

Path loss change:

```
ΔL = 20 × log₁₀(R_new / R_baseline)
   = 20 × log₁₀(500 km / 250 km)
   = 20 × log₁₀(2) = 6.02 dB additional loss

New margin = 25.66 dB - 6.02 dB = 19.64 dB ✓ (still robust)
```

6.2 RF at Extended Range (500 km)

Path loss change:

```
ΔL = 20 × log₁₀(500 / 250) = 6.02 dB additional loss

New margin = 2.8 dB - 6.02 dB = -3.22 dB × (link fails)
```

Conclusion: Optical maintains adequate margin at 2× range; RF link fails.

---

7. ADVANTAGES AND DISADVANTAGES

7.1 OPTICAL (LASER) Crosslinks

Advantages

1. **Exceptional Link Margin (25.66 dB)** - We calculated 369× more power than required, which gives us a massive robustness buffer
2. **Compact Size (10 cm)** - Here's what's impressive: we get 106.1 dBi gain from a small aperture, all thanks to that short wavelength
3. **Low Power (0.122W)** - Calculated from detector requirements; it's about 10× less than RF
4. **Unlimited Scalability** - We calculated 15.66 dB margin at 10 Gbps, and there's no spectrum constraints holding us back
5. **No Spectrum Licensing** - Optical frequencies are unregulated — one less headache
6. **Low Interference** - Calculated beam divergence of 18.9 μrad (4.73 m spot at 250 km) essentially eliminates cross-talk between satellites
7. **Secure** - Good luck intercepting a beam that narrow

Disadvantages

1. **Stringent Pointing (±8 μrad required)** - The calculated half-power beamwidth requires FSM for ±8 μrad pointing accuracy, which adds roughly $500k in NRE
2. **Complex Acquisition** - That narrow beam means we're looking at 30-60s acquisition time
3. **Lower TRL (7-8)** - Less flight heritage for small satellites compared to RF's TRL 9
4. **Higher Development Cost** - We're estimating $8M NRE versus $5M for RF
5. **Sun Avoidance** - Background noise forces us into geometry constraints
6. **Limited Vendors** - Fewer COTS suppliers to choose from (Tesat, ATLAS, Mynaric)

7.2 RF (Ka-band) Crosslinks

Advantages

1. **Relaxed Pointing (2.19°)** - Calculated beamwidth is 2,000× wider; standard ACS is sufficient

2. **Fast Acquisition (5-10s)** - Wide beam means rapid link establishment
3. **High TRL (9)** - Extensive heritage across Starlink, OneWeb, Iridium NEXT
4. **Mature Supply Chain** - Multiple vendors available (Viasat, L3Harris, Honeywell)
5. **Lower Development Cost** - $5M NRE; this is well-understood territory
6. **Lower Risk** - Predictable performance, and no FSM needed

Disadvantages

1. **Minimal Link Margin (2.8 dB)** - We calculated only 1.91× more power than required — there's basically no degradation buffer here
2. **Large Apertures (30 cm)** - Calculated gain requires 3× larger antennas, which complicates deployment
3. **Higher Power (1.2W)** - Calculated at 10× more than optical; impacts the power budget significantly
4. **Spectrum Limitations** - Ka-band's getting crowded, and ITU coordination is required
5. **Limited Scalability** - Calculated failure at 2 Gbps; we're bandwidth-constrained
6. **Interference Risk** - With mega-constellations proliferating, RF congestion is growing

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8. RECOMMENDATION

8.1 Primary Recommendation: OPTICAL (LASER) CROSSLINKS

Confidence Level: HIGH

8.2 Quantitative Justification

Decision Drivers (with calculations):

1. **Superior Link Performance**
    - Calculated margin: 25.66 dB versus 2.88 dB (an 8.9× ratio)

- Linear power ratio: 369× versus 1.91× safety factor
- Degradation tolerance: We could lose 22.66 dB and still meet requirements

2. **Optimal SWaP for Small Satellites**
    - Calculated aperture: 10 cm versus 30 cm (3× smaller, 9× less area)
    - Calculated power: 0.122W versus 1.2W (10× reduction)
    - Mass estimate: roughly 2.2 kg versus 4.2 kg (2 kg savings translates to about $10k in launch cost)
3. **Proven Scalability**
    - Calculated 10 Gbps margin: 15.66 dB (still excellent)
    - Calculated 100 Gbps margin: 5.66 dB (adequate)
    - RF calculated to fail at 2 Gbps (-0.21 dB margin)
4. **Range Robustness**
    - Calculated margin at 500 km: 19.64 dB (optical) versus -3.22 dB (RF fails)
    - 2× range tolerance demonstrated

8.3 Addressing the Pointing Challenge

Optical pointing requirement: ±8 μrad (calculated from half-power beamwidth for -3 dB loss)

RF pointing requirement: 2.19° = 38,200 μrad (calculated beamwidth)

Ratio: 4,775× easier for RF (in linear angle), or roughly 2,000× easier in solid angle

Note: Optical beam divergence to first null is 18.9 μrad, but the pointing requirement is based on the half-power beamwidth (8 μrad) to achieve the -3 dB pointing loss budget.

BUT: Here's where optical's 25.66 dB margin becomes really useful — we can trade some of that margin for relaxed pointing:

- If pointing degrades to 12 μrad → roughly -4.5 dB loss instead of -3 dB
- New margin: 25.66 - 1.5 = 24.16 dB (still excellent)

- That margin gives us flexibility to ease pointing requirements

Heritage FSM Technology:

- EDRS: Has demonstrated <5 μrad pointing accuracy since 2016 (better than our 8 μrad requirement)
- LCRD: Demonstrates similar performance since 2021
- Technology risk is manageable here

8.4 Cost-Benefit Calculation

20-Satellite Constellation:

- Optical total: $8M NRE + 20×$150k + 10yr×$50k = $12.3M
- RF total: $5M NRE + 20×$100k + 10yr×$30k = $7.3M
- **Premium: $5.0M (68% more)**

What We Get for That Premium:

- 8.9× better margin (calculated)
- 10× lower power per satellite (calculated)
- 3× smaller apertures (calculated)
- 10× data rate scalability (calculated: 10 Gbps versus 1 Gbps)
- Launch savings: 20 sats × 2 kg × $5k/kg = $200k

Net premium: $5.0M - $0.2M = $4.8M for transformational performance

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9. CONCLUSION

This trade study analyzed optical (laser) versus RF (Ka-band) crosslinks for a LEO satellite constellation using rigorous link budget calculations.

Key Calculated Results:

- **Optical:** 25.66 dB margin, 0.122W power, 10 cm aperture, ±8 μrad pointing requirement
- **RF:** 2.8 dB margin, 1.2W power, 30 cm aperture, 2.19° pointing requirement

Quantitative Comparison:

- Link margin: Optical 8.9× better (calculated ratio: 369×/1.91× in linear terms)
- Aperture: Optical 3× smaller (9× less area)
- Power: Optical 10× lower
- Pointing: RF roughly 4,800× easier (in linear angle)
- Scalability: Optical scales to 10+ Gbps (calculated 15.66 dB at 10 Gbps); RF fails at 2 Gbps (calculated -0.21 dB)

Recommendation: OPTICAL CROSSLINKS

Optical wins 4 of 5 key parameters. That enormous calculated margin (25.66 dB versus 2.88 dB) provides:

1. Robustness to degradation (22.66 dB buffer above requirement)
2. Data rate scalability (calculated 15.66 dB at 10× higher rate)
3. Range tolerance (calculated 19.64 dB at 2× range)
4. Flexibility to ease pointing requirements (we can trade margin for simpler FSM)

RF has significantly easier pointing (calculated roughly 4,800× wider beamwidth), but this advantage is outweighed by optical's transformational performance benefits and the availability of heritage FSM technology (EDRS, LCRD achieving <5 μrad).

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- Planck's constant: $h = 6.62607015 \times 10^{-34}$ J·s
- Speed of light: c = 299,792,458 m/s (exact)
- Boltzmann constant: $k_B = 1.380649 \times 10^{-23}$ J/K

APPENDIX: Formula Reference

Optical Link Budget Formulas

```
n = Q / η                               [photons/bit]
E_photon = h × c / λ                    [J/photon]
E_bit = n × E_photon                    [J/bit]
P_req = E_bit × R_b                     [W]

L_s = (λ / (4πR))²                      [linear]
G = (πD / λ)²                           [linear]

P_rx = P_tx × L_s × G_tx × G_rx × L_pt × L_o [W]
Margin = 10 × log₁₀(P_rx / P_req)       [dB]

θ = 1.22 × λ / D                        [radians]
```

RF Link Budget Formulas

```
FSPL = 20 × log₁₀(4πR/λ)              [dB]
G = η_ant × (πD/λ)²                    [linear]
EIRP = P_t + G_t                       [dBW]

N_0 = k_B × T_sys                      [W/Hz]
C/N_0 = P_rx - N_0                     [dB-Hz]
(C/N_0)_req = (E_b/N_0)_req + 10×log₁₀(R_b)  [dB-Hz]
Margin = C/N_0 - (C/N_0)_req           [dB]

θ_3dB ≈ 70 × λ / D                     [degrees]
```

Constants Used

```
c = 3 × 10^8 m/s              (speed of light)
h = 6.626 × 10^-34 J·s        (Planck's constant)
k_B = 1.38 × 10^-23 J/K       (Boltzmann constant)
```