Free-Space Optical Communication

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• Factoids

• Opportunities & challenges

• The technology

• An example
The Diffraction Limit

Two terminals 40,000 km apart supporting 10 Gbps...

Data Rates and Distances

10 Gbps

1 Gbps

100 Mbps

10 Mbps

1 Mbps

10 km

100 km

1000 km

10000 km

light second

light minute

light hour
The Diffraction Limit

...can only support 1 Mbps if 100x40,000 km apart

Overview-4
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All the High-Rate Links Anyone Could Be Interested In (until we travel to the stars)

Over six orders of magnitude of distance = 120 dB of technology to span
All the High-Rate Links Anyone Could Be Interested In (until we travel to the stars)

Highly lossy links means always receive classical signals
Far-field means no spatial information about source
Radio Frequency (RF) vs Optical

- $10^{15}$ Hz (PHz) - 0.3 μm
- $10^{12}$ Hz (THz) - 0.3 mm
- $10^9$ Hz (GHz) - 0.3 m

More diffraction loss for same size transmit and receive apertures
Radio Frequency (RF) vs Optical

10^{15} \text{ Hz} \quad 0.3 \, \mu\text{m}

10^{12} \text{ Hz} \quad 0.3 \, \text{mm}

10^9 \text{ Hz} \quad 0.3 \, \text{m}

10^9 \text{ photons per second} = 128 \text{ pW at 1.55 \, \mu m}

Fewer photons per watt
Radio Frequency (RF) vs Optical

Higher frequencies are more power efficient by \( \sim f \) in freespace*

*More on this later

\( 10^{15} \text{ Hz} \)

\( 10^{12} \text{ Hz} \)

\( 10^9 \text{ Hz} \)
Opportunity/Challenge – Achieve Narrow-Beam Benefits of Optical

10^4 times higher frequency has potential to greatly increase data rate capabilities

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Overview-10
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Challenge – Achieve Optimum Coded Efficiency

*Channel/noise-limited capacities
Arbitrary modulations

Pre-amplified QAM or multi-level homodyne can achieve high bandwidth efficiency. Holevo predicts should be able to improve power efficiency by 4-6 dB.

Bandwidth (Channel Usages Per Bit)

Photons per Bit (dB)
Challenge – Achieve Optimum Coded Efficiency

*Channel/noise-limited capacities
Arbitrary modulations

Photon-counted Pulse Position Modulation can achieve high power efficiency. Holevo predicts should be able to achieve that with >10x less bandwidth.
Challenge – Achieve Optimum Coded Efficiency

*Channel/noise-limited capacities
Arbitrary modulations

Note: RF uses pre-amplified receivers. Optical technology has potential to have 7-9 dB better efficiency on top of “f” advantage, in addition to $h\nu/kT$ difference (another 10 dB or so)
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Parts of a Free-Space Communications System – RF

- Digital Processor
- Modulator
- TWTA
- Diplexer
- Receiver Front End
- Demod
- Digital Back End
- RF Osc (Local) Osc
- Antenna 1'-50'
- 2 slightly frequency-offset RF carriers
- RF Waveguide
- Steering Actuator
- Steering Control

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Parts of a Free-Space Communications System - Optical

- **Diode Laser**
- **Opt Osc**
- **Erbium-Doped Fiber Amp**
- **Telescope 3” – 36”**
- **Digital Processor**
- **Modulator**
- **EDFA**
- **Offset (Point-Ahead) Steering**
- **Diplexer**
- **Pt/Trk Actuator**
- **PAT Control**
- **Other Stabilization Devices**
- **Single Mode Fiber**
- **Demod**
- **Receiver Front End**
- **Digital Back End**
- **PAT (Local) Osc**
- **Various types of receiver/demods**

Various types of devices: MIT Lincoln Laboratory.
What’s Hard About Optical?
In Both Vacuum and Atmospheric Links

• Finding (acquiring) where to point
• Stabilizing (tracking) very narrow beam in face of platform micro-vibrations
• Subsystems must withstand vibrations of launch, wild temperature swings, and radiation
What’s Hard About Optical?
In Atmospheric Links

- Transmitting beam up through atmosphere and preserving high gain in face of turbulence
- Receiving low-power signal via large aperture and coupling light into single-mode (or other small) receiver in face of turbulence
- Extremely narrow-band filtering of received light when pointed near sun
- Dealing with wide power fluctuations
- *Clouds, fog, trees*
What’s Hard About Optical Technologies

- High-optical-power, low-electrical-power transmitters that can achieve high speed, high peak powers, high optical quality, etc.
- Receiver components and architectures that can achieve near-optimum performance at desired rates and desired aperture sizes.
- Present-day photon-counting technologies not simply suitable for space environment.
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To be world’s first lunar lasercom

*Space terminal to fly on Lunar Atmosphere and Dust Environment Explorer (LADEE)*

**Main lasercom goals**
- 622 Mbps downlink
- 20 Mbps uplink
- Sub-centimeter real-time ranging

LADEE Launch
August 2013
- 1 month cruise
- 1 month lasercom orbits
- 3 months science orbits
Summary

- Present technologies adequate for achieving wide range of high-performance (optical) communications systems
- Stage is set for optical transmission and reception based on quantum properties of light