New Codes for the Optical Channel*

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Abstract

We present new codes and modulation formats for the deep space optical channel. By taking maximum advantage of inherent physical constraints on the communications link, these codes and modulation formats substantially close the large gap between state of the art systems and the Shannon limit. The new codes include a binary turbo code previously thought difficult to match to the high-order modulation used on the optical channel, and new modulation formats designed for maximum throughput.

1 Introduction

Despite many improvements in lasers, detectors, pointing methods, and telescopes, a mainstay of state-of-the-art optical communications systems has been the use of Pulse Position Modulation (PPM), Reed-Solomon (RS) coding, and an assumption of Poisson or Gaussian statistics. For example, the Free-space Optical Communications Analysis Software (FOCAS) link-budget tool in use at JPL handles only RS-coded PPM, and uses Gaussian approximations for the detector statistics. Recent work on multipulse PPM, overlapping PPM (OPPM), Differential PPM (DPPM), on-off keying (OOK), etc. has often relied on unrealistic assumptions such as a noiseless channel or Poisson statistics, and has primarily concentrated on PPM only.

As a result of the historic emphasis on RS-coded PPM signaling, there remain large gaps between current state-of-the-art technology and the Shannon limit on the deep space optical channel. The Shannon limit for PPM on the deep space optical channel is as much as 8 dB above the operating point of RS-coded PPM [1]. Furthermore, when the PPM channel is substituted with a more general slotted channel, the Shannon limit becomes even higher [2], resulting in a 10+ dB potential improvement for non-RS non-PPM schemes.

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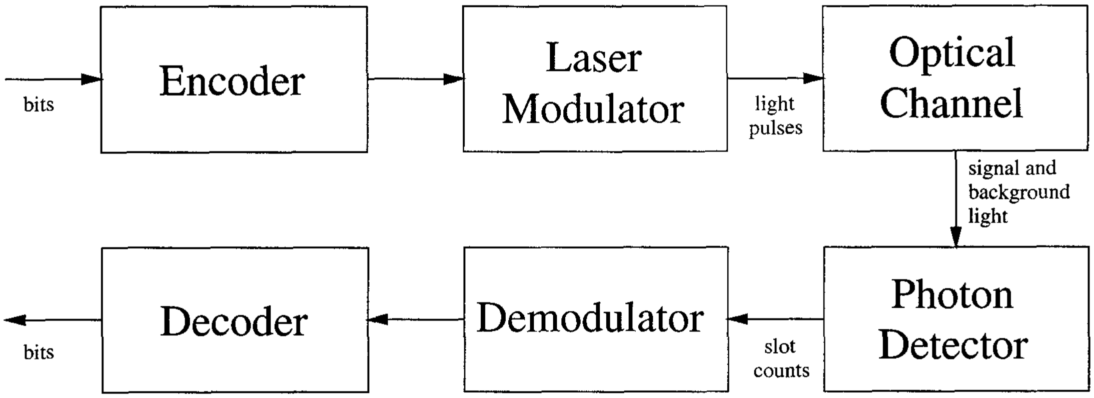


Figure 1: An optical communications system.

We present a few methods to begin closing this gap. These include (a) more general run-length constrained slotted signaling, (b) turbo coding, and (c) full use of soft channel outputs. The power saved may be traded by systems engineers for increased data rate, smaller spacecraft apertures, lower transmitter efficiency, higher tolerance for atmospheric losses, and smaller ground stations. It will also allow missions to travel into further reaches of space and for longer periods of time than is possible with current technology. Importantly, these gains do not depend on improvements in any hardware such as lasers, optical telescopes, or detectors—it is the result merely of signaling in a more intelligent way, guided by information theory.

2 Preliminaries

2.1 The Optical Channel

The channel under consideration is shown in in Figure 1. When the major components of the optical channel remain fixed—such as the laser, the atmosphere, the receiving optics and detector, the system may be improved by using better codes and modulation schemes. We propose replacing the encoder/decoder and modulator/demodulator portions of the system. The encoders and decoders are operated with software, and the modulator is controlled by a piece of equipment that may be reprogrammed to use slotted schemes more general than PPM. Thus, the major results of this work are relatively easy to implement and are independent of improvements in the hardware portions of the system.

The modulator typically is a pulse position modulator (PPM) in which a block of k bits is mapped to 2^k slots, exactly one of which contains a laser pulse. At the receiver, light is focussed on a photodetector.

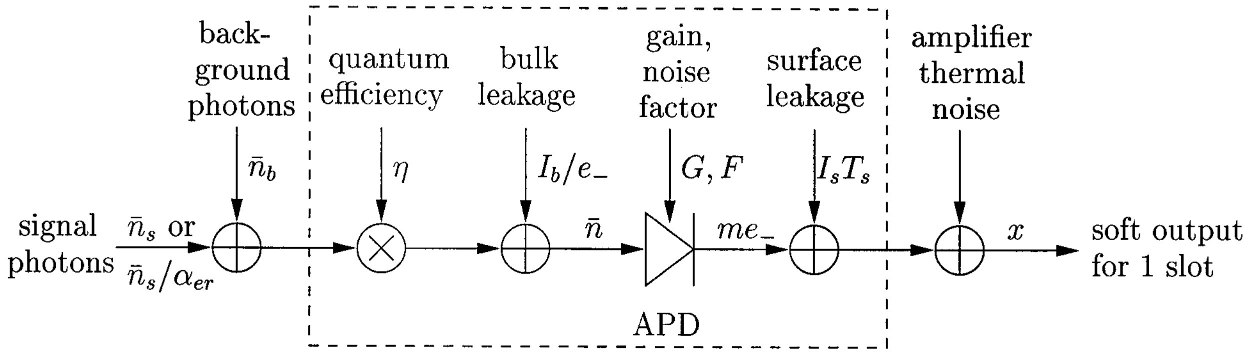


Figure 2: The soft APD demodulator.

The leading detector under consideration by NASA for optical missions is a an Avalanche PhotoDiode (APD) detector, shown in Figure 2, because it maintains an acceptable quantum efficiency for typical link budgets analyzed thus far [3]. The detector integrates over slot times to produce slot counts. The number of photons incident on a detector from an incident optical field of known intensity is a Poisson distributed random variable [4]. However, the secondary electrons at the output of the detector may have a much more complicated probability distribution [5]. This must be taken into account when optimizing the modulation and coding scheme— using Poisson or Gaussian approximations can lead to very inaccurate results [4].

3 New Codes and Modulations

3.1 Turbo Codes

The primary difficulty of applying a turbo code to an optical channel is that of matching turbo code symbols to high order PPM symbols. The optimal PPM order for low SNR space applications can be 256 or higher [6], whereas 256-ary turbo codes are a practical impossibility because turbo decoding complexity is exponential in the symbol alphabet size. At the other extreme, binary turbo codes can be applied to 2-PPM [7], but at the expense of photon efficiency [6].

The symbol matching problem is largely a perceived one. Using previously published turbo decoding algorithms, binary turbo codes can make full use of 256-PPM soft demodulator outputs by suitably initializing a priori probabilities in the turbo decoder. The performance would likely be better with nonbinary turbo codes, but the binary turbo codes also perform well, and represent an improvement over RS codes.

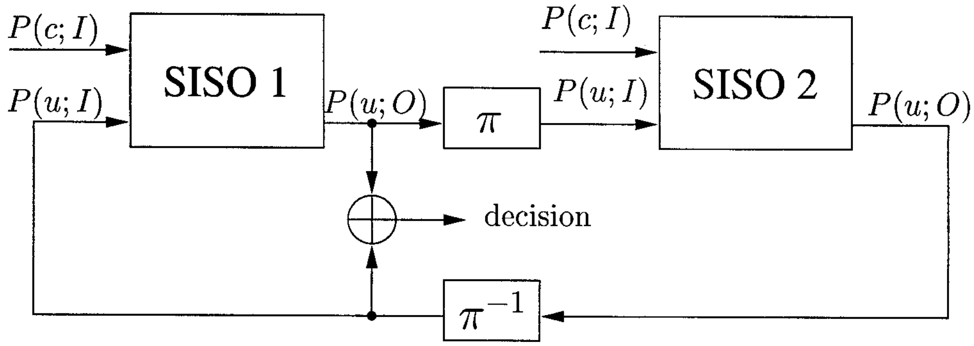


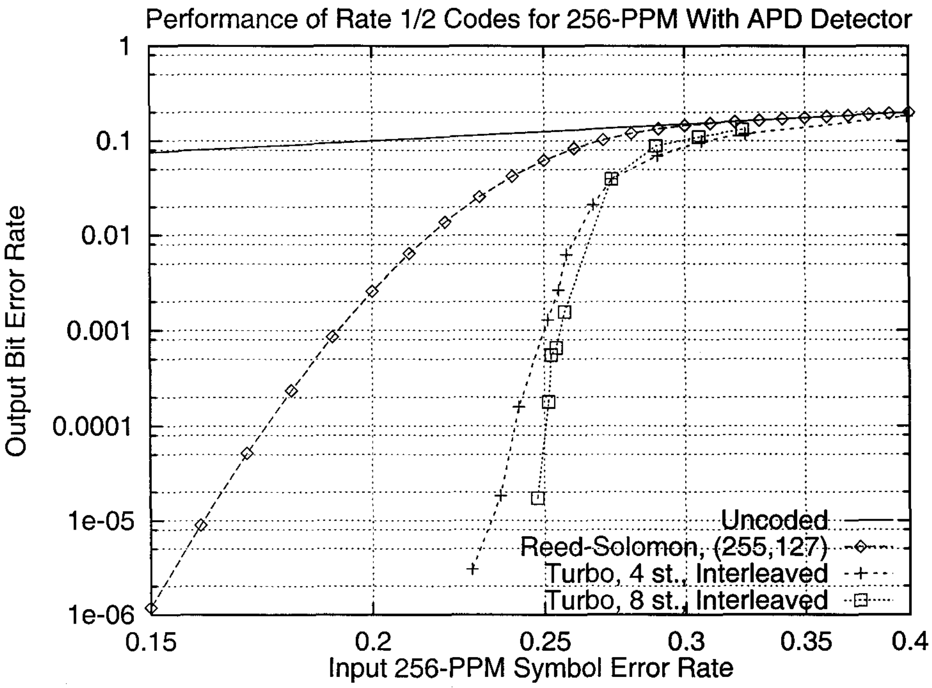
Figure 3: Turbo decoder.

We use a turbo decoder structure and notation as in [8], shown in Fig. 3. To properly initialize the turbo decoder, we must determine the a priori probability of codewords for each constituent code. Space limitations do not permit a complete description of how this is accomplished. Briefly, we define a likelihood ratio, equal to the ratio of the pulsed and non-pulsed probability density functions for a slot, and write the conditional probability of the ith PPM symbol being sent, given the received vector of soft counts, as the ratio of the likelihood ratio in the ith slot to the sum of the likelihood ratios in all the slots of the symbol. In this way, the customary a priori probabilities of the turbo codewords are determined. In each iteration, these are updated. Care must be taken to properly account for which bits of the turbo code are used in common PPM symbols. Algebraically, this is not a complex thing for a computer to implement, and the turbo coded PPM can operate at nearly the same speed as it would on a regular RF channel.

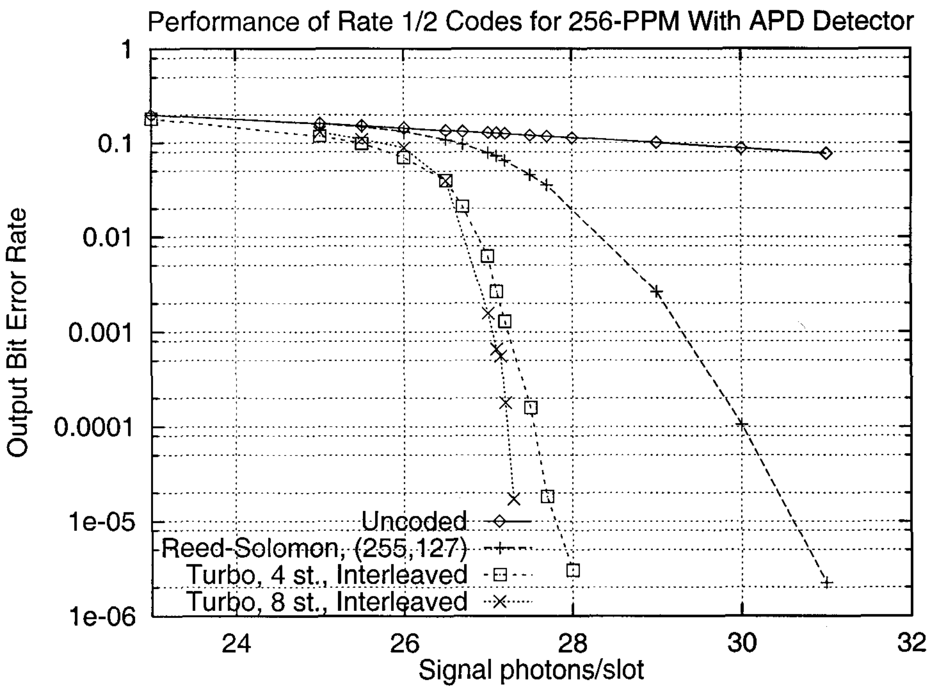
3.1.1 Performance

Using the method of the previous section, simulations were conducted. We used very simple rate 4- and 8-state 1/2 binary turbo codes, 256-PPM, a 20ns slot with, an average of 10 background incident photons per slot, and a SLiK APD. Metrics were computed using a multiplicative method, as opposed to an additive method using additional log() and exp() calls. As the errors occur in clusters, with most blocks containing no errors and some blocks containing many errors, the simulations were continued until 100 error-containing blocks were processed (with a maximum of 163 million bits processed per simulation). This usually implied the simulation of 10,000 or more bit errors.

Fig. 4 shows the performance of coded 256-PPM as a function of input SER, for coding rate 1/2. Part (a) and (b) of the figure shows the same simulation data in two different ways. Since the turbo decoder does not make an explicit determination of PPM symbols, the input SER is technically not defined for turbo



(a)



(b)

Figure 4: Performance of rate 1/3 codes as a function of (a) input SER, and (b) signal photons per slot.

codes; the SER used in the plot is that which would have occurred had a maximum likelihood rule been used to make PPM symbol decisions. The three curves for turbo codes represent the 4-state noninterleaved PPM, 4 state interleaved PPM, and 8 state interleaved PPM simulations. By noninterleaved PPM, we mean that the bits at the output of the turbo encoder are grouped into 8-bit blocks directly and PPM modulated. This order is $(x_0, x_{1p}, x_{2p}, x_0, x_{1p}, x_{2p}, \ldots, x_0, x_{1p}, x_{2p})$. For the interleaved PPM, the order of the bits at the turbo encoder output has been randomized. The effect of the interleaver before the modulator is to spread out related bits into different PPM symbols. Thus, when chance yields misleading soft information, the effect is spread across the entire block, instead of clustered together.

We define the coding gain as the savings in signal photons per information bit for one system over another. At an output BER of 10^{-5}, the coding gain of the very simple 4-state rate 1/2 binary turbo code is $10\log_{10}(30.6/27.3) = 0.5$ dB above that of a (256,127) RS code.

3.2 New Modulations

Aside from new codes, there are some gains to be had with new modulation formats. One improvement is to use truncated PPM, in which we omit all nonsignaling slots after each signaling slot within a PPM symbol. This reduces the average size of the PPM symbol by 1/2, thereby increasing the data rate. This is just one simple apprach. More generally, we may use run-length constrained modulation types, in which fixed-length symbols are not used, but following every laser pulse is a certain number of non-signaling pulses which represent the time the laser requires to recharge. These so-called d-k codes have been used in magnetic media, for example, but thus far have not been proposed for the optical channel. New synchronization algorithms for varying symbol durations may be needed for these modulation formats.

We have computed performance bounds for various modulation types, including PPM, DPPM, OOK, d-k codes, and variants, for a deep space optical channel producing soft outputs according to a Webb distribution. These are analyzed by computing the capacity limits when restricted to these types of modulations. Depending on specific parameters affecting the channel statistics, it was found that the most general d-k codes offer a capacity advantage of up to 5 dB over a channel constrained to use PPM.

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