Question 6: Friis' Formula and High-Frequency Communication Challenges

Demonstration, Implications, and Practical Examples

Cédric Sipakam

ULB | VUB

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Outline

1. Demonstration of Friis' Formula

2. Challenges of High-Frequency Communication

3. Illustrative Example: 5G Link Comparison

4. Conclusion

Demonstration of Friis' Formula

Introduction and Hypotheses

- The **Friis transmission formula** is a fundamental equation used to calculate the power received by one antenna from another in idealized conditions.
- It serves as the baseline for path loss calculations in Line-of-Sight (LOS) scenarios.

Hypotheses

- The antennas are in **free space**, with no obstructions or reflections.
- The antennas are in each other's **far-field**.
- The antennas are perfectly **aligned** and **polarization-matched**.
- The channel is **reciprocal**.

Setup and Geometry

pictures/friis-setup.png

Derivation Step 1: Power Density at the Receiver

- A transmitter radiates a total power P_{TX}. An isotropic antenna would radiate this power uniformly in all directions.
- The gain of the transmit antenna, $G_{TX}(\theta_{TX}, \phi_{TX})$, concentrates this power in a specific direction.
- The power density, S, at a distance d from the transmitter is the power per unit area:

$$S = \frac{\text{Power radiated in direction of RX}}{\text{Surface area of sphere at distance } d}$$

$$S = \frac{P_{TX} G_{TX}}{4\pi d^2}$$

- The term $P_{TX} G_{TX}$ is known as the Effective Isotropic Radiated Power (EIRP).

Derivation Step 2: Power Captured by the Receiver

- The receiving antenna captures a portion of this incident power density.
- The amount of power it captures is determined by its **effective area** (or effective aperture), A_{eRX}.

$$P_{RX} = S \cdot A_{eRX}(\theta_{RX}, \phi_{RX})$$

- Substituting the expression for S:

$$P_{RX} = \left(\frac{P_{TX} G_{TX}}{4\pi d^2} \right) A_{eRX}$$

Derivation Step 3: Relating Effective Area and Gain

- A fundamental property of any antenna, derived from reciprocity, relates its gain G to its effective area A_e:

$$A_e = \frac{\lambda^2}{4\pi} G$$

  where λ is the wavelength of the signal.

- For our receiving antenna, this means:

$$A_{eRX} = \frac{\lambda^2}{4\pi} G_{RX}$$

Derivation Step 4: The Final Friis Formula

- We now substitute the expression for A_{eRX} into our equation for P_{RX}:

$$P_{RX} = \left(\frac{P_{TX} G_{TX}}{4\pi d^2} \right) \left(\frac{\lambda^2}{4\pi} G_{RX} \right)$$

- Rearranging the terms yields the final Friis formula:

$$\boxed{P_{RX}(d) = P_{TX} G_{TX} G_{RX} \left(\frac{\lambda}{4\pi d} \right)^2}$$

Interpretation

The received power is proportional to the transmitted power and the gains of both antennas, and it decreases with the square of the distance and the square of the frequency.

Challenges of High-Frequency Communication

Introduction to the Challenges

- The Friis formula itself reveals the first challenge of using higher frequencies.
- Beyond this, other physical phenomena, not accounted for in the ideal Friis model, become increasingly problematic as frequency increases.
- We will explore these challenges in both LOS and NLOS (Non-Line-of-Sight) scenarios.

Challenge 1: Increased Free-Space Path Loss (LOS)

- The path loss is the ratio of transmitted to received power, $L = P_{TX}/P_{RX}$. From Friis' formula:

$$L_{FS} = \frac{1}{G_{TX} G_{RX}} \left(\frac{4\pi d}{\lambda} \right)^2$$

- Since wavelength $\lambda = c/f$, where f is the frequency, we can rewrite the path loss as:

$$L_{FS} = \frac{1}{G_{TX} G_{RX}} \left(\frac{4\pi d f}{c} \right)^2$$

- **Conclusion**: For fixed antenna gains, the free-space path loss is proportional to the square of the frequency ($L_{FS} \propto f^2$).

Challenge 1: Physical Interpretation

- Why does path loss increase with frequency for the *same antenna gain*?
- The relationship $A_e = \frac{\lambda^2}{4\pi} G$ is key.
- To maintain a constant gain G at a higher frequency (smaller λ), the physical size of the antenna must shrink.
- However, the effective area A_e shrinks proportionally to λ^2.
- The receiving antenna presents a smaller "target" to the incoming wave, thus capturing less power.

Example

Doubling the frequency from 3 GHz to 6 GHz increases the free-space path loss by a factor of 4, which is a 6 dB penalty.

Challenge 2: Atmospheric Absorption (LOS & NLOS)

- The Friis formula assumes a lossless medium. Earth's atmosphere is not lossless, especially at high frequencies.
- Molecules of water vapor (H_2O) and oxygen (O_2) absorb radio frequency energy at specific resonant frequencies.
- This absorption adds significant attenuation on top of the free-space path loss.

Challenge 2: Atmospheric Absorption (LOS & NLOS)

pictures/atmospheric-attenuation.png

Challenge 3: Penetration and Diffraction (NLOS)

- High-frequency signals have shorter wavelengths. This severely impacts their ability to propagate in cluttered NLOS environments.
- **Penetration Loss**: Shorter wavelengths are less effective at passing through obstacles like walls, foliage, and even human bodies. The attenuation from building materials increases significantly with frequency.

Challenge 3: Penetration and Diffraction (NLOS)

- **Diffraction Loss**: The ability of waves to "bend" around sharp corners is reduced for shorter wavelengths. This makes it harder for signals to fill in shadow regions behind obstacles.

Consequence

High-frequency systems are much more susceptible to blockage, making reliable NLOS communication very difficult. Links often require a clear or near-clear Line-of-Sight.

Challenge 4: Impact of Weather (Rain Fade)

- The impact of hydrometeors (rain, snow, fog) on radio waves is highly frequency-dependent.
- At frequencies below 10 GHz, rain attenuation is generally negligible.

Challenge 4: Impact of Weather (Rain Fade)

- Above 10 GHz, the wavelength becomes comparable to the size of raindrops, causing significant absorption and scattering of the signal.
- This phenomenon, known as **rain fade**, is a major design constraint for satellite and terrestrial microwave links in the Ku-band (12-18 GHz), Ka-band (26-40 GHz), and higher.

Illustrative Example: 5G Link Comparison

Scenario: Urban Microcell Link

- Let's compare two 5G links over a distance of $d = 200$ meters.
- We assume the same transmit power and antenna gains for both systems to isolate the effect of frequency.
  - **System A (Mid-Band)**: $f_A = 3.5$ GHz
  - **System B (mmWave)**: $f_B = 28$ GHz

Path Loss Calculation

The antenna-independent path loss in dB is:

$$L_0[\text{dB}] = 20\log_{10}(d) + 20\log_{10}(f) - 147.56$$

Results: LOS vs. NLOS

- **System A (3.5 GHz)**:

$$L_{0,A} = 20\log_{10}(200) + 20\log_{10}(3.5 \times 10^9) - 147.56 = \mathbf{89.34\ dB}$$

- **System B (28 GHz)**:

$$L_{0,B} = 20\log_{10}(200) + 20\log_{10}(28 \times 10^9) - 147.56 = \mathbf{107.4\ dB}$$

Results: LOS vs. NLOS

LOS Analysis

In a clear LOS path, the mmWave system already suffers an additional **18 dB** of path loss compared to the mid-band system. This is a factor of ≈ 63 in power.

Results: LOS vs. NLOS

- Now, let's place a single concrete wall in the path (**NLOS**).
- **Penetration Loss (Typical Values)**:
  - At 3.5 GHz: ≈ 10 dB
  - At 28 GHz: ≈ 25 dB

Results: LOS vs. NLOS

- **Total NLOS Path Loss**:
  - System A: $89.34 + 10 = \mathbf{99.34\ dB}$
  - System B: $107.4 + 25 = \mathbf{132.4\ dB}$

NLOS Analysis

The total path loss difference is now **33 dB**. The mmWave signal is over 2000 times weaker than the mid-band signal after passing through just one wall. This illustrates the extreme sensitivity of high-frequency systems to blockage.

Conclusion

Summary and Conclusion

Friis' Formula

- Provides the fundamental relationship for received power in an ideal free-space LOS channel.
- It demonstrates that path loss inherently increases with the square of the frequency ($L \propto f^2$) due to the reduced effective area of antennas with constant gain.

Summary and Conclusion

High-Frequency Challenges

As frequency increases, wireless communication becomes more challenging due to a combination of phenomena:

- **Higher Free-Space Path Loss**: An unavoidable consequence of physics.
- **Atmospheric and Rain Attenuation**: Gaseous absorption and rain fade become dominant loss factors at mmWave frequencies and above.
- **Poor Penetration and Diffraction**: Signals are easily blocked by obstacles and struggle to propagate in NLOS environments.

Thank You