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Utilizing time-bandwidth space for efficient deep-space communication

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ABSTRACT

We discuss modulation formats that warrant high information efficiency of deep-space optical links under given power constraints. The discussion is framed using the theoretical concept of orthogonal optical modes occupying the available time-bandwidth space. With diminishing average signal power, the challenge is to concentrate the entire optical energy in very few of these modes. In the generic case of pulse position modulation (PPM), where optical modes occupy separate time bins, this results in increasing peak-to-average power ratio requirements for the transmitter light source. Equivalent information efficiency can be attained using frequency shift keying (FSK) employing modes that do not overlap in the spectral degree of freedom and have uniformly distributed instantaneous optical power in the temporal domain. Recently, efficient modulation formats have been proposed that use words composed from the binary phase shift keying (BPSK) alphabet. Such words can be converted after transmission into the PPM format with the help of structured optical receivers. Selected technical aspects of physical implementations of links based on different modulation formats are briefly reviewed.

Keywords: photon-starved communication; pulse position modulation; frequency shift keying; structured optical receivers

1. INTRODUCTION

Communication links exploiting the optical rather than the radio-frequency band hold great promise for large-volume data transfers from deep space missions [1,2]. In order to attain high information efficiency in deep space communications it is necessary to choose carefully the modulation format. The current standard is pulse position modulation (PPM), which encodes information in the temporal position of a light pulse within a frame of otherwise empty time bins. As illustrated in Fig. 1, the optimal PPM order, i.e. the number of time bins that form one symbol frame, grows unboundedly with the diminishing received signal power, implying increasing temporal concentration of the optical power in the generated signal. This becomes problematic for downlink transmission, as pulsed laser sources typically have lower overall electrical-to-optical conversion efficiency compared to their cw counterparts. Importantly, the unrestricted growth of the peak-to-average power ratio occurs also for PPM links optimized in presence of background noise [3,4].

The purpose of this paper is to discuss modulation formats with uniformly distributed instantaneous optical power that can offer information efficiency equivalent to that of PPM links. We focus our attention on two alternatives. The first one is conventional frequency shift keying (FSK) [5], which can be viewed as the spectral-domain analog of PPM. The second, recently proposed approach uses words composed from the binary phase shift keyed (BPSK) alphabet [6,7]. Such words can be converted into the PPM format after transmission with the help of structured optical receivers. From the theoretical perspective, modulation formats discussed here can be conveniently described within the unifying framework of orthogonal optical modes occupying the available time-bandwidth space. We also discuss here briefly selected technical aspects of downlink transmission utilizing these formats. Importantly, overcoming the peak-power limitations of onboard transmitters combined with advanced error correction can substantially extend the range of optical communication links. Such a combination of hardware and software refinements in principle enables one to attain information rates that scale linearly with the detected signal power, i.e. as r^{-2} with the distance r from the spacecraft [4]. This would present a dramatic improvement compared to earlier analyses of optical PPM links which indicated the information rate scaling as r^{-4} for large distances, rendering them useless in the very deep space [8].

This paper is organized as follows. In Sec. 2 we use the concept of orthogonal optical modes to discuss high-order modulation formats: PPM, FSK, and BPSK words along with selected technical aspects of their physical implementations. A viable design for a structured optical receiver converting phase-polarization patterns into the PPM format is presented in Sec. 3. Finally, Sec. 4 concludes the paper.

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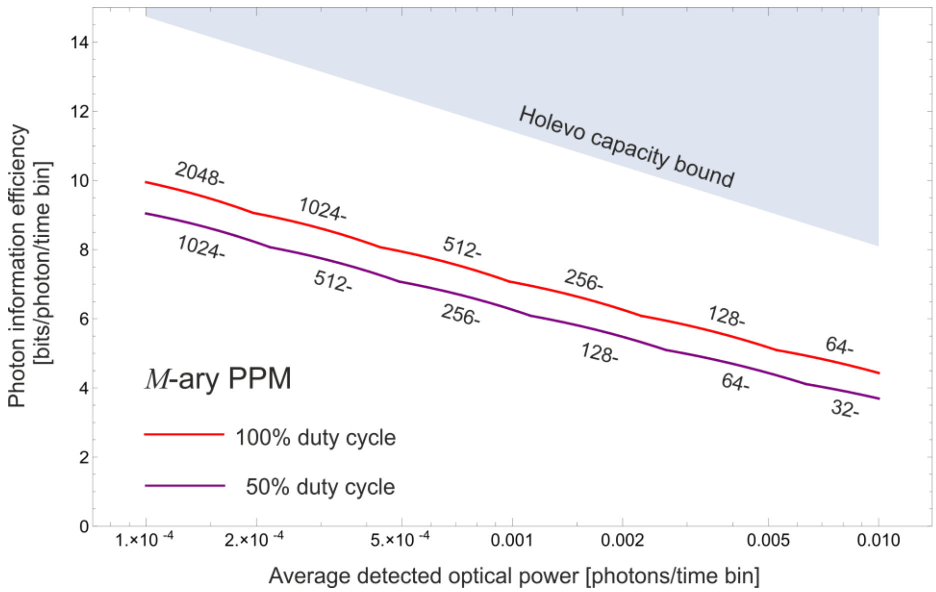

Figure 1. Photon information efficiency in bits/photon/time bin as a function of the average detected signal power, expressed in photons per time bin, for the PPM format optimized over an order taken as an integer power of 2, in the case of 100% and 50% duty cycle. The edge of the greyed area marks the ultimate Holevo quantum limit on the capacity of an optical channel.

2. HIGH-ORDER MODULATION FORMATS

2.1 Pulse position modulation

In the case of M-ary PPM, information to be transmitted is encoded in symbols defined by the position of a single light pulse in a frame of M otherwise empty time bins. It is helpful to visualize this modulation scheme using the time-frequency diagram shown in Fig. 2(a). The optical link uses a bandwidth B centered around the carrier frequency f_c which defines a continuous strip parameterized with time. In the case of the PPM format the time-bandwidth space is partitioned into cells with the minimum temporal duration $\tau \sim B^{-1}$ permitted by the time-frequency uncertainty relation. Each cell spreads over the entire available bandwidth. The cells included in one PPM frame of the order M cover the time-frequency area equal to $M\tau \times B \sim M$.

Mathematically, the jth PPM symbol, $j = 1, \dots, M$, can be described by a complex waveform $u_j^{\mathrm{PPM}}(t)$ multiplied by the overall field amplitude which determines the optical energy carried by the signal. As illustrated with Fig. 2(a), the jth waveform is concentrated to a good approximation in the jth time. It can be obtained from a generic pulse waveform $u(t)$ by a simple temporal shift:

$$u_j^{\mathrm{PPM}}(t) = u(t - j\tau) \tag{1}$$

Because each one of PPM symbols occupies the entire available bandwidth, their spectra are identical, as also shown in Fig. 2(a).

The set of waveforms describing individual PPM symbols can be viewed as an example of a family of M optical modes $u_j(t)$, $j = 1, \dots, M$, that are defined in the temporal domain. It is customary to assume that each mode is normalized to one, while modes corresponding to different symbols are mutually orthogonal. These two conditions can be written jointly as

$$\int dt\ \left[u_j(t)\right]^* u_{j'}(t) = \delta_{jj'} \tag{2}$$

where $\delta_{jj'}$ is the Kronecker delta and * denotes complex conjugation. In the case of the PPM format the orthogonality follows from the fact that for individual PPM symbols the pulse occupies distinct time bins.

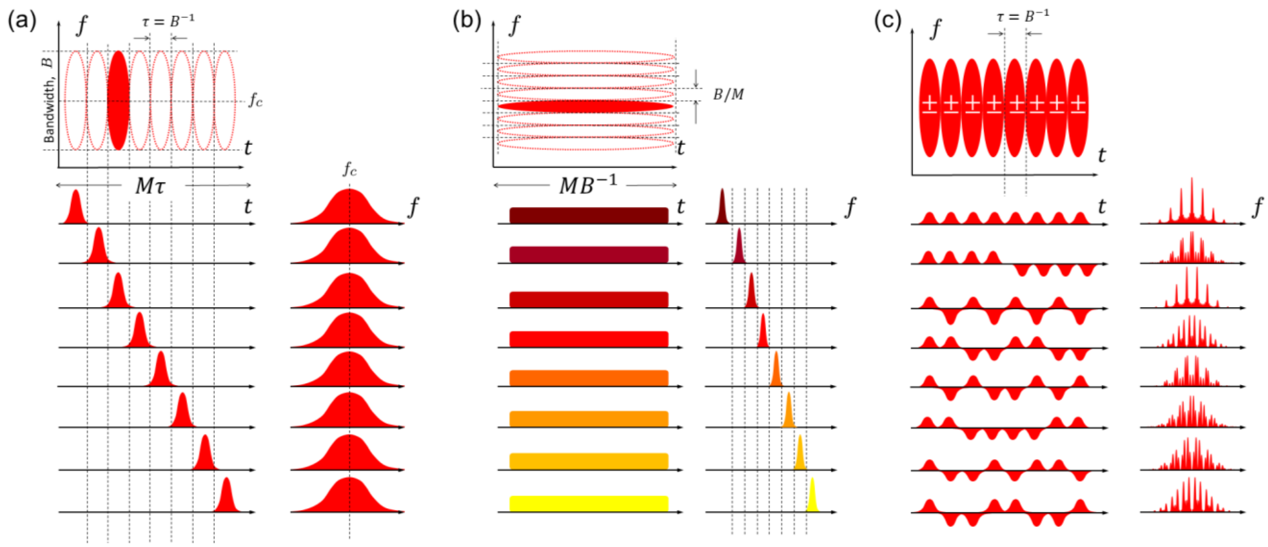

Figure 2. Time-bandwidth representations of (a) PPM, (b) FSK, and (c) BPSK Hadamard words modulation formats. Waveforms corresponding to individual symbols are shown as a function of time t along with their spectra parameterized with the frequency f.

An important advantage of the PPM link is the comparative simplicity of its physical implementation. To generate the PPM signal one needs a pulsed light source emitting pulses on-demand at well-defined instances of time. The standard solution is to use the master oscillator power amplifier (MOPA) architecture, where the output of a low-power cw laser is fed into an electro-optic amplitude modulator to generate individual pulses. The pulses are subsequently amplified using e.g. an erbium-doped fiber amplifier. The receiver employs a photon counting detector with sufficient temporal resolution to discriminate individual time bins in PPM frames. Mode distortions caused by e.g. atmospheric turbulence broaden the signal spot on the detector, which can be accommodated with a sufficiently large sensitive area.

2.2 Frequency shift keying

The well recognized problem with the PPM format is that with the increasing order M the optical energy of the entire temporal frame needs to be concentrated in a single time bin, which results in the peak to average power ratio scaling proportional to M. A remedy would be to resort to a different modulation format in which the instantaneous optical power is distributed more evenly in the temporal domain. In mathematical terms, this corresponds to identifying another set of M orthogonal mode functions $u_j(t)$ introduced in Eq. (2) that would occupy the time-bandwidth area $MB^{-1} \times B \sim M$, but would not be strongly peaked in the time variable. One possible solution satisfying the above requirements is the frequency shift keying (FSK) format, shown schematically in Fig. 2(b). In this approach, the time-bandwidth space is sliced along the temporal axis into M cells occupying different spectral regions. Optical signals corresponding to individual symbols have duration MB^{-1} and are shifted in the frequency domain by multiples of B/M.

In the context of free space optical communication, FSK modulation has been implemented by selecting individual spectral components from a multi-wavelength light source using a sequence of electrooptically controlled Mach-Zehnder interferometric filters [5]. The 100 GHz spacing between FSK symbols used in the demonstration ensured sufficiently high extinction ratio between individual wavelengths of the light source given the filter bandwidth in the range of tens of GHz. More densely packed FSK symbols could be generated using serrodyne frequency shifting [9,10] which has the capability to cover the spectral range of several GHz. A major challenge in utilizing this technique would be to suppress transfer of the optical power to spurious frequency components other than the desired one. On the receiver end, a prerequisite to achieve high information efficiency is direct detection with single-photon sensitivity. Discriminating FSK symbols at the single-photon level would require a high-resolution spectrometer followed by a photon counting array. The technology of such arrays currently undergoes rapid maturation [11]. Furthermore, contemporary astrophysical spectrographs reach resolving powers of 500,000 [12], which could in principle enable detection of FSK formats spaced at hundreds of MHz. However, despite these developments the actual construction of a photon counting receiver for a densely spaced FSK format would present a formidable challenge, as the high spectral selectivity for individual FSK symbols would have to be reconciled with satisfactory overall detection efficiency. One detrimental factor may be the impact of uncorrected wavefront distortions on the spectral resolution of the receiver.

2.3 BPSK words

Interestingly, one can also construct high-order modulation formats using mode functions which overlap both in time and frequency. A scalable example, shown in Fig. 2(c), is provided by words composed from the standard BPSK alphabet according to a recipe devised by Guha [6]. The construction is based on the so-called Hadamard matrices, which are square, symmetric and orthogonal matrices defined for dimensions $M = 2^m$ that are integer powers of 2, with entries $H_{jk} = \pm 1$. The orthogonality property implies that the scalar product between any two different rows is zero, $\sum_{k=1}^{M} H_{jk} H_{j'k} = 0$ for $j \neq j'$. The mode functions describing these Hadamard words (HW) are given explicitly by

$$u_j^{\mathrm{HW}}(t) = \frac{1}{\sqrt{M}} \sum_{k=1}^{M} H_{jk}\, u(t - k\tau) \tag{3}$$

where $u(t)$ is the waveform of a generic pulse residing in a single time bin. It is straightforward to verify that the modes $u_j^{\mathrm{HW}}(t)$ satisfy the orthogonality condition introduced in Eq. (2). Individual waveforms along with corresponding spectra are shown in Fig. 2(c).

The essential appeal of the above format is that the signal can be produced using a standard BPSK transmitter driven electronically by a suitable encoder which maps the input data onto a stream of Hadamard words. One can therefore envisage a single transmitter operating in the differential phase shift keying (DPSK) mode [13] and the photon-starved mode with an adjustable format order, all without any substantial change in the emitted optical power. This simplicity has to be balanced with a more complicated construction of the receiver. The operating principle of structured optical receivers proposed so far [6,7] is to concentrate the optical energy of an entire Hadamard word either in one output port of a linear optical circuit, or in a single time bin, whose position unambiguously identifies the chosen Hadamard word. However, this functionality relies respectively on optical routing of individual BPSK pulses into distinct input ports of a linear circuit, or fast optical polarization switching of segments of incoming Hadamard words. In either case, synchronization of the receiver with the incoming signal would be required.

3. PASSIVE STRUCTURED OPTICAL RECEIVER

The need for signal synchronization and active optical routing or polarization switching in structured optical receivers for Hadamard words discussed in Sec. 2.3 can be eliminated altogether using an alternative modulation scheme shown in Fig. 3. In this scenario, information is encoded in the temporal position of sequences comprising $M = 2^m$ light pulses each. All sequences are prepared in one well-defined phase-polarization pattern. The pattern uses two phases differing by $180°$ and two orthogonal polarizations, represented in Fig. 3(a) as horizontal and vertical orientations of pulses. In order to ensure rotational invariance between the transmitter and the receiver terminals, left- and right-circular polarizations should be used for transmission and converted into the rectilinear basis at the receiver entrance using a birefringent optical element.

In the present scheme, the purpose of the structured optical receiver is combine the optical power of the entire pattern into a single pulse synchronized with the arrival time of the sequence, as shown in Fig. 3(a). That way the incoming signal is converted into the standard PPM format that can be detected in a conventional manner using time-resolved photon counting. In order to avoid an overlap between consecutive sequences, guard-time intervals equal to the pattern duration need to be inserted between individual PPM frames. In the case of 50% duty cycle, when the pattern duration is equal to the PPM frame length, this results only in a minor decrease of the effective photon information efficiency as seen in Fig. 1.

The structured optical receiver processing phase-polarization patterns consists of a series of $m = \log_2 M$ modules depicted in Fig. 3(b). The kth module, $k = 1, \dots, m$, introduces a $2^{m-k}\tau$ delay between horizontal and vertical polarizations and subsequently rotates the polarization of the output beam by $45°$. The phases and the polarizations of individual pulses in the input sequence are chosen in such a way that the action of each module results in a two-fold contraction of the sequence leading to temporal concentration of the optical energy. The last module produces a single pulse in a time bin synchronized with the arrival time of the pattern.

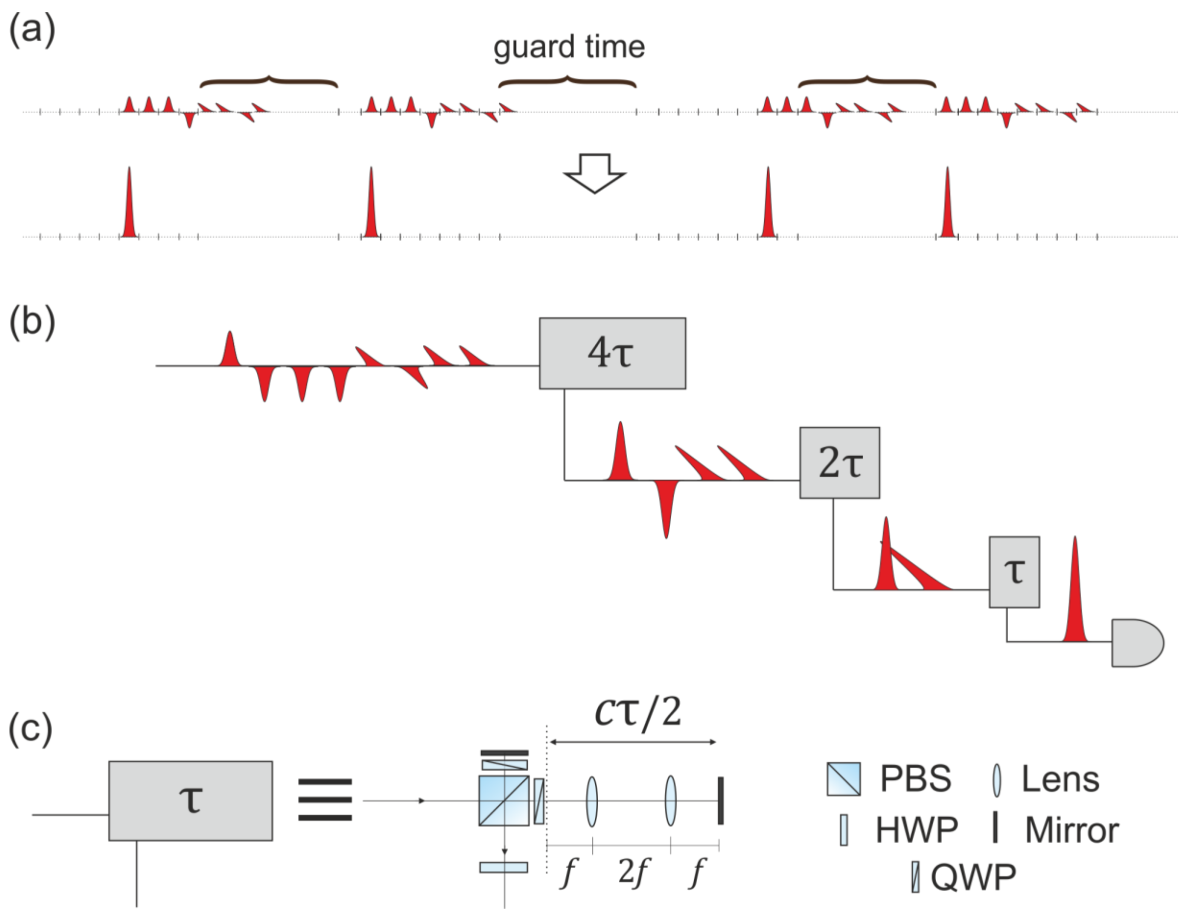

Figure 3. Passive structured optical receiver for photon-starved communication using phase-polarization patterns. (a) The receiver combines the optical power carried by the entire pattern into a single pulse synchronized with the arrival time of the pattern. Overlap between consecutive patterns is avoided by inserting guard times between PPM frames. (b) Block diagram of the receiver. The modules are labelled with the delay introduced between horizontal and vertical polarizations at the input. (c) Optical layout of one module. PBS, polarizing beam splitter; HWP, half-wave plate; QWP, quarter-wave plate.

An exemplary optical layout for a single module is shown in Fig. 3(c). The delay between the horizontal and the vertical polarizations is introduced in an unbalanced Michelson-type configuration with the central beam splitter replaced by a cube polarizer and quarter-wave plates inserted in front of the mirrors. Because for deep-space links it is of paramount importance to maximize the collected optical power, the receiver should tolerate wavefront distortions of the input signal occurring for large receive apertures. This problem is analogous to the one faced when designing a DPSK receiver robust against wavefront distortions [14] and it can be solved by placing imaging optics in the arms of an unbalanced Michelson interferometer [14,15]. An alternative solution is to insert into the longer arm a block of glass with a carefully chosen combination of its refractive index and thickness so that the optical path difference becomes independent in the leading order of the angle of incidence of the input beam [14,15]. Either of these arrangements can be used also to introduce a polarization delay in a Michelson-type configuration, provided that wavefront distortions at the receiver input are polarization-independent. Detailed characterization of a wavefront-distortion tolerant Michelson interferometer has been recently carried out with the aim to develop a time-bin qubit analyzer for space quantum key distribution [15]. The proof-of-principle demonstration yielded interference visibility reaching 90% for 800 nm input light, delivered at the angle of incidence up to $0.2°$ by a $105\ \mu$m core step-index multimode fiber. The optical path difference was in the range $0.57-2.0$ ns. Further refinements of the optical setup have been reported to deliver increased interference visibility up to 97% [15]. This allows for optimism regarding the feasibility of concatenating several interferometric modules according to the design depicted in Fig. 3(b). Let us note that coherent combination of optical power carried by orthogonal polarization components is currently investigated also in the context of multiaperture receivers with phased array antennae [16].

While the construction of the passive structured optical receiver described above is rather standard, generation of phase-polarization patterns goes somewhat beyond the most elementary modulation. The required pattern can be produced e.g. using a chain of two crossed phase modulators fed with a sequence of linearly polarized pulses, with each modulator imprinting the phase on a $+45°$ or $-45°$ polarization component and transmitting the unmodulated one. An alternative solution would be to combine at a polarizing beam splitter two independently phase-modulated laser beams. The latter approach has been used recently in a transmitter for a self-referencing coherent free-space optical communication link [17]. If the optical signal prepared either way were to undergo amplification in a MOPA architecture, it would be necessary to ensure that the optical gain is polarization-independent and uniform across the entire phase-polarization pattern.

4. CONCLUSIONS

High-order modulation formats for photon-starved communication have been discussed using the general concept of orthogonal optical modes. This unifying framework can inspire a more systematic search for efficient modulation formats. We have seen that the need to concentrate the optical energy in only one of the modes poses rather distinct technical requirements for the construction of communication terminals, specific to the chosen format. This provides a certain degree of flexibility in shifting the complexity of the actual implementation between the transmitter and the receiver setups, which may be particularly useful for asymmetric links.

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