# Quantum Limits of Space-to-Ground Optical Communications[1]

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**Abstract**: Quantum limiting factors contributed by the transmitter, the optical channel, and the receiver of a space-to-ground optical communications link are described. Approaches to move toward the ultimate quantum limit are discussed.

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The vast difference between the telecommunication frequencies at optical (~$10^{14}$ Hz) and microwave (~$10^{9}$ Hz) bands results in major (physics driven) limitations at one end of this spectrum, which are minor at the other end. The high energy of optical photons, coupled with the low ambient background at optical frequencies makes detection of, and discrimination between, individual photons possible. In the direct detection of coherent states (ideal laser light), a photon-counting approach can suppress the thermal noise of the detector, receiver and amplifier electronics, such that the output statistics are dominated by shot noise. Quantum-limited detection is the result of the residual intrinsic quantum-mechanical uncertainty. In a coherent detection scheme, superposition of a weak received optical signal with a strong local oscillator also results in shot-noise-limited performance. Prior to the 1970's, it was assumed that the quantum limit on the photon information efficiency [PIE] of an optical communication system was at 1 nat/photon or 1.44 bits/photon, achievable by heterodyne detection [1]. Pierce recognized that the PIE is unbounded for an optical communication link if an ideal photon-counting scheme can be applied.

In the classical treatment of information theory, Shannon's capacity sets limits on the highest reliability of data communications, given receiver's architecture. In the quantum-mechanical treatment of information theory, Holevo optimized link capacity over the best possible receiver [2]. Theoretical predictions of an optical receiver, optimized via quantum mechanics, to achieve quantum-limited detection have 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 [3]. This limit for space-to-ground communications is a balance between PIE and dimensional information efficiency (DIE). 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.

Figure 1 represents a block diagram of a space-to-ground optical communication system consisting of three primary components. Quantum limits of free-space optical communications are driven by limits imposed by each of these three components.

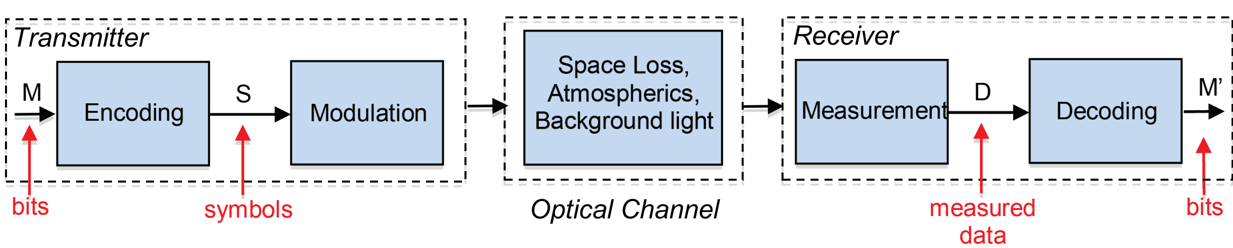


**Fig. 1** Block diagram of a typical free-space optical link, where encoded and modulated data at the transmitter terminal traverses through the medium, is then detected, and decoded at the receiver terminal.

**Limits Imposed by the Transmitter** – Encoding and modulation are the two major drivers of this subsystem. <u>Encoding</u>: Optical codes approaching within a fraction of 1 dB of the Shannon limit have been developed [4]. New concatenated coding has been proposed for quantum optimal coding to closely approach the Holevo limit [5].

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Modulation: The best-known approach to achieve the ultimate quantum limit is with coherent state modulation [6]. 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 [7]. Since exceedingly high (multi-Tb/s) modulation rates are now practically achievable, the modulation bandwidth itself is not a real limitation. Implementation of efficient links at high data rates necessitates high peak-to-average power lasers and high modulation extinction ratio (driven by the PPM order being implemented). The required ratio of powers is not always practical, and that sets a limitation. The achievable modulation extinction ratio is limited by the amplified spontaneous emission generated by the source (amplifier). The best oscillator modulation extinction ratio achievable today is on the order of 80 dB [8].

**Limits Imposed by the Optical Channel** – 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; sub-optimal quantum decoding; quantum limit of noise in optical or electronic amplifiers; and capacity efficiency limits. A rare known example of a quantum-mechanically optimal receiver is the Dolinar receiver [9]. Figure 2 shows a plot of DIE vs. PIE with trades on modulation and detection techniques for free-space links assuming constrained average power. This plot shows which combinations of modulation and detection scheme can more closely approach the ultimate quantum limit. An early JPL experiment demonstrated 2.5 bits/photon [10]. Current research objectives are 10 bits/photon (initially in the near-field) [3].

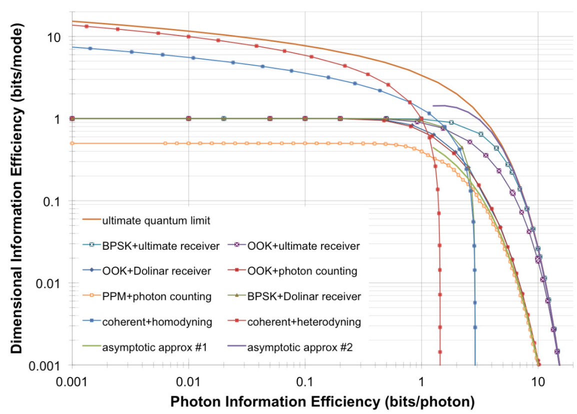


**Fig 2**. Plot of the ultimate quantum limit, and theoretical limits on tradeoffs between photon information efficiency (bits/photon) and dimensional information efficiency (bits/dimension). OOK = on-off-keying, PPM = pulse-position-modulation, and BPSK = binary-phase-shift-keying.

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