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# Transmission of multi-Tera-bits/sec to quantum bits over Space intra- and inter-orbital links

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## ABSTRACT

Optical transmission over space links between satellites in intra-orbital constellations or inter-orbital constellations and optical ground stations are currently attracting a lot of attention, both for their ultra-high capacities reaching multi-tera-bits/sec and for their use in quantum key distribution for coding to transmitting over public channels. This paper outlines the followings: (i) Multi-dimensional considerations to reach Tera-bits/sec that include multiplexing of polarized modes, high-order modulation formats, high speed integrated photonic complex modulations, digital signal processing techniques etc.; (ii) Continuous variable quantum key distribution (CV-QKD) achieved through constant amplitude zero auto-correlation (CAZAC) sequence for quantum level signaling with phase-coded BB84-protocol, decorrelation , high order sampling rate and digital signal processing for quantum key recovery. (iii) Discussion of advantages and disadvantages of both coherent and self-coherent reception techniques for space transmission channels for multi-photons to sub-photon energy reception and transmission; (iv) Presentation of initial transmission results and Terabits/s optical transmission systems; (vi) Analytical considerations of CV-QKD space self-homodyne and homodyne reception system employing CAZAC and cross-correlation decoding as a photonic-pre-processor.

**Keywords:** Terabits/s transmission, Space optics; CV-QKD; Inter-satellite optical links.

## 1 INTRODUCTION

The ambition to connect as many of the earth's people as possible has recently drawn a lot of interest to space communications. In particular, the coverage of telecommunications to mobile devices and unmanned vehicles with remote space communications and networking is desired.

The transmission capacity over the space channels can be either inter-orbital satellites in the same constellation or inter-orbital constellation with distances ranging from 7000km in LEO orbits to 17,000km and 43,000km in MEO and GEO orbits. The data transport capacity can reach several Terabits/sec. (Tbps) and the number of hops between satellite nodes can increase to a point where links around the full orbit can be established. Hence the challenges in creating optical receptions with ultra-high capacity, ultra-low noise accumulation and high sensitivity require significant effort in the research and development of novel techniques for space communication systems and networks.

Space optical communication systems with Tbps have benefited from ultra-high capacity fiber communication transmission systems which reach multi-Tbps employing ITU-T grids of 50, 100GHz [1]and even lower down to 6,25GHz. Space optical communications can benefit from such development in terrestrial fiber optic long haul and ultra-high-capacity systems. Simultaneously to the long haul transmission fiber optic system, the fiber to the x (x= home/building/premises, to the building etc…, so FTTx) and cable TV via guided optical media, require high power optical amplifiers. The advances of optical amplification for the C-band have progressed with Er-Ytterbium doped fibers in which if pumped by 975nm laser, would offer output power reaching 35dBm to 43 dBm from the last amplifier stage of a multi-stage optical amplifiers [2].

These advanced developments have enabled design and considerations for ultra-high-capacity transmission over space channels to mitigate the high losses caused by the great separation between satellites and between optical ground stations (OGS) and satellites.

Accordingly, the objectives of this article are to firstly present the transmission of wavelength division multiplexing of a number of optical carriers that are modulated with complex signals (the in phase and quadrature components) as well as polarization multiplexing, so that for 100G the symbol rate may only be 25GSy./sec. Similarly, 200Gbps per wavelength carrier can be achieved with 50 GSy./sec.

Besides high data rates, transmission of data under extremely confidential or secure conditions over space channels are currently attracting significant attention, in particular with optical laser technology. Over the years discrete variable quantum key distribution (DV-QKD) is investigated for which single photon detectors and single photon sources are required along with practical issues. On the other hand, continuous variable QKD (CV-QKD) uses standard telecommunication equipment and employs a sequence of digital key bits whose average power reaches the noise level of the system with a bit error rate (BER) of unity or higher together with the security protocols between Alica and Bob such that they agree to the transmission and modulation/demodulation schemes of quantum key bits over the optical channels.

The paper is organized as follows: (i) an introduction to the space channels and transmission optics at the transmitting and reception ends so as to enable the transmission of ultra-high density Tbps capacity system an emulated free space optical medium; (ii) Generation and detection of ultra-high bit rate channels of different optical frequencies and multiplexing techniques to generate multi-Tbps; (iii) Current technological developments of optical transceivers and their potential to carry multi-Tbps channels over intra-orbital and inter-orbital constellations of satellites that incorporate optical add/drop multiplexers. (iv) A sample of power budget for such all-optical routing and transmission for free space communications (v) Over such orbital transmission channels the uses of ultra-low optical signals are designed for quantum key distribution (QKD) is considered and proven that continuous variable QKD (CV-QKD) can be the selected security communications of secret keys for further secure data coding and transmission over free space, furthermore DWDM can also be employed with novel optical channel between Alica and Bob can be established for high order of security.

## 2 INTER-ORBITAL AND INTRA-ORBITAL SPACE CHANNELS

### 2.1 System and network overview

The HYDRON program of the European Space Agency [3] has pushed the limits of transmission capacity in space communications. Such ultra-high-capacity transmission systems can be depicted as in Figure **1**. The optical ground station can consist of a wavelength multiplexer which multiplexed all optical channels whose lightwave carriers are $\lambda 1, \ldots, \lambda_N$. Their spacing can fall into the ITU-T grids as for terrestrial fiber optic systems of 50, 100 or 200GHz and even narrower – but not for high data rate but service channels, to 6,25GHz [4]. Adopting such ITU-T grids has the benefit of utilizing optical system technology advancements, such as wavelength selective switches, reconfigurable add/drop multiplexers, optical switches, etc., which are well-developed and mature in such fiber optic networks.

The optical channel can be from an OGS to satellites in cascade separated with space channels. The wavelength-carrier channel can then be further transmitted to other satellites of the constellations or dropped to other satellites of another orbital constellation, such as LEO, MEO or GEO. To account for the space channel losses, optical amplifiers, the booster OPA, and highly sensitive optical preamplifiers are needed.

The space optical communication systems and networks considered here are all-optical transmitting and routing that is possible under present technological developed subsystems, that is electronic domains under O/E optical to electrical conversion and E/O vice versa are all placed in ground stations. Different optical wavelength channels can be added or dropped into the optical transmission paths as desired.

### 2.2 Space channel

Here we summarize the main characteristics of the free space channel including the ideal vacuum equivalent transmission for intersatellite communication link (ISCL) and Ground to satellite link of partial atmospheric media.

#### 2.2.1 Space loss

Transmission path losses $G_L$ over a distance $L$ of a specific optical carrier can be estimated as

$$G_L = \left(\lambda/_{4\pi L}\right)^2 \tag{1}$$

The TX Antenna gain (on-axis) with truncation can be written as[5]

$$G_{TX} = \frac{2}{\alpha^2}\left[e^{\alpha^2}-1\right]^2\left(\pi\, {}^{D}\!/_{\lambda}\right)^2 \tag{2}$$

where α=D/ω or ratio between aperture diameter and the optical operating frequency The antenna TX and reception are denoted as optical heads (OH) in which a beam pointing and its control for stability of tracking and alignment to other optical OH. The gain given in Eq.(3) indicated a strong dependence on its aperture diameter and the diffraction limit [6] which follows a Bessel function distribution,

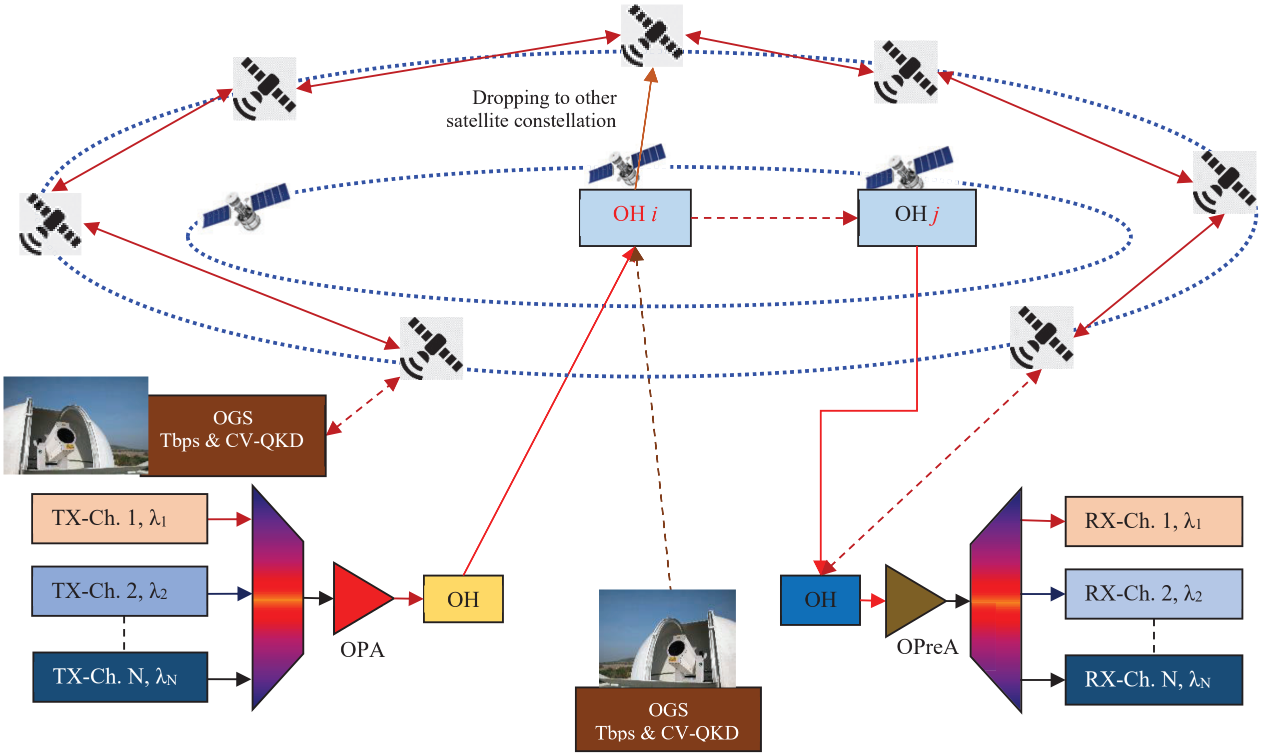

Figure 1: Space DWDM Optical communication channels and inter- intra-orbital networking. Legends: OGS= optical Ground Station. OH = optical head with pointing control. λ = wavelength.

both from centrifugal towards and backward the outer region of the aperture. A null degradation of such diffraction occurs at [πD/λ sin θ] = 3.83 with optical aperture diameter *D* and the angular width θ = 1.22 λ/D. Thus, there is an optimal optical aperture for a receiving and transmitting antenna. Typical diameters are 60, 80, 120 and 162,5mm etc. depending on specific applications. In addition to the commonly known satellite orbits there are presently high demand for optical communications of high capacity between drones and space or ground terminals.

Similarly, the RX antenna of the reception end is given by

$$G_{RX} = \left(\pi\, {}^{D}\!/_{\lambda}\right)^2 \tag{3}$$

Then the combined gain of Tx and Rx of FSOL (Free space optical link) can be approximated as

$$G_{FSOL} = \frac{2}{\alpha^2}\left[e^{\alpha^2}-1\right]^2\left(\pi\, {}^{D}\!/_{\lambda}\right)^2\left({}^{\lambda}\!/_{4\pi L}\right)^2\left(\pi\, {}^{D}\!/_{\lambda}\right)^2 \sim \frac{\boldsymbol{D^4}}{\boldsymbol{\lambda^2\, L^2}} \tag{4}$$

That is a quad exponential proportionality with the aperture diameter and inversely proportional to quadratic factor of wavelength and link distance *L*. The link distance is dependent on link scenarios of LEO-LEO, MEO-MEO, LEO-MEO, LEO-GEO, MEO-GEO and possibly from these orbital satellites to and from drones.

### 2.2.2 Optical amplifications and optical antennae gains

To compensate for the high-level optical propagation losses over a long space channel, optical telescopes are used at both the TX and RX sub-systems. Further optical booster amplifiers and low noise optical pre-amplifiers are used at the transmitting and receiving ends respectively to compensate for such high losses. The net losses of the propagation and antenna gains over various space channels links can range from -73dB to -80dB. Thus, one must boost the optical power to about 30dBm to 40dBm at the TX end and reception power level should be sufficiently low with low noise amplifiers place at front of the photoreceiver, commonly in order of -60dBm to -10dBm with saturation level output at -10 to +10dBm.

### 2.2.3 Pointing and tracking

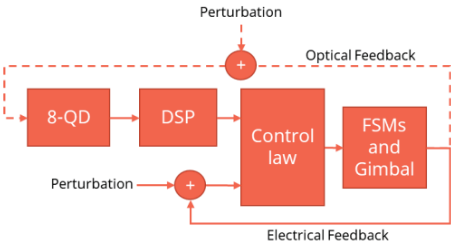

Figure 2: Simplified block diagram of control feedback system for tracking and pointing system. 8-QD is a quad detector consisting of four photodetectors arranged in two differential pairs in crossing with each other to give signals which can indicate alignment left or right or up or down. DSP is a digital signal processor.

Figure **2** depicts a simplified block diagram of a digital control system for tracking stabilization of the pointing system of the modulated laser beam. The main objectives of such a system are to reduce the residual error with less micro vibrations from optical platform, improved performance of control loop, lower noise from free space motion and other actuators, and improved tracking detector performance. The frequency responses and noise spectral density of the pointing angle is shown in Figure **3** where a 3dB passband can be found. Thence by integrating over the passband we can find out the total signal penalty as follows: Pointing noise spectral density (mRad$^2$/Hz) =5e-3 at 80Hz, thence integration over the spectral area (dotted box in Figure **3** to give ~ 0.22µRad. Thus, the wavefront error (WFE) can be estimated as 0.22µRad/7µRad or (3.1%) ~ 0.5dB penalty. This WFE can be directly related to error vector magnitude in the signal processing of complex signal. This dynamic penalty can be included in the operating margin of a digital coherent communication system [7]. This dynamic penalty can be offset by setting operating safety margin allowance of the system of about 2dB. The overall system dynamic and allowable operating margin can be set at -6 to -10dB within the receiver sensitivity of a transceiver operating at 100G with modulation format QPSK25 (Quadrature phase shift keying) such as 25 GBaud PDM-QPSK of 15dB from -26dBm to -42dBm and less for QPSK50 with bit rate of 200G.

The frequency passband of the pointing occurs at around 28 to 180Hz. This creates jittering of the high data rate sequence, thus error in sampling. A one-tap filtering at the DSP in the receiver can mitigate this effect. The DSP processing developed for coherent reception has enhanced and permits true coherent optical communications as this can mitigate the frequency offset between the lightwave channel carrier and that of the LO laser, distortion due to dispersion, jittering and skew effects of two polarized channels etc.[1] The optic heads and the beam pointing can generate errors on the QAM constellation that in turn degrade the bit error rate, and hence a penalty on the OSNR (optical signal-to-noise ratio) as shown in Figure **4**. Indeed WFE can be directly related to the error vector magnitude (EVM) which is commonly used in determination of BER of complex signals using either realtime sampling or just sampling oscilloscope [8].

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[1] Mynaric Lasercomm, private coimmunications.

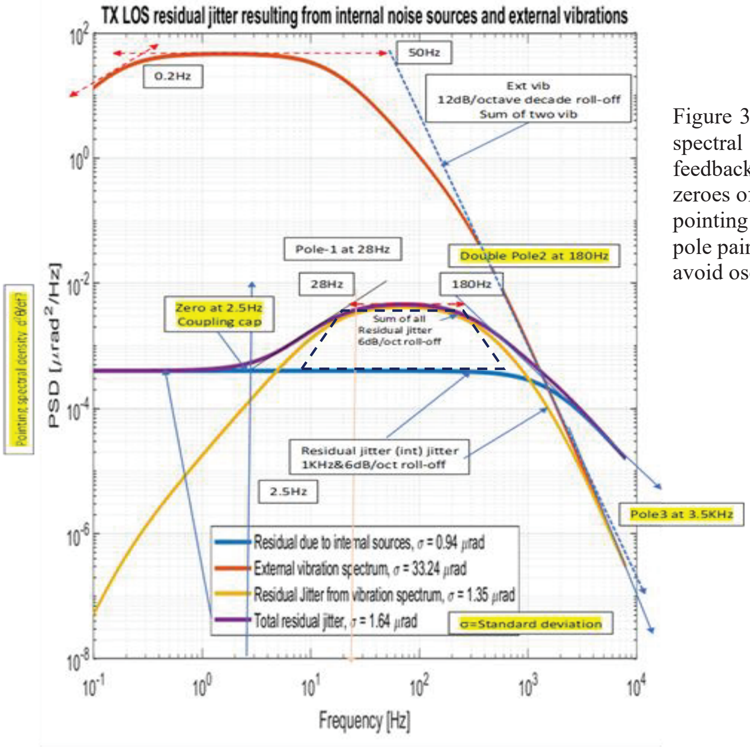


Figure 3: A typical pointing angle noise spectral density (PSD) of the controlled feedback system of Figure 2. Poles and zeroes of the feedback control system for pointing stability are identified. Complex pole pair are nulled by complex zeroes to avoid oscillation.

### 2.2.4 Channel transmittance and spectral region

The spectral window of the transmittance of laser beam over the space channel is shown in Figure **5**. The transparent windows are well corresponding to the C- and L-band of the Ge2O:silica fiber employed in terrestrial optical network. The transparent window is 1525nm to 1575nm with the attenuation factor of about 0.01dB/km for ISCL and 0,3dB/km inside the atmospheric region as shown in Figure **5**. Thence, a total attenuation can be estimated over the satellite link between satellites of different orbits and/or to drones or ground stations.

It is noted that the spectral window around 1064 nm, e.g., 1030nm to 1070nm, can also be used with some additional losses but isolated from the 1550nm region to avoid any impairments due to nonlinear effects. The window is large enough to accommodate all channels whose wavelength are in both C- and L-bands of fiber optic communications. It is therefore an advantage to take the advancement of optical sub-systems which have been developed over the last decade on Tbps capacity [9].

The optic systems for launching and receiving can add distortion, i.e., the wave front error (WFE). This WFE is equivalent to the EVM (Error vector magnitude) in digital modulation as shown in Figure **4**.

## 3 TBPS SPACE OPTICAL COMMUNICATION SYSTEMS (SOCS)

### 3.1 Coherent modulation format

Figure 6 shows a schematic diagram of a multi-Tbps laser coherent communications system in which a number of optical transceivers operating at 100G and 200G whose modulation formats can be QPSK or Mary-QAM (Quadrature amplitude modulation) whose symbol rate can be either 25GSy./sec or 50GSybol/sec plus polarization diversity of dimension 2, resulting in a composite bit rate of 2 polarization x 2 bits/symbol x 25 GSy/sec to give 100Gbps. Similarly, for 50GSy/sec. If M=16 or 4 bits/symbols then we can also obtain 200Gbps with 25GSy/sec. The constellation of such modulation formats can be illustrated in Figure **7**.

The constellation of 16QAM formats can be illustrated in Figure **7**. The upper row constellations are transmitted from TX end with probability shaping, i.e., randomly distribution such that the Euclidean distance between consecutive points is at largest. The lower rows constellations represent those obtained at the receiving ends under possible effects of propagation in space links, for example the Doppler effects and/or pointing WFE or scintillation over the atmospheric conditions. The rotation of the constellation indicates the offset in frequency of the local oscillator (LO) and the carrier frequency. The blurry constellation points indicate that the wave front errors due to optical systems in launching optical beams in space.

It is noted that statistical shaping can be superimposed to QAM modulation so that the Euclidean distance can be as far as possible so that the PDF (Probability Density Function) can be minimized, hence improving the bit error rate (BER), for the case of 3,19 bits/symbol.

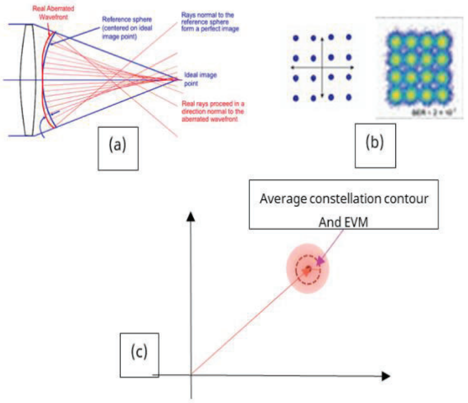


Figure 4: Illustration of EVM (error vector magnitude and WFE similarity for inter-relationship to signal penalty. (a) wave front error (WFE) (b) digital complexed signal in ideal and distorted constellations (c) direct relation between WFE and EVM.

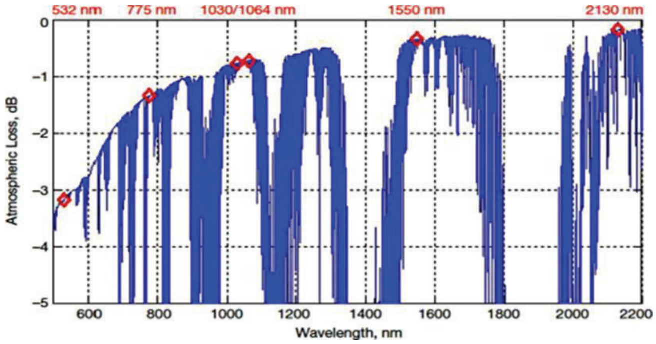


Figure 5: Free space spectral windows for laser communication.

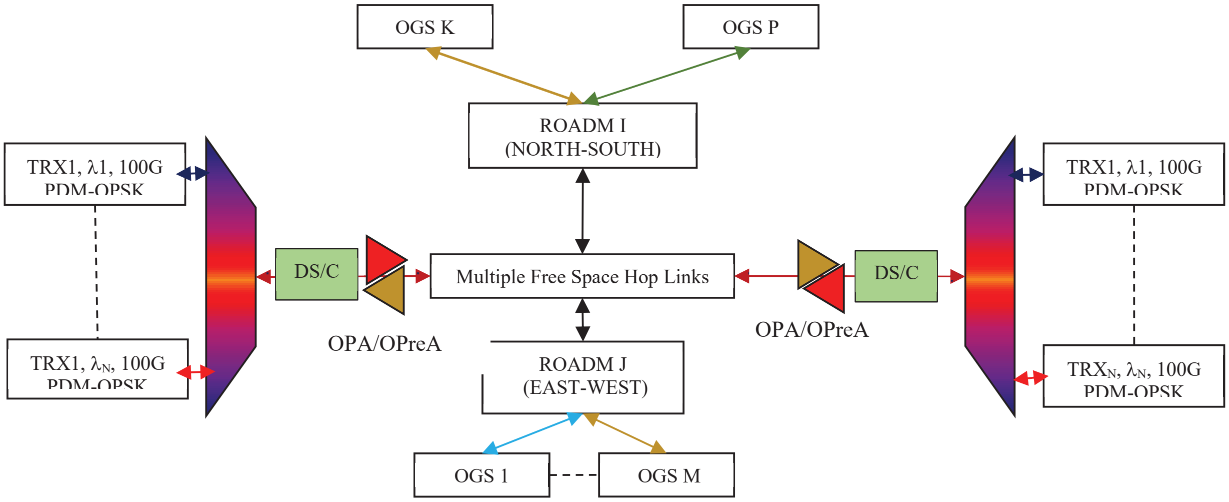


**Figure 6**: Space optical communication systems (SOCS) with reconfigurable add/drop multiplexer for inserting and dropping of optical channels in space networks. The dotted boxes indicate a space hop-to-hop link N.E.W.S. (North-East-West- South) are the optical demultiplexers for directing the add and dropped channels to other satellites or OGS. ROADM = reconfigurable optical add/drop multiplexer. TRX = Optical transceiver. OPA = optical Power Amplifier; OPreA = Optical Pre-Amplifier. DS/C dichroic splitter/combiners

## 3.2 Coherent transceiver structures

Figure **8** shows the schematic structure of an optical transceiver that can transport 100Gbps or 200Gbps channels over space medium. The transmitter section (the upper part) consists of an optical modulator sub-section which is driven by the output analog form signals derived from the DAC (Digital to analog converter) of an integrated digital signal processor which produces 4 lanes each with 25GSy/sec so that both polarized lanes (2 per polarization of in-phase and quadrature phase lanes). The processing algorithms are embedded in the DSP as shown in Figure 10. Indeed, the offset frequency between the channel carrier and that of the LO laser can be compensated by the carrier phase equalizer so that homodyne reception can be achieved and hence an improvement in receiver sensitivity. Although there may be some small difference in the frequency offset, the reception can be termed as intradyne reception.

The coherent receiver section of Figure **8** consists of (a) an optical pre-processor which is a 90° hybrid coupler which accepts both lightwaves from the local oscillator laser and transmitted signal with two polarizations. Both orthogonally polarized channels are split and superimposed on the pair of balanced detectors to obtain a 3dB improvement as compared to that of a single detector. The photocurrents are then amplified by a transimpedance amplifier of bandwidth of about 18GHz for 25GSy./sec and 28GHz for 50GSy./sec rates. A shared DSP or two separate digital processors can be used to generate digital signal modulation formats and to process received signals and mitigate the impairments of the distorted signals after space transmission. Figure **9** shows a theoretical estimation of the bit error rate (BER) versus the signal to noise ration per bit for QPSK and 16QAM modulated signals. It is also noted here that for the same modulation format QPSK the OSNR for 50GSy./Sec is about 3-4dB worse than that for QPSK at 25GSy./sec due to the fact that the bandwidth required for 50GSy./Sec is about twice of that required for QPSK, thus the noise power is double, thus 3dB worst for the doubling symbol rate.

## 3.3 Processing and equalization algorithms

These distorted constellations can be compensated to its original via the algorithms embedded in the DSP as outlined in Figure 10. The demultiplexed channel at output of a WSS used as wavelength demultiplexer, is polarization control to maximize its matching with the orientation of the polarization beam splitter and mixing with those components of the local oscillator laser for coherent reception. The beating signals as products of that of the LO and channel lightwaves in the balanced photodetectors (BPD) are fed to ADC and then to the DSP in which they are transformed to spectral domain by an FFT process, thence by a matched filtering to reshaping the pulse sequence for minimum error in sampling. This is followed by a dispersion compensation in the case that phase distortion occurs due to a channel transmitted through atmospheric channel. The IFFT transform back to time domain and an MIMO (multiple input multiple output) processing is used to re-balance the two polarized channels. Further equalization processes can be used such as MLSE and transversal equalization or filtering if necessary. Finally, decision on the logic states of the sampled pulse is given.

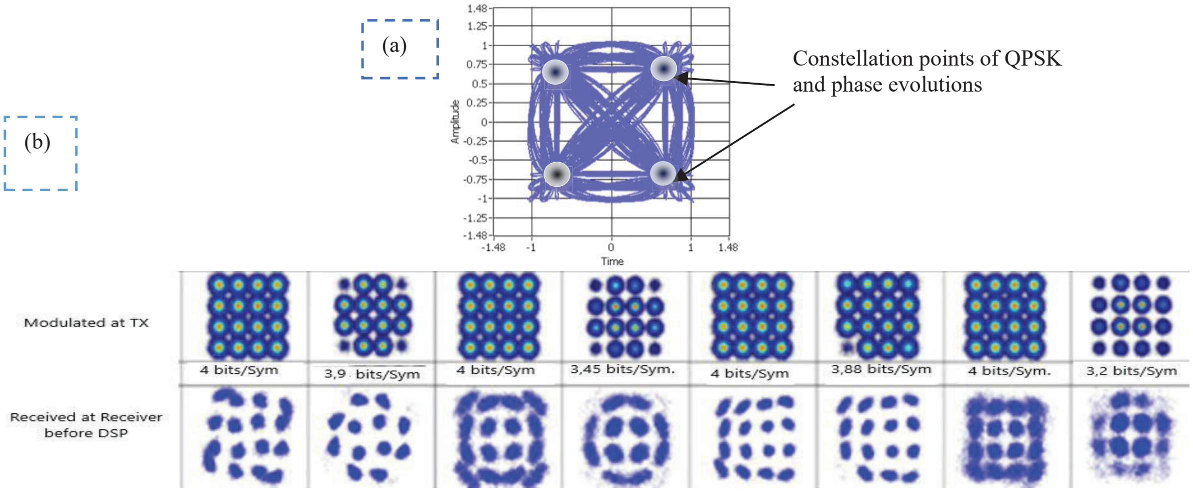


Figure 7: Modulation constellation (upper row) and received constellations (lower row) with corresponding number of bits per symbol indicated in the middle row. 16QAM constellation is illustrated in first column. (a) QPSK constellation and evolution of phase (b) constellation of 16-QAM under different statistical shaping to minimize the impairment of transmission space channel fluctuations, with effective number of bits/symbols.

## 3.4 Doppler shift and LOFO

In space laser communication system links, the rotation velocity can be different, e.g. from LEO to GEO, the Doppler shift can be from -7GHz to +7GHz twice a day. This Doppler shift can degrade the coherent reception due to the limited bandwidth of the receiver subsystem. This effect LOFO (LO frequency offset) can be mitigated by a Viterbi to Viterbi phase carrier compensation. The algorithms sequence is shown in Figure 10. The QPSK constellation of a commercial 100Gbps is shown in Figure 10(a), (b) and (c) for a LOFO of 2, 4.5 and 6GHz, respectively. At LOFO of 6GHz the RX can no longer mitigate the LOFO as observed by the constellation in Figure 11 (c).

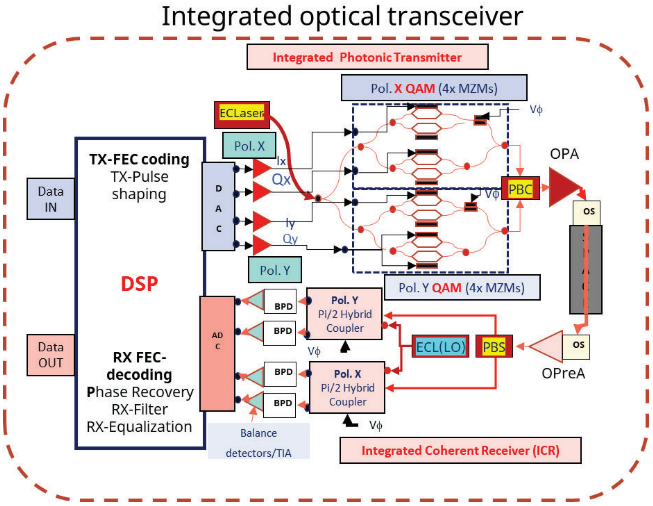


Figure 8 Schematic of a coherent Transceiver module. Upper section: 2x IQ modulation sections for two orthogonal polarizations and polarization combiner in integrated optic forms and lower section 2x optical coherent reception subsections with incorporated polarization splitter. Legends: PBC = polarization combiner, X, Y = polarization directions; ADC /DAC = analog to digital and digital to analog converters. OS = optical head system, FEC = forward error coder; TX = transmitter; RX = receiver. BPD = balanced photodetectors; ECL = external cavity laser.

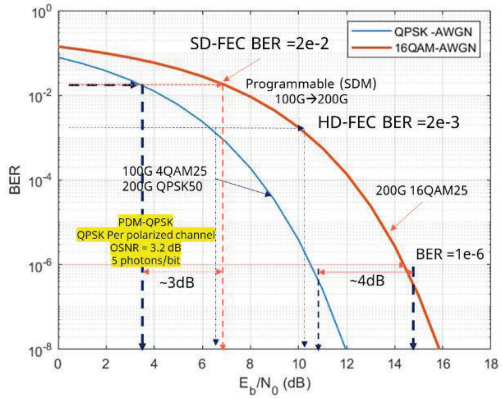


Figure 9: BER versus energy/Noise per bit of QPSK and 16QAM under FEC of soft decision and hard-decision as well as designed rate of 1e-6.

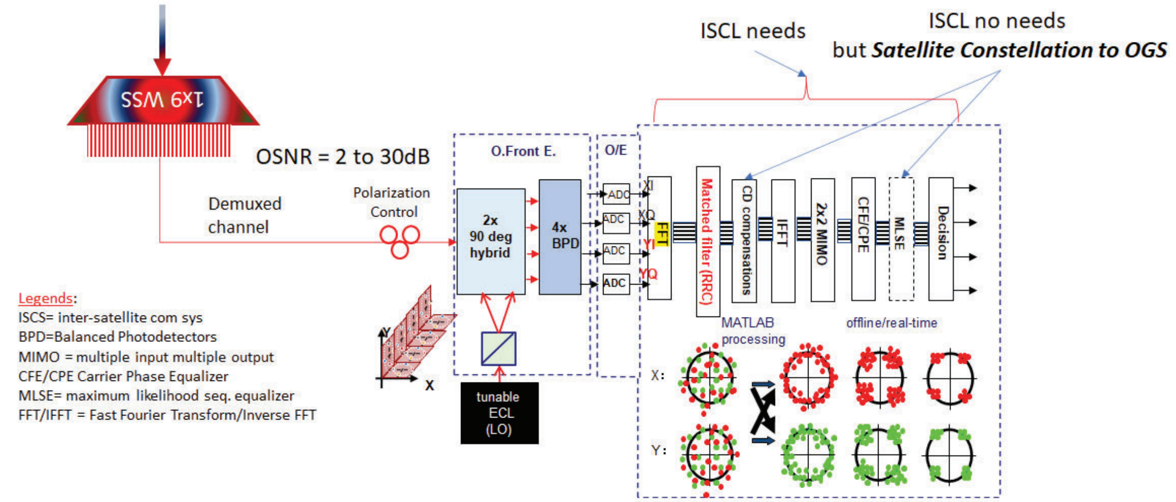


**Figure 10**: Embedded processing algorithms in the digital processor of a DSP-based ORx. Legends: WSS = wavelength selective switch equivalent to an optical wavelength demultiplexer, OSNR = optical signal to noise ratio. O-Front-E: = optical front end to split polarized channels and the in-phase and quadrature components; LO = local oscillator laser; OSNR = optical signal to noise ratio; MLSE = maximum likelihood sequence equalizer; CPE = carrier phase equalizer.

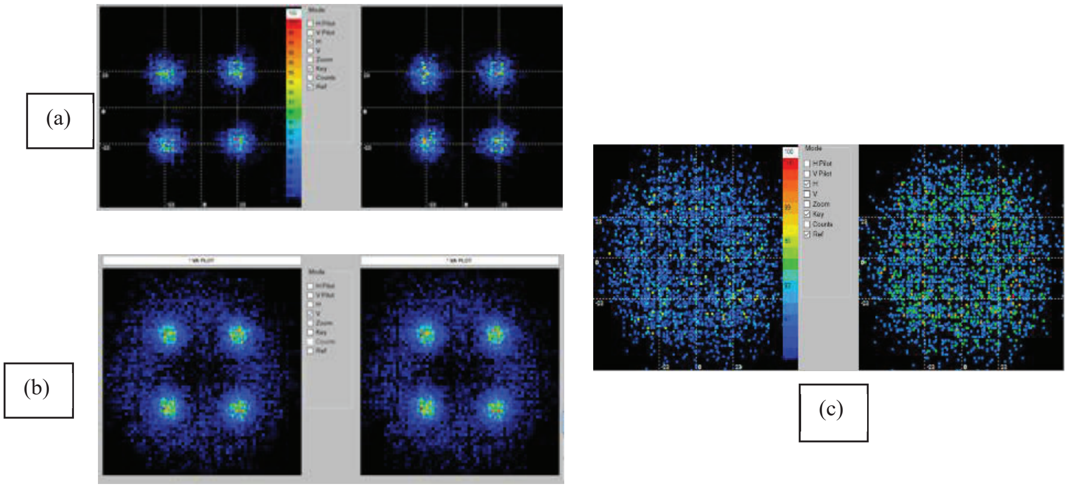


**Figure 11**: PDM-QPSK Constellations at (a) LOFO= 2GHz and (b) 4,5GHz and (c) 6GHz; at BER =2.42e-2, RX signal power = -25.8dBm; OSNR=32.3dB. Note on phase rotation of Constellations of (b), i.e., phase mismatched by several 2π (cycles). PDM = polarization division multiplexing; QPSK = quadrature phase shift keying; LOFO = local oscillator frequency offset.

## 3.5 Channel spacing and packing capacity for multi-Tbps transmission over free space

### 3.5.1 Pulse shaping and packing and sensitivity

In free space optic systems, for bidirectional transmission and reception, a dichroic Beam TX/RX separator can be designed with different spectral windows for either direction of channels for TX & RX to allow (a) dual polarization system for each single carrier/wavelength enables use of coherent COTS/terrestrial modules. However, it requires a minimum "dead band" between TX/RX of >10 nm (on axis) and 20 nm (+/- 2° internal range). Note that the transmittance and reflectance – OLPF and OBPF (optical low/Band pass filter) with a gap for bidirectional TX and RX possibly by multi-layer thin-film filters. The best performance of the optical amplifiers for space applications, developed under current technology, can operate in the window of 1545nm to 1565nm. This spectral window allows >12x100G or >8x200G for either range (see Figure **12**). The channel numbering can set under the ITU-T grid of 100GHz spacing, but not necessarily compulsorily, and specified channel frequency in GHz and channel wavelength in nm. For example channels No. 14 to 22 and channels 34 to 42 are for transporting/transmitting of 100G or 200G data channels. Services channels at 10G bps are allocated in channels 13 and 43 using intensity modulation and direct detection. Narrower spacing such as 50GHz spacing can be used. No restriction in space laser communications systems. Indeed, unequal spacing should be used to avoid nonlinear crosstalk in fiber at output of booster high power amplifiers

Under pulse shaping 50GHz spacing can be used for 200G (16QAM) so 2x600 GHz to offer 24 channels of 200G to obtain 4,8Tbps or 24x400G (16QAM50[10]) for 9.6Tbps. Furthermore, such a "red/green" system provides improved optical isolation between RX/TX path in excess of 100dB even without pilot / tracking tone electrical signal filtering. This tremendously reduces also false light / straylight constraints for optics is capable of handling also (very) high-power levels (with high TRL) and will not place constraint on link scenarios (East/West in green/red) and with two optical ground stations (red & green) at each location (also for throughput).

The obtained receiver sensitivity is -42dBm to -26dBm at 100Gbps QPSK25 or 5photons/bit at the minimum level. For 200G QPSK50 about -35dBm to -21dBm with a LOFO to 5GHz with minimum penalty of the receiver sensitivity.

### 3.5.2 Nonlinearity and channel spacing

Nonlinearity over short length of Single mode fiber (SMF) connecting the output of the booster amplifier and the optical head telescope can be serious due to SBS (Stimulated Brillouin scattering), SRS (Stimulated Raman scattering) under Kerr effects and cross phase modulation, thence intermodulation, due to the nonlinear coefficients $n_2$ of the GeO2 doped silica. These effects are serious of a few mW average power over a long length of the SMF (1km to 22km), but for 1000mW level the nonlinear distortion and cross talks can exist to a length of a few meters and even shorter. To avoid such nonlinearity the fiber length should be much shorter than a meter or redesign of the multi-stage optical amplifiers.

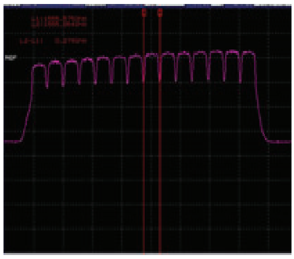
# 4 QUBITS OVER SPACE CHANNELS

## 4.1 Remarks

This section outlines the major principles of CV-QKD over space channels, especially the long distance of space channels and its high propagation loss to the transmission of quantum state bits of over 70dB as we have seen in the previous sections on transmission of Tbps. Such attenuation of quantum state bits would give an average power level of more than -150dBm for 10Mbps key rate. At this level no sensitive optical pre-amplified coherent receiver can be designed for detection. A generic CV-QKD schematic and coherent systems are shown in Figure **13** and Figure 14, respectively in which coherent reception and modulation techniques are used. IT is noted that both Tbps transmission and CV-QKD systems are very similar, except the signal levels one is ultra-high rate of several photon energy per bit and one with low key rate and low noise low level at quantum energy.

## 4.2 CV-QKD system

In Figure 14 a schematic diagram of a self-coherent CV-QKD setup is depicted. A MZDI is used to interleave the qubits and high-power bits of the sequence, thence self-coherent reception can be conducted to obtain both the pilot pulse and the qubits. The high-power bit sequence is optically phase modulated in a scheme which is also known by Alica and Bob so that a demodulation scheme can be established to start the transmission of qubits, e.g., a $\pi/2$ phase shift by Alica would be detected via the optical modulator of Bob by modulating the optical phase modulator by either $\pi/2$ or $-\pi/2$ to generate a constructive or destructive interference output in order to form an agreement or disagreement protocol procedure such as the BB84 or BB92 [11,12].



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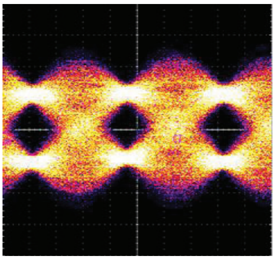
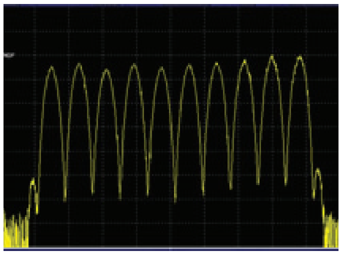
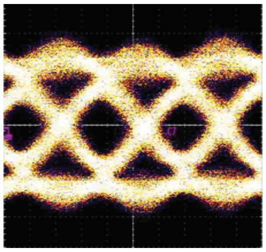


(a2)



(b1)



(b2)

Figure 12: Packing of 100G channels with 50GHz spacing between channels to obtain >1.0Tbps (a1) spectrum of 12 channels under pulse shaping with root raise cosine (RRC) and (b1) 10 channel spectrum when no pulse shaping is used. (a2) eye diagram of a channel under RRC pulse shaping and (b2) eye diagram of channel sequence under no pulse shaping.

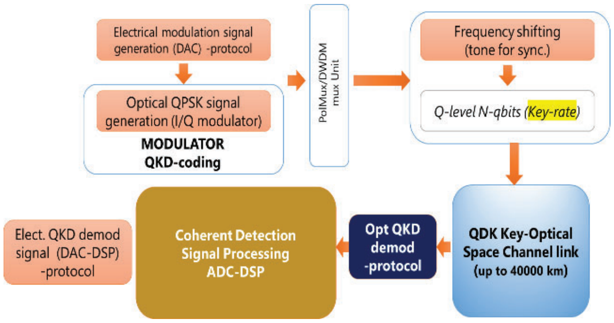


Figure 13: Coherent optical transmission for CV-QKD over a space channel. Legends: QKD = Quantum key distribution; ADC-DSP = analog to Digital converter – digital signal processor- I/Q = inphase / quadrature; Demod = demodulation.

The high-power pulse sequence permits the total average power to reach appropriate level for booster amplification to transmit over the free space channel. At the receiving reception end an optical pre-amplifier is used in association with the coherent reception to obtain signals reaching the level sufficient for ADC and digital processing. The noises and signal level of the qubits are almost in par. This means a possible BER = 1 or 1,1 or similarly the qubits level is just about 10% above noise level. We can use QPSK modulation scheme to modulate qubits. Thence the QPSK constellation can be overlapped such that it is not possible to separate the constellation points so that the probability of Eve dropping or attacking is high enough so that it is impossible to tap the secure key bits. The sampling rate can be a factor of the Nyquist rate to recover the qubits error rate (QBER). The high intensity pulse sequence can be in one polarization and the qubits can occupy the other polarization mode. Either self-coherent or intradyne coherent reception can be used. For intradyne coherent case a coupled and mixed in the PD pair in balance, the followed by a low noise high impedance amplifier and ADC plus DSP system.

The modulation is arranged in such a way that the BER of the QAM constellation to reach unity or 1.1 in linear scale, that is a large overlapping between the constellation points and randomly distributed of sampling points so that Eve cannot do dropping unless the phase demodulation can be agreed with Alica's scheme. Bob, once demodulating the conventional modulated scheme of Alica then can sample the qubit sequence with the alignment of the high intensity transmitted pulse and conduct the DSP processing to recover the qubits with a BER of 2e-3 which reaches the forward error coding limit with 20% overhead. This key bit sequence is then used via a random number generator for coding the data sequence for secure transmission..

In the transmission of CV-QKD over space channel which is much longer than for the fiber optic terrestrial case, about 7,000kms to 45,000kms depending on satellite orbits, the channels can be changing in particular the turbulence and variation of the refractive indices of air layer scintillation. It is important that the transmission medium characteristics be is known at the receiving end. CAZAC sequence is a constant amplitude zero autocorrelation sequence which has a constant amplitudes of all pulses and a zero autocorrelated product. That is similar to a phase coded bits of the sequence whose phase can be chirped up or down to product a cross-correlation product of significant value. Thus one can identify these phase evolution of the CAZAC to identify the free space transmission medium. This allows the receiver to conduct any required equalization of the high amplitude pilot pulses and that of the qubits.

## 5 CONCLUDING REMARKS

With the maturity of high-speed optical transceivers developed for terrestrial networks, multi-Tbps transmission capacity as well as for the quantum key distribution techniques, can employ and adapt to space laser communication systems and networks in which multi-hop intersatellite links and inserting or dropping of channels from and to optical ground stations, can be structured. The major obstacles are the ultra-high attenuation and beam pointing in space links that can be compensated with care by using optical power amplifiers and low noise sensitive input level optical pre-amplifiers. Furthermore, such amplifications cannot be avoided in the transmission of quantum key bits. The coherent reception and digital signal processing techniques with advanced modulation formats can offer for both multi-terabits and QKD technologies tools for practical implementations for inter- and intra-orbital communications with all optical routing and add/drop to OGS as desired.

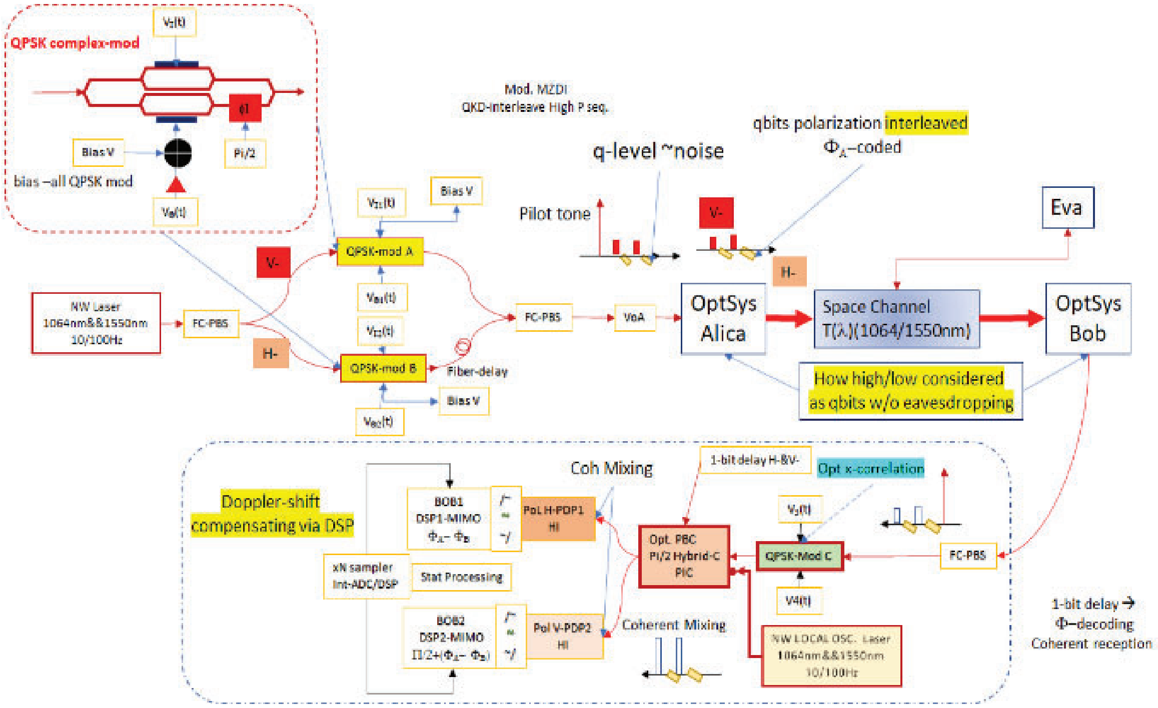


Figure 14 Schematic diagram of a self-coherent CV-QKD SCOCS. MZM = Mach Zehnder modulator; MZDI = Mach Zehnder delay interferometer. PDP = Photodetector pair or balanced PD. Bob = secure transmitter; Alice: secure receiver. Optical booster amplifiers and Optical Pre-amplifiers not shown. Inserts are dual drive MZM and single-drive MZM with biasing features. LO= Local oscillator

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