# HAP-LEO Link Communication Systems Based on Optical Technology

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**Abstract.** One among the most recent configurations in satellite architectures, is enhanced with respect to the traditional ones, by the presence of HAPs (High Altitude Platforms). Those balloons are located at stratospheric altitudes, and make possible to separate the link from LEO to ground into two segments: the former crosses the highest levels of atmosphere and can be developed by optical technology, the latter is more sensitive to scattering and absorption, since it crosses lower atmosphere, so it must be carried out in RF domain where more consolidated technology can be used. The insertion of HAPs in the global architecture enhances the system performance in terms of LEO-Ground link capacity, connectivity and flexibility; in addition the wide band-width offered by optics makes more and more effective those improvements. Even better results can be obtained if a proper coding system is designed.

## 1 Scenario Description

For a HAP-LEO link an optical communication system based on 1550 nm technology is proposed. This wavelength ensures a wide capacity and the consolidated technology used in terrestrial links. In addition EDFA (Erbium Doped Amplifiers) optical amplifiers work in that band, offering some important improvements in terms of system performance. The optical communication subsystem should be designed starting from the knowledge of the operative scenario. In the case we consider, data stream is mainly transmitted from LEO to HAP: LEO can collect information during its orbit, for example from high resolution Earth Observation imageries. Instead of transferring data to a Ground Station with a RF link in the visibility window, it is possible to increase the downloading effectiveness by locating a HAP just above the destination Ground Station [1,3,4]. As a matter of fact, the HAP location at 20 km allows to avoid the most limitative atmosphere layers making possible to carry out an optical link from LEO to HAP (Fig. 1). With a 10 Gbit/s link, even in a very short time window for download it is possible to transfer up to some Terabit per day. HAP can transmit stored data to Ground Station until the next time LEO becomes visible to HAP and it starts its downloading again. Between two consecutive accesses there is a time delay, that sometimes is some hours long, depending on the HAP latitude. That means HAP has a quite long time to empty its memory, so the link to Ground does not require a wide band [5]. During this silent delay, HAP

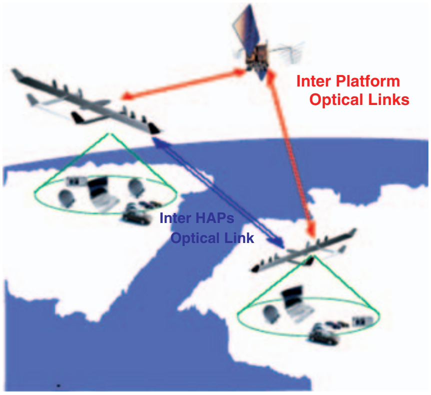


**Fig. 1.** HAP-Satellite link scenario: by integration of optical and RF technologies it is possible to enhance system performance.

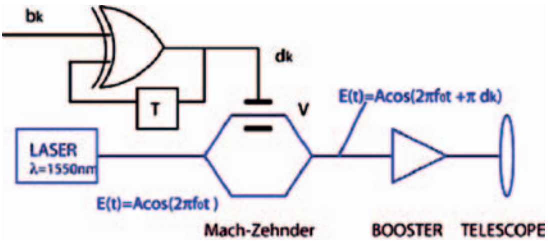


**Fig. 2.** LEO optical transmitter. The laser wave is externally modulated by a Mach-Zehnder interferometer that is electrically driven by a differential encoded stream.

can transmit data even to another HAP exploiting optical technology, as well. That can improve the downloading speed and the network connectivity.

## 2 Transmitter

The transmitter subsystem foresees the presence of a semiconductor laser that generates an optical CW (Continuous Wave) signal at the desired wavelength. One can design the system assuming that each LEO can transmit on its own optical carrier in order to reduce interference and to increase the global capacity. The phase modulation is carried out by the use of a differentially encoded stream in the electrical domain, as shown in Fig. 2. Such electrical stream can be used as driver voltage for the Mach-Zehnder modulator, that creates a phase modulation in the optical domain on the CW.

The incoming optical field is equally splitted inside the modulator, along one branch the driving voltage changes the refractive index, thus induces a phase shift that affects the outgoing field. Thus, a differential encoded phase can be assigned to the field that exhibits amplitude variation according to the phase value. Notice that the modulator can change the phase with a finite response time, such a parameter will affect the received eye diagram. A deeper explanation will be given in the proper section.

The optical field is then amplified by a booster (EDFA – Erbium Doped Fibre Amplifier) and transmitted by a telescope, whose diameter ($D_t$) gives a measurement of the transmitter gain by the following law [6]:

$$G_t = \frac{\pi^2 D_t^2}{\lambda^2} \tag{1}$$

The transmitted field can be written as:

$$E(t) = A\cos\left\{\omega_0 t + [\varphi(t)]\right\} \tag{2}$$

where it has been assumed that the phase undergoes continuous changes from bit to bit, in a transition time that is within the range 3–6 ps.

## 3 Receiver

On the receiver hand, a telescope focuses the optical power on the first optical band pass filter, whose goal is to reduce the background noise. It worth to observe that the proposed scheme is well suited for a WDM communications system, where each HAP can download simultaneously streams from different LEOs that use different optical carrier. In that case, the optical received spectrum can be represented as in Fig. 3, where the $4^{th}$ channel is dropped by a direct filtering [7].

Between the background filter and the selective filter is placed an optical preamplifier (EDFA), that increases the receiver performance in terms of electrical signal to noise ratio [13]. The desired channel is then selected, it is divided into two component by a 3dB splitter, each component feeds one of two branches of the interferometer. That configuration implements the differential demodulation scheme in the optical domain. In one branch, the field undergoes a delay equal to the bit duration ($T_b$), then the components are coupled again in another coupler that sums the field again.

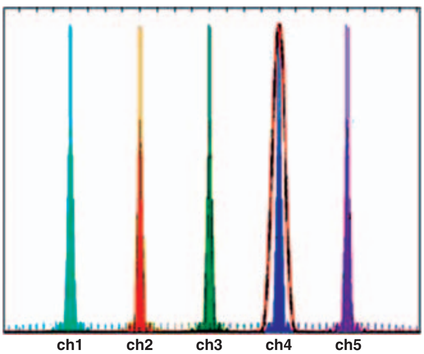


**Fig. 3.** From a WDM comb, the desired signal is selected by a direct filtering whose spectral shape is represented with the black line.

Thus, the photodetector receives the following optical field:

$$E_{pin}(t)=\frac{1}{\sqrt{2}}E(t)+\frac{1}{\sqrt{2}}E(t-T_b) \tag{3}$$

then, the current is generated by a beating of the signal that gives:

$$I(t)=\frac{E_b}{T_b}\left\{1+cos\left[\Delta\theta_k+\varphi_N(t)\right]\right\} \tag{4}$$

where $\varphi_N$ is the phase noise and the phase variations can be calculated as follows:

$$\Delta\theta_k=\omega_0 T_b+\pi\left(a_k-a_{k-1}\right) \tag{5}$$

notice that the first term in previous equation is related to the laser chirp, and it can be controlled in the receiver end chain inside the demodulator phase controller; the second term is the phase variation that contains information.

As shown in Fig. 5, the eye diagram is similar to a RZ signalling. That is a consequence of the differential encoding. As it has been explained before, each phase variation is carried out, on the transmitter modulator, in a finite time interval, creating a high level ("1") on the demodulated signal. Thus, the field imaginary component becomes nonzero in correspondence of such phase variations, and the received current undergoes a "return to zero" dynamics. This pattern effect is only present when a sequence of "1" is demodulated, that is related to a sequence of bit to bit variations.

Another scheme is proposed for the same system. It is based on a balanced receiver: the current is obtained by separating the demodulated field in a 3dB splitter, whose branches end into a photodetector, as shown in Fig. 4. After the 3dB coupler the optical field on each branch is:

$$E_{pin}(t)=\frac{1}{\sqrt{2}}E(t)+\frac{1}{\sqrt{2}}E(t-T_b) \tag{6}$$

$$E_{pin}(t)=\frac{1}{\sqrt{2}}E(t)-\frac{1}{\sqrt{2}}E(t-T_b) \tag{7}$$

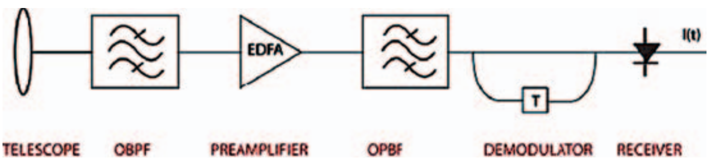


**Fig. 4. (a)** DPSK receiver scheme with a non balanced photodetector.

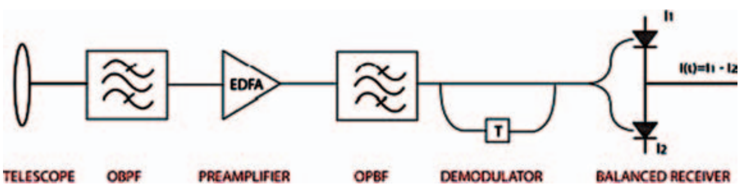


**Fig. 4. (b)** Scheme for DPSK signalling, based on balanced receiver.

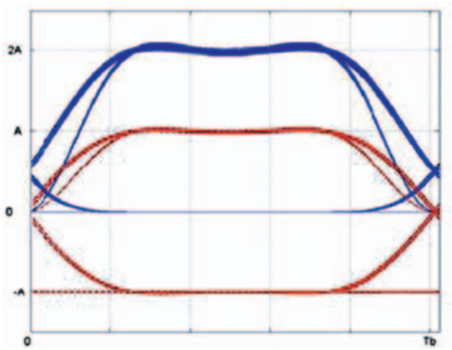


**Fig. 5.** Eye diagram for the current obtained by a non balanced receiver in solid line, and by a balanced receiver in dashed line.

resulting from the scattering matrix for the coupler:

$$[S] = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix} \tag{8}$$

The detected current exhibits a dynamics from positive and negative values, as it can be observed from the eye diagram in Fig. 5.

$$I(t) = I_1(t) - I_2(t) = \frac{E_b}{T_b} cos(\theta_k) cos\left[\varphi_N(t)\right] \tag{9}$$

By now we have considered a phase noise term in the received field. It worth to point that, this noise can be generated by the receiver itself, pointing error [8] on the transmitter side, wrong Doppler correction [9,10]. All these sources contribute to make the phase noise arise, with a distribution we have supposed to be uniform with zero mean over a narrow range of some degrees.

## 4 Doppler Compensation

The Doppler effect arises when the source or destination is moving with respect to its counterpart. Many techniques to suppress the phenomenon or reduce its impact on the system performance have been proposed [10]. An interesting solution is to use a direct filtering locked on the desired channel, by exploiting the deterministic nature of Doppler phenomenon. As a matter of fact, if the HAP is supposed to be placed within a spot of few squared kilometres, the relative distance between source and destination can be "a priori" known by calculation from LEO orbit geometric parameters. Thus, it is possible to predict with a negligible error, the Doppler shift that affects each optical carrier, by solving:

$$\Delta f(t) = f_0 \cdot \frac{v(t)}{c} cos[\alpha(t)] \tag{10}$$

where $f_0$ is the optical carrier, $v(t)$ is the relative speed and $\alpha(t)$ is the angle between the velocity vector and signal propagation direction.

When a new link is established, LEO approaches HAP until the minimum range is reached, thus the frequency shift in the signal spectrum is positive for the first half time of each access, then it becomes negative. For the proposed scenario it is possible to upper bound the shift within a 10 GHz band, centred at the optical carrier. This value can be relevant if the transmitted data rate is low, i.e. few Gbit/sec. In that case the narrow band filter after the preamplifier can not increase the receiver effectiveness as it would be if there was no Doppler shift. For that reason, when a low data rate link is established, a frequency controller on the receiver end should be implemented, in order to lock the narrow band filter at the received signal spectrum and change its central frequency with the Doppler shift fluctuations (Fig. 6).

This approach is somehow expensive in terms of software complexity, but the enhancement of the received OSNR is relevant. Another case is when the transmitter data rate is very high, i.e up to 40 Gbit/sec. In that instance the signal bandwidth can reach 80 GHz, and the optical filter bandwidth increasing due to Doppler shift is quite negligible.

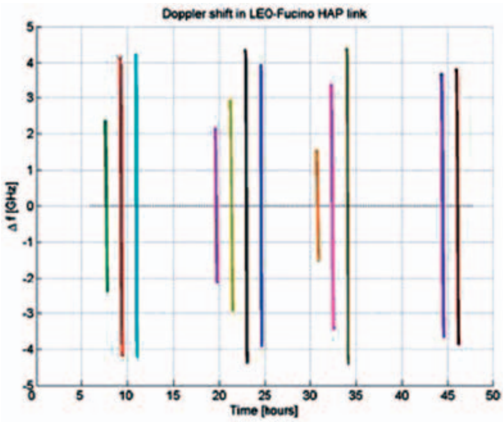


**Fig. 6.** Doppler shift for an optical link LEO-HAP (on Fucino), at 1550 nm.

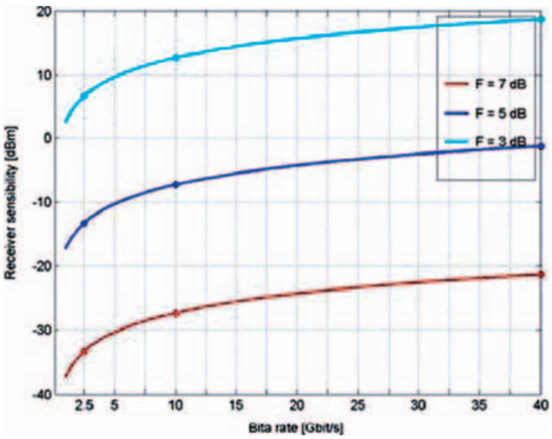


**Fig. 7**. Receiver sensitivity increase for different noise figure (F), with the signal data rate.

## 5 System Performance

The LEO-HAP link performance are limited in terms of Optical Signal to Noise Ratio on the receiver end. That parameter is affected by different impairments, as: pointing error, HAP random motion due to wind, high background noise and so on.

A first approach to improve system performance is related to the correct device and hardware choice. For example, higher diameter lenses guarantee a higher gain both in the receiver and the transmitter end.

But this leads to the decrease of the spot size as well, with the consequence of a more complicated pointing procedure. The availability of a wide spot reduces the time required to carry out the connection establishment, this for the higher probability to find an intersection of the uncertain area of the target and the transmitter spot.

The use of wavelength around 1550 nm gives a partial compensation for that reduction of the beam width. The choice of the transmitter and receiver lenses diameters has to be made taking into account all these implications: the increase of the available gain can not always compensate the time consumption required to scan the uncertain area where the target can be found if a narrow beam is used. Another factor the spot size depends on is the link range, as shown in Fig. 8. As a matter of fact, a LEO-HAP link is rather short, if compared with other scenarios, (i.e., LEO GEO link), and just a section of stratosphere is crossed by the optical beam, a very high gain for the transmitter telescope is not required. This reduction of the lenses leads to a wider optical spot, occurrence that can simplify the pointing procedure for the relative reduction of the uncertain area related to the spot size at the link range [11]. The receiver embarked on HAP payload, has been already described in the receiver section. A telescope focuses the received beam on a background filter. This first filter has an important role: it reduces the impact of the stars and Sun noise field on the signal bandwidth. Its importance becomes more relevant for the proposed scheme, where the optical preamplifier could be saturated by a strong incoming noise making its performance worst. The preamplifier can reduce the system Bit Error Rate by the increase of receiver sensitivity. A second optical filter is designed to reduce the impact of Doppler on the signal spectrum [12,10]. The presence of an

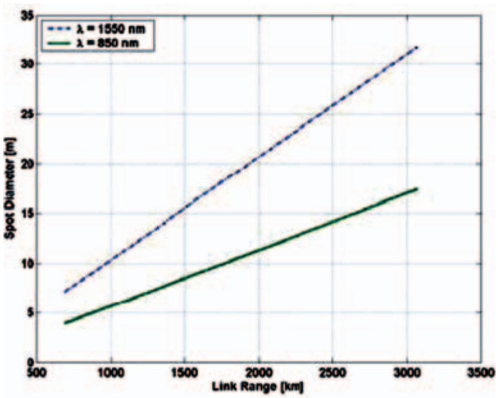


**Fig. 8.** Spot diameter increase with range link for a 15 cm diameter lens.

optical preamplifier is relevant for the improvement in the receiver sensibility, that can be written as:

$$P_{in} = R \cdot hf \cdot F \left[ \gamma^2 + \gamma \sqrt{\frac{\Delta f_{opt}}{R}} \right] \tag{11}$$

where $R$ is the data rate, $F$ is the preamplifier noise figure, $\gamma$ is the optical signal to noise ratio and $\Delta f$ is the optical filter bandwidth. The dependence on the data rate has been graphically shown in Fig. 7.

The high speed offered by optical technology increases the available capacity of a LEO-HAP link to some Terabit per day. A 10 Gbit/sec link has been considered. Then the actual connection window has been calculated. In particular, from geometrical parameter obtained via simulation with AGI-STK, the theoretical connection window can be easily calculated considering as start time the moment HAP and LEO become visible each other. Actually, the pointing procedure must be completed before the communication link can be established, in addition sometimes the distance is too high to ensure a connection that satisfies the required BER.

The BER calculation have been implemented assuming no phase error affects the signal, even if that hypothesis can be easily removed with no large lost in performance. In particular, if a limited phase noise with uniform distribution is assumed, it has been proved that the increase of the receiver sensitivity is about 1 dB [9]. The BER can be found by solving [14]:

$$P_e = Q_1(a,b) - \frac{1}{2} e^{-\frac{(a^2+b^2)}{2}} \cdot I_0(ab) \tag{12}$$

where $Q_1$ is the Marcum Q function and $I_0$ is the first kind modified Bessel function of order zero. The terms $a$ and $b$ are related to the phase error:

$$a = \sqrt{SNR(1-cos\theta)}$$
$$b = \sqrt{SNR(1+cos\theta)}.$$

Within the actual connection windows, it could be calculated the overall amount of information the link can transmit. That leads to start investigations in new applications for satellite network: at first, data relay becomes more effective since hard memory is now enormous, if compared to the RF link capacity. A huge hard memory can be embarked on HAP and it can be used to storage information downloaded from LEO at 10 Gbit/sec in the connection window. On the other hand, an RF link from HAP to Earth can download all data even with a reduced bandwidth.

This architecture offers a wide band link also to places located at middle latitude, where the LEO-HAP connection time is shorter, for examples Rome. In particular three different locations have been considered: Fucino (Rome), Shadnagar (India) and Poker Flat (Alaska). For these latitudes the available capacity for each day has been calculated and the results are reported in Fig. 9. The most effective site is Poker Flat, with a very high latitude if compared to Fucino and Shadnagar. Anyway the presence of an optical link from LEO to HAP ensures even at low latitude, as for Shadnagar, a capacity of some Terabit/day.

At Fucino the capacity reaches value of 10 Terabit/day if the transmitted power is 10 dBm. The link becomes even more effective if the power increases. In particular, in Fig. 10 has been shown the trend of link efficiency with respect to the optical transmitted power. It worth to notice that 10 dBm corresponds to a low efficiency, that

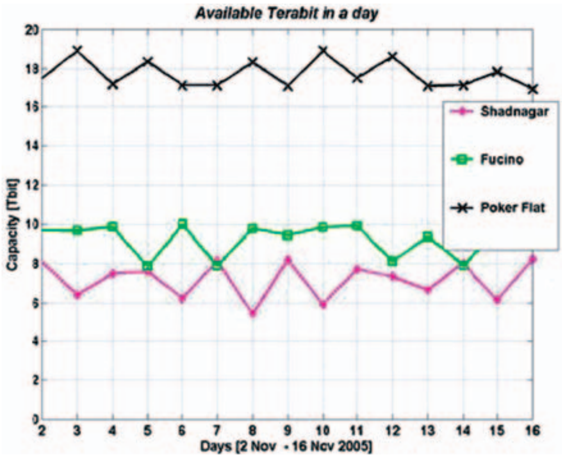


**Fig. 9.** Maximum available capacity for an optical link, operating at 1550 nm with 10 dBm transmitted power. Different results have been found for the considered ground stations: Poker Flat, Shadnagar and Fucino.

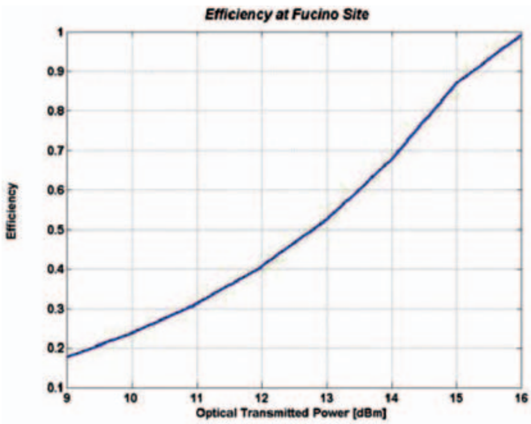


**Fig. 10.** Link efficiency with the increase of the optical power.

means a wide part of time intervals where LEO and HAP are visible is not actually used for transmission because the link does not satisfy the quality constraints, or the visibility is too short to let the pointing procedure end successfully.

### 5.1 Coding Effects on System Performance

To improve the performance of Hap-Leo link we have considered two different kinds of coding (block and convolutional) and two techniques of decision (hard and soft). The results have been obtained considering SNR available at Fucino site for a scenario period of two days.

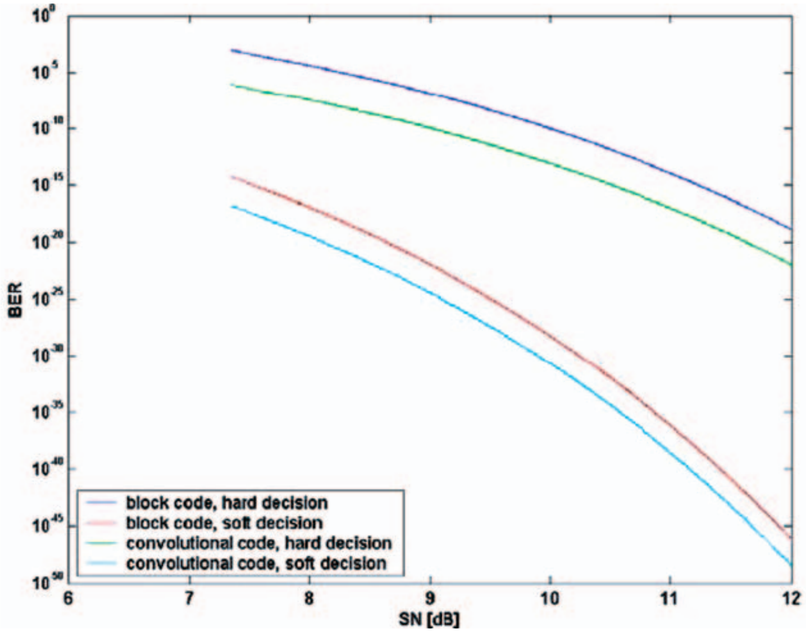


**Fig. 11.** BER vs. SNR for different codes and decision techniques.

The use of codes requires a lower OSNR at the receiver end for a given BER. In particular, the optical power requested shows a higher decrease with convolutional techniques compared with the block ones, as can be seen in Figs. 11 and 13. It is also clear that soft decision involves a lower required power than hard decision, for an assigned Bit Error Rate and a specified code.

The plots of Fig. 11 were obtained considering codes with equal correction power and with equal coding rate ($R_c = 1/2$). Bit error probability for the codes has been calculated from [2]:

$$\left.\begin{aligned} P_{e\_HD} &\leq \frac{2t+1}{n}(2^k-1)\left(\sqrt{4P_e(1-P_e)}\right)^d \\ P_{e\_SD} &\leq \frac{2^k-1}{2}\, erfc\left(\sqrt{\frac{E_b}{N_0}}\right) \end{aligned}\right\}\text{Block codes} \tag{13}$$

$$\left.\begin{aligned} P_{e\_HD} &\leq 2^d P_e^{d/2} \\ P_{e\_SD} &\leq \frac{1}{2} e^{-d(E_b/N_0)} \end{aligned}\right\}\text{Convolutional codes} \tag{14}$$

where $t$ is the number of errors that can be corrected at the receiver end, and $d$ represents the maximum number of errors detectable; $P_e$ is given by

$$P_e = \frac{1}{2}\, erfc\left(\sqrt{\frac{E_b}{N_0}}\right) \tag{15}$$

for On–Off–Keying (OOK) modulation, or by equation (12) for DPSK modulation.

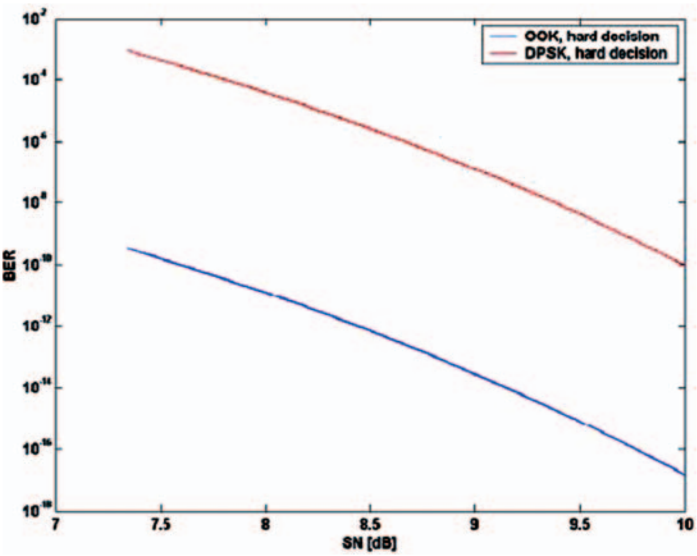


**Fig. 12.** BER vs. SNR for different modulation format.

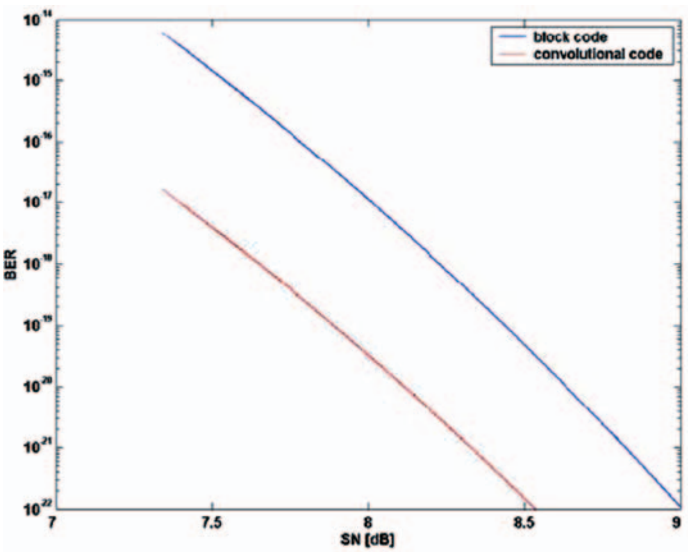


**Fig. 13.** BER vs. SNR for block/convolutional codes, with soft decision.

The performance of OOK and DPSK in terms of BER against SNR in case of hard decision technique is reported in Fig. 12. We can see that an OOK modulated signal grants to reach, for a given SNR, a BER lower than that achievable with a DPSK modulated signal.

In Fig. 13 the case of soft decision is shown for block and convolutional codes. It is worthwhile to point out that, in case of soft decision, the Bit Error

Rate is independent of modulation scheme, as can be deduced from equations (13) and (14).

The reported plots in this Figure confirm that convolutional codes have better performance than block codes, in term of BER.

## 6 Conclusions

By the cooperation of RF and optical technology it is possible to develop high performance satellite network. The increase in the communication effectiveness is related to the possibility of data dump even for medium latitude and to the enlarge of downloadable volumes. These features give a contribution to the future earth observation systems. In particular, STK simulations have shown the possibility to carry out some optical links from LEO to HAP located above low latitude sites such as Shadnagar or Fucino, with very actractive performance in terms of available capacity per day. Those calculations have been performed considering some constraints on the minimum received power (optical sensibility) in order to guarantee the required Bit Error Rate.

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