Quantum Limits of Space-to-Ground Optical Communications

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**Dominant Limits for Optical and Microwave Frequencies**

**RF/Microwave frequencies (~10^9 Hz)**
- Thermal noise dominates the fundamental sensitivity of a receiver
- Coherent detection gives near optimal performance
- In general, Gaussian noise statistics prevail (central-limit theorem)

**Optical frequencies (~10^{14} Hz)**
- Quantum measurement noise dominates the fundamental sensitivity of a receiver
- Photon-counting becomes asymptotically optimal at the photon-starved limit
- Heterodyne detection becomes asymptotically optimal at the bandwidth-starved limit
- Noise statistics depend on measurement
**Detection Schemes**

Coherent detection scheme:
- Superposition of a weak received coherent-state optical signal with a strong local oscillator results in shot-noise-limited performance.

Direct detection scheme:
- Photon-counting detection of coherent states (ideal laser light) can suppress the thermal noise of the detector, receiver and amplifier electronics, such that the output statistics are also shot noise limited.

Quantum-limited detection is the result of the residual intrinsic quantum-mechanical uncertainty.
Prior to the 1970’s
• It was assumed that the quantum limit on the photon information efficiency [PIE] of an optical comm system was at 1 nat/photon or 1.44 bits/photon, achievable by heterodyne detection.

Pierce (1978)
• Recognized that the PIE is unbounded for an optical communication link if an ideal photon-counting scheme can be applied.
Capacity

**Shannon’s Capacity (classical treatment of information theory)**
- Set limits on the highest reliability of data communications, given receiver’s architecture.

**Holevo’s Capacity (quantum-mechanical treatment of information theory)**
- Optimized link capacity over the best possible receiver.
  - Theoretical predictions of an optical receiver, optimized via quantum mechanics, to achieve quantum-limited detection
  - *Has not completely materialized yet.*

*New transmission/detection techniques are required to bridge the gap between the Shannon and the Holevo treatments to achieve the ultimate quantum limits in communications.*
The ultimate quantum limit for space-to-ground communications

- A balance between **PIE** and **DIE** (dimensional information efficiency).
  - DIE is measured in bits/dimension, where the dimensions are **spatial**, **temporal**, and **polarization modes**.
  - Communication links with PIE >> 1 bit/photon are possible, but at the cost of DIE << 1 bit/mode.
  - Inversely, DIE >> 1 bit/mode transmission is achievable, but at the cost of PIE << 1 bit/photon.
**Single-Mode Deep-Space Channel Capacity**

- Single-mode capacities with several transmitter/receiver technologies, having average photon number constraint
  - The ‘ultimate receiver’ curves are Holevo information bounds
  - Specified receiver curves are Shannon information bounds

Increasing photon efficiency

 Increasing channel-use efficiency
Optical Communications at the Quantum Limit

- Communications link is fundamentally quantum mechanical
  - Measurements inherently yield random observations
  - Statistics of measurement outcomes determine channel capacity

- Quantum limits of free-space optical communications are driven by limits imposed by each of these three components.
  - The ultimate capacity of optical communications must therefore optimize over the alphabet of optical states, the priors for the optical states, the measurement at the receiver

Credit: Baris Erkmen (JPL)
Limits Imposed by the Transmitter

Encoding
• Optical codes approaching within a fraction of 1 dB of the Shannon limit have been developed.
  • New concatenated coding has been proposed for quantum optimal coding to closely approach the Holevo limit.

Modulation
• The best-known approach to achieve the ultimate quantum limit is with coherent state modulation.
  • Since exceedingly high (multi-Tb/s) modulation rates are now practically achievable, the modulation bandwidth itself is not a real limitation.
  • Phase noise of current lasers is a limitation on the best phase modulation quality for coherent detection.
  • Pulse-position-modulation (PPM) in conjunction with photon-counting detection has been shown to deliver quantum-noise-limited performance with unbounded photon efficiency.
  • The achievable modulation extinction ratio is limited by the amplified spontaneous emission generated by the source (amplifier).
Photon Efficiency Limits Due to Finite Extinction Ratio

- Require 44.5dB extinction ratio to achieve PIE = 10 bits/photon
  - The best oscillator modulation extinction ratio achievable today is on the order of 80dB.

- Each curve in these plots is the capacity efficiency tradeoff for a given PPM order $M$, and is generated by varying the average number of signal photons.
The atmosphere causes significant degradation of coherently modulated optical signals.

- Without a daytime-/nighttime-operating adaptive optics (AO) system, significant errors are introduced into the link.

- Background light, inevitably accompanying the transmitted signal onto the receiver, can set severe limitations on achievable link capacity.

- Pulse spreading, a problem with fiberoptics communications, is not a limiter in free-space optical communications since there is very minimal dispersion from the medium.
Limits Imposed by the Receiver

Limitations on the receiver include:

- Sub-optimal quantum detection
  - Photo-detector dark noise
  - Photo-detector timing jitter
  - Photo-detector blocking loss
- Sub-optimal quantum decoding
- Quantum limit of noise in optical or electronic amplifiers
- Capacity efficiency limits
**Fundamental Free-space Capacity Limits vs. State-of-the-art Optical Systems**

This is the ultimate quantum limit: Joint dimensional and photon efficiencies outside this curve (i.e., above and to the right) are unachievable.

Inferior curves represent theoretical limits with various constraints on the modulation and/or receiver.
**Losses due to Detector Jitter**

- Jitter is the *random delay* from the time a photon is incident on a photo-detector to the time a photo-electron is detected.
- Jitter losses are a function of the *normalized jitter standard deviation*:
  \[
  \frac{\sigma}{T_s}
  \]

**Jitter limits:**
- data rate
- ability to mitigate dark noise
- ability to decrease the slot width without incurring loss.

<table>
<thead>
<tr>
<th>Device</th>
<th>$\sigma$ / ns</th>
</tr>
</thead>
<tbody>
<tr>
<td>InGaAs(P) PMT</td>
<td>0.9</td>
</tr>
<tr>
<td>InGaAs(P) GM-APD</td>
<td>0.3</td>
</tr>
<tr>
<td>Si GM-APD</td>
<td>0.24</td>
</tr>
<tr>
<td>NbN Superconducting Nanowire</td>
<td>0.03</td>
</tr>
</tbody>
</table>
**Photodetector Blocking**

* Certain photon-counting photodetectors are rendered inoperative (blocked) for some time $t$ (dead time) after each detection event.
  * 10 to 50 ns, Si GM-APD
  * 1 to 10 ms, InGaAs GM-APD
  * 3 to 20 ns, NbN Super-conducting Nanowire

* Mitigating Blocking
  * Decreasing the peak incident photon rate (per detector)
  * Temporally
    - *Increase the slot-width and reduce the photon rate, while preserving the photons/slot.*
    - *Reduces impact of blocking, but lowers the date rate (bits/s), and integrates more noise*
  * Spatially
    - *Increase Focal length, to decrease signal intensity in the focal (detector) plane*
    - *Integrates more noise*
Summary

• For a pure loss channel, the ultimate capacity can be achieved with classical coherent states (i.e., ideal laser light)
  • Capacity-achieving receiver (measurement) is yet to be determined.
  • Heterodyne detection approaches the ultimate capacity at high mean photon numbers.
  • Photon-counting approaches the ultimate capacity at low mean photon numbers.

• A number of current technology limits drive the achievable performance of free-space communication links.
Summary, cont.

• Approaching fundamental limits in the bandwidth-limited regime
  • Heterodyne detection with high-order coherent-state modulation approaches ultimate limits.
    • SOA improvements to laser phase noise, adaptive optics systems for atmospheric transmission would help
  • High-order intensity modulation and photon-counting can approach heterodyne detection within approximately a factor of 2.
    • May have advantages over coherent detection in the presence of turbulence

• Approaching fundamental limits in the photon-limited regime
  • Low-duty cycle binary coherent-state modulation (OOK, PPM) approaches ultimate limits
    • SOA improvements to laser extinction ratio, receiver dark noise, jitter, and blocking would help
  • In some link geometries (near field links) number-state transmission could improve over coherent-state transmission