A physical layer perspective on wide-area networks (WANs)

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CS4450: Introduction to Computer Networks
Wide-area networks

Span large geographic areas to interconnect locations across the world
Wide-area networks
A wide-area network (WAN) forms an administrative domain or an AS.
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Wide-area networks

Many WANs on the Internet that carry traffic for applications we care about.
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Types of wide-area networks

ISP WANs
(Comcast, ATT)
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Cloud WANs
(MSFT, Google, Meta)
Types of wide-area networks

- **ISP WANs**
  (Comcast, ATT)

- **Cloud WANs**
  (MSFT, Google, Meta)

- **Non-terrestrial WANs**
  (Loon, Starlink)
Challenges of implementing WANs

1. “long-haul” connectivity
2. High operating expenses
   - Billions of dollars to provision (capital expense)
   - Millions of dollars to maintain (operating expense)
Long-haul network connectivity
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Long-haul network connectivity

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Long-haul network connectivity

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   3. Physical connection between them
Long-haul network connectivity: basics
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I know how to reach prefix 1.0.0.0/24
Long-haul network connectivity: basics

Let me send you traffic towards 1.0.0.0/24

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Long-haul network connectivity: optical fiber

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Electromagnetic spectrum
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![Electromagnetic spectrum](image)

- UV
- Visible
- Infrared

Wavelength (nanometers) 850 1300 1550
Long-haul network connectivity: optical fiber

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   • Scattering of light
   • Absorption of light
Long-haul network connectivity: optical fiber

1. A wavelength ($\lambda$) carrying bits on fiber is a unit of signal
   - A portion of the optical spectrum
2. Frequency ($f$) and wavelength ($\lambda$) are used interchangeably: $\lambda = \frac{1}{f}$
3. Spacing between wavelengths to ensure signals don’t overlap at the receiver
4. 50GHz space between wavelengths, total 4THz bandwidth means 80 wavelengths on fiber (4000/50)
Long-haul network connectivity: signal modulation

1. Transmitter modulates light signals (wavelengths)
   1. Encode bits on a wave or pulse
   2. By changing the properties of the signal
2. Receiver decodes the signal to retrieve bits
3. Digital (bits n Tx) —> analog (optical signal) —> Digital (bits on Rx)
4. Example modulation format: NRZ

Non-return zero (NRZ) modulation
Long-haul network connectivity: signal modulation

1. Modulation format decides:
   1. Changes to the signal from a set of alternatives (symbols)
   2. Each symbol communicates a fixed number of bits
   3. Number of levels in a symbol = M, number of bits per symbol, \( N = \log_2 M \)

2. Symbol rate decides:
   1. number of symbols per second (baud rate)

Baud rate = 4, \( N = 2 \)
Hartley’s Law:

\[ R = f_p \log_2 M \]

Where,

- \( R \) = data rate, bit rate in bits/second
- \( f_p \) = symbol rate or baud rate in symbols/second
- \( M \) = number of levels in a given symbol

Long-haul network connectivity: optical fiber

Baud rate = 4, N = 2
1. Modulation packs bits on a signal
   • Some formats pack more bits than others
2. Types of modulations
   1. Change *amplitude* of the signal
   2. Change *phase* of the signal
3. For example: Phase shift keying (PSK) modulation changes the phase of the signal.
Long-haul network connectivity: exercise

QAM: quadrature amplitude modulation uses a mix of different amplitude levels and phase shifts to create different symbols (see right).
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Constellation Diagram of 16-QAM
Long-haul network connectivity: exercise

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Exercise: If the baud rate of the transmission is 50 Gbaud, what is the data rate of a wavelength modulated with 16-QAM modulation?
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*Hint:* 16-QAM has 16 levels per symbol
Long-haul network connectivity: Shannon-capacity
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Long-haul network connectivity: Shannon-capacity

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Signal quality of a wavelength on fiber in North America
Long-haul network connectivity: Shannon capacity

Shannon–Hartley Law states the max. rate at which information can be transmitted over a noisy channel

\[ R = B \cdot \log_2(1 + SNR) \]

Where,

- \( R \) = data rate, bit rate in bits/second
- \( B \) = bandwidth in Hz of the channel
- \( SNR \) = signal to noise ratio (measures signal quality)

\[ R \approx 0.332 \cdot B \cdot SNR \]
Long-haul network connectivity: Shannon capacity

Exercise: What is the maximum data rate that could be supported by this wavelength at the time shown by the cross if the bandwidth of the wavelength is 50GHz?

Where,

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Long-haul network connectivity: optical fiber

Under-sea fiber

Terrestrial fiber
WANs need high infrastructure investment

1. High capital expense (billions of $)
   1. Hardware costs for switches
   2. O(100,000) miles fiber

2. High operational expenses (millions of $ annually)

3. Crucial to operate efficient WANs