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Research Article

INTERSATELLITE OPTICAL COMMUNICATION LINK A NOVEL APPROACH

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ABSTRACT
Intersatellite links are employed to provide connections between earth stations in the service area of one satellite to earth stations in the service area of another satellite when neither of the satellites covers both sets of earth stations. There are two different links possible radio and optical links depending on the mass and power consumed. Radio links are more advantageous for low throughputs (less than 1 M bit/s). For high capacity links (several tens of M bit/s) optical links command attention. In this paper we explained the basic idea of Radio link and main focus is given to Optical link intersatellite technique.

Key Words: *ISL, GEO, LEO, SNR, Coherent Detector, Optical Link*

INTRODUCTION
Intersatellite links are links between satellites. Three types of Intersatellite links can be considered:
- GEO to LEO links between geostationary (GEO) satellites and low earth orbit (LEO) satellites, also called interorbital links (IOLs);
- GEO to GEO links between geostationary satellites;
- LEO to LEO links between low earth orbit satellites. Of course one could consider intersatellite links between satellites in any type of orbit, but the above configurations are those most considered in practice.

If the satellites are separated by angles large enough to make parts of the Earth's surface visible to only one or other of the two, then an ISL may be used to extend the service area available to users of the network. However, in the case of geostationary satellites this involves fairly long ISLs, so the problem of excessive time delay is not fully solved.
Constellations of satellites in low-Earth orbits sometimes incorporate a pattern of ISLs to enable long overland routes to be covered without recourse to multiple satellite hops via intermediate earth stations.

1. Frequency Bands
Table 1 indicates the frequency bands allocated to intersatellite links by the Radio communication Regulations. These frequencies correspond to strong absorption by the atmosphere and have been chosen to provide protection against interference between intersatellite links and terrestrial systems. However, these bands are shared with other space services and the limitation on interference level is likely to impose constraints on the choice of the defining parameters of intersatellite links (CCIR Reports 451, 465, 874, 951). Table 1 also indicates the wavelengths envisaged for optical links. These result from the transmission characteristics of the components.

2. Radio-frequency Links
Propagation losses reduce to free space losses since there is no passage through the atmosphere. Antenna pointing error can be maintained at around a tenth of the beamwidth and this leads to a pointing error loss of the order of 0:5 dB. The antenna temperature in the case of a GEO–GEO link, in the absence of solar conjunction, is of the order of 10 K. Table 2 indicates typical values for the terminal equipment. For practical applications, antenna dimensions are of the order of 1 to 2 m. considering a frequency of 60GHz and transmission and reception losses of 1 dB leads to:
- A receiver figure of merit G=T of the order of 25 to 29 dBK^{-1};
- A transmitter EIRP of the order of 72 to 78 dBW.

Because of the relatively wide beamwidth of the antenna (0.2^o at 60 GHz for a 2m antenna), establishing the link is not a problem. Each satellite orientates its receiving antenna in the direction of the transmitting satellite with a precision of the order of 0.1^o to acquire a beacon signal which is subsequently used for tracking.

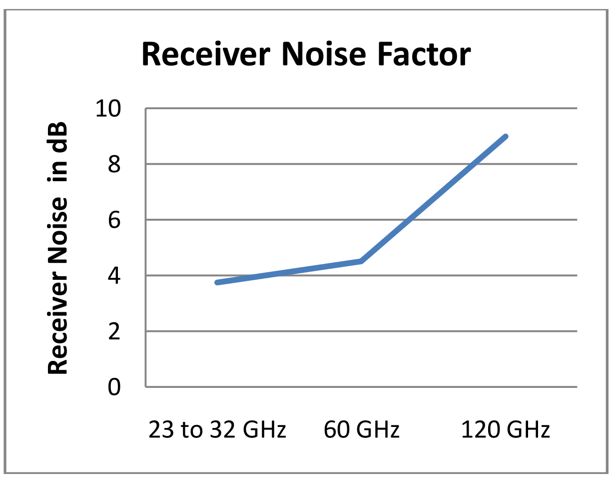
The development of high-capacity, radio-frequency inter satellite links between geostationary satellite systems implies re-use of frequencies from one beam to another. In view of the small angular separation of the satellites, it is preferable to use narrow beam antennas with reduced side lobes in order to avoid interference between systems. Consequently, and in view of the limited antenna size imposed by the launcher and the technical complexity of the deployable antennas, the use of high frequencies is indicated. The use of optical links may be usefully considered in this context.

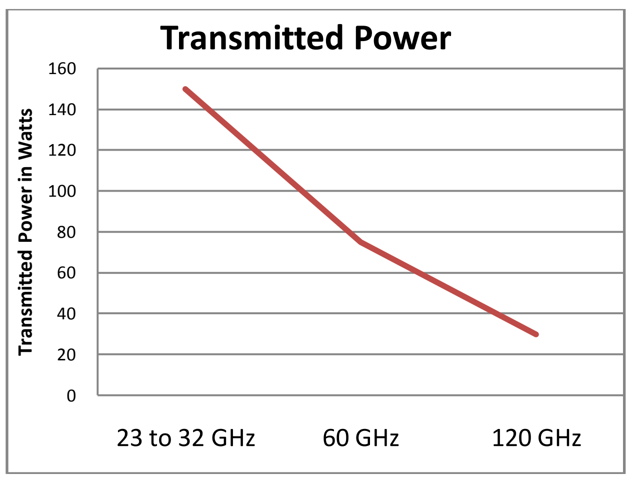
Table 1: Frequency bands allocated to intersatellite links by the Radio communication Regulations

Intersatellite service	**Frequency bands**
Radio frequency	22.5 to 23.5 GHz
	24.4 to 24.75 GHz
	32 to 33 GHz
	54.25 to 58.2 GHz
Optical	0.8 to 0.9 µm (AlGaAs laser diode)
	1.06 µm (Nd:YAG laser diode)
	0.532 µm (Nd:YAG laser diode)
	10.6 (CO_2 Laser)

Table 2: Typical values of terminal equipment of radio frequency intersatellite link

Frequency	**Receiver noise factor**	**Transmitter power**
23 to 32 GHz	3-4.5 dB	150W
60 GHz	4.5 dB	75W
120 GHz	9 dB	30W





In comparison with radio links, optical links have specific characteristics which are briefly described here. For a more complete presentation, refer to (Kaitzman, 1987; Gagliardi, 1991; Peters, 1988; Begey, 2000).

2.1 Establishing a Link

Two aspects should be indicated:

- The small diameter of the telescope is typically of the order 0:3 m. In this way, one is freed from congestion problems and aperture blocking of other antennas in the payload.
- The narrowness of the optical beam is typically 5 micro radians. Notice that this width is several orders of magnitude less than that of a radio beam and this is an advantage for protection against interference

between systems. But it is also a disadvantage since the beamwidth is much less than the precision of satellite attitude control (typically 0.1 ^{o} or 1.75 mrad). Consequently an advanced pointing device is necessary; this is probably the most difficult technical problem.

There are three basic phases to optical communications:

- ***Acquisition***: the beam must be as wide as possible in order to reduce the acquisition time. But this requires a high-power laser transmitter. A laser of lower mean power can be used which emits pulses of high peak power with a low duty cycle. The beam scans the region of space where the receiver is expected to be located. When the receiver receives the signal, it enters a tracking phase and transmits in the direction of the received signal. On receiving the return signal from the receiver, the transmitter also enters the tracking phase. The typical duration of this phase is 10 seconds.
- ***Tracking:*** the beams are reduced to their nominal width. Laser transmission becomes continuous. In this phase, which extends throughout the following, the pointing error control device must allow for movements of the platform and relative movements of the two satellites. In addition, since the relative velocity of the two satellites is not zero, a lead-ahead angle exists between the receiver line of sight and the transmitter line of sight. As demonstrated below, the lead-ahead angle is larger than the beamwidth and must be accurately determined.
- ***Communications:*** information is exchanged between the two ends.

2.2 Lead-ahead Angle

Consider two satellites, S_1 and S_2, respectively moving with velocity vectors V_{S1} and V_{S2}, whose components orthogonal to the line joining S_1 and S_2 at time t are respectively the two vectors represented in Figure 1by V_{T1} and V_{T2}.

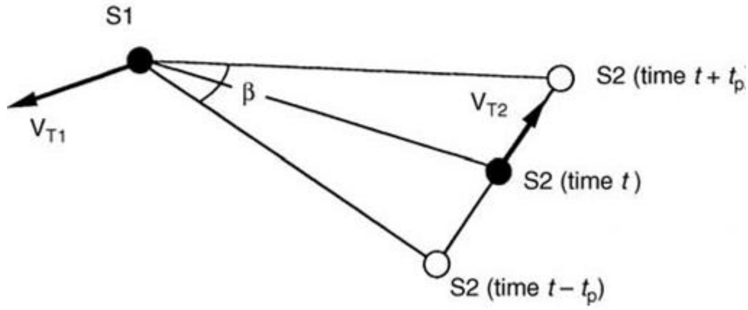


Figure 1: Lead-ahead angle for link between two satellites S_1 and S_2 with velocity vector components V_{T1} and V_{T2} in a plane perpendicular to the line joining S_1 and S_2 at time t; t_p is the propagation time of a photon from S_1 and S_2

The propagation time of a photon from S_1 to S_2 is t_p =d/c, where d is the distance between the two satellites at time t and c is the speed of light.

The lead-ahead angle β is given by:

$$\beta = \frac{2|V_{T1}-V_{T2}|}{c}\ (rad) \quad \text{--- (1)}$$

Where $|V_{T1} - V_{T2}|$is the modulus of the difference vector $V_{T1} - V_{T2}$

Two situations are now considered:

- Intersatellite links between two geostationary satellites;
- Interorbital links between a geostationary satellite and a low earth orbiting satellite.

3.1. GEO Satellites Separated by Angle α

As both satellites are on the same circular orbit (Figure 2), the velocity vectors V_{S1} and V_{S2}, which are tangential to the orbit, have equal modulus:

$$|V_{S1}| = |V_{S1}| = \omega(R_o + R_E) = 3075\ m/s \quad \text{--- (2)}$$

Where:

$\omega$is the angular velocity of a geostationary satellite = 7.293X10^{-5} rad/s

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R_0 is the altitude of a geostationary satellite = 35,786 km
R_E is the earth radius = 6378 km

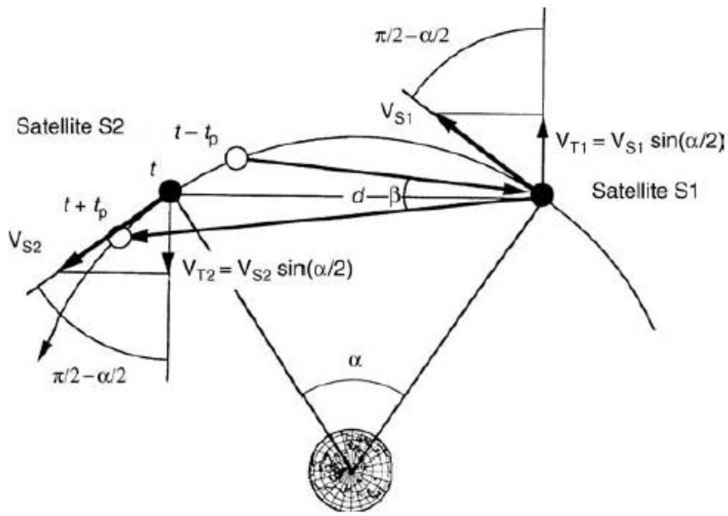

Figure 2: Lead-ahead angles for intersatellite links between two geostationary satellites

The component vectors V_{T1} and V_{T2}, perpendicular to the line joining S_1 and S_2 at time t, both lie in the plane of the orbit and are opposite. They are at an angle $(\frac{\pi}{2} - \frac{\alpha}{2})$ with respect to vectors V_{S1} and V_{S2}. Therefore:

$$|V_{T1} - V_{T2}| = 2\omega(R_o + R_E)\cos\left(\frac{\pi}{2} - \frac{\alpha}{2}\right) = 2\omega(R_o + R_E)\sin\left(\frac{\alpha}{2}\right) \quad m/s \qquad \text{--- (3)}$$

From equation of β

$$\beta = \frac{2|V_{T1} - V_{T2}|}{c} = 4\omega(R_o + R_E)\sin\left(\frac{\alpha}{2}\right)/c \quad rad \qquad \text{--- (4)}$$

Figure 3 displays the lead-ahead angle b as a function of the separation angle a between the two geostationary satellites. Note that, for a separation angle larger than 15^o, the lead-ahead angle is larger than the beamwidth (typically 5 microradian). For instance, β=10.6 microradian for α=30^o β = 20.5 microradian for α=60^o, and β = 35.5 microradian for α= 120^o.

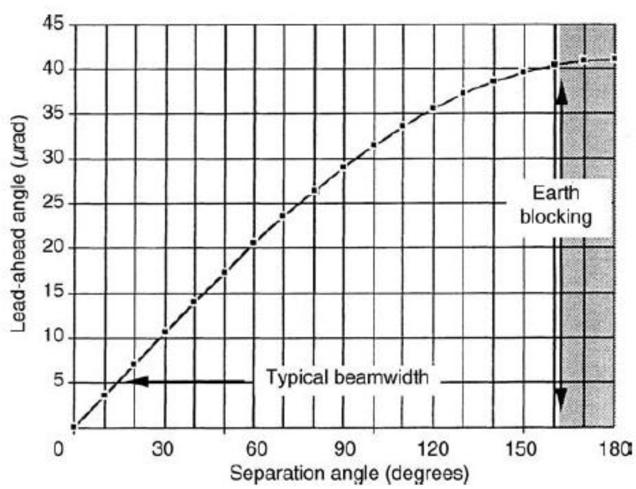

Figure 3: Lead-ahead angle as a function of the separation angle between two geostationary satellites

3.2. A GEO Satellite and a LEO Satellite with Circular Orbit

The relative velocity of the two satellites varies with time and so does the value of the lead-ahead angle. Its maximum value is obtained when the LEO satellite crosses the equatorial plane. Denoting as i the LEO satellite orbit inclination, then:

$$|V_{T1} - V_{T2}| = \{|V_{S1}|^2 + |V_{S2}|^2 - 2|V_{S1}||V_{S2}|cosi\}^{1/2} \qquad \text{--- (5)}$$

Where:

$|V_{S1}| = \omega_{GEO}(R_o + R_E) = 3075\ m/s$

$|V_{S2}| = \omega_{LEO}(h + R_E)$

h is the LEO satellite altitude and $\omega_{LEO} + \mu^{\frac{1}{2}}(h + R_E)^{-\frac{3}{2}}$ is the LEO satellite angular rate (μ=3.986x10^{14} m^3/s^2) and

$$\beta = \frac{2|V_{T1} - V_{T2}|}{c} = (2/c)\{|V_{S1}|^2 + |V_{S2}|^2 - 2|V_{S1}||V_{S2}|cosi\}^{1/2}\ rad \qquad \text{--- (6)}$$

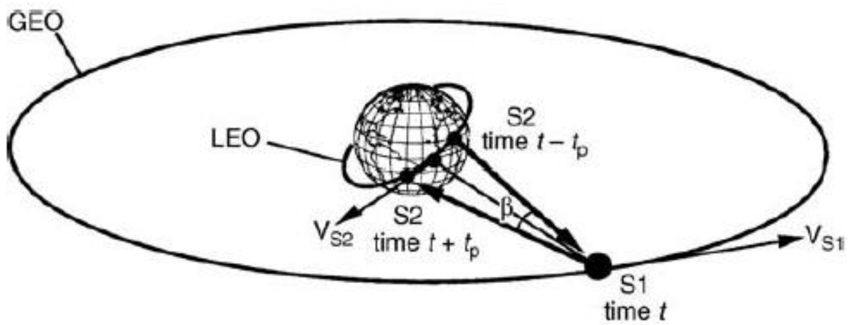

Figure 4: Lead-ahead angle at a GEO satellite for interorbital links between it and a LEO satellite

The lead-ahead angle is the same for the two satellites. Considering i = 98:5^o and h = 800 km, then β= 57 microradian. Note this value is even larger than for intersatellite links between two geostationary satellites.

3.3. Transmission

Laser sources operate in single and multi-frequency modes. In single frequency mode, spectral width varies between 10 kHz and 10 MHz In multi-frequency mode; it is from 1.5 to 10 nm. The power emitted depends on the type of laser. Table 3 gives orders of magnitude. Modulation can be internal or external. Internal modulation implies direct modification of the operation of the laser. External modulation is a modification of the light beam after its emission by the laser. The intensity, the frequency, the phase and the polarization can be modulated. Phase and polarization modulation are external. Intensity and frequency modulation can be internal or external. Polarization modulation requires the presence of two detectors in the receiver, one for each polarization. Because of this, it is preferable to reserve polarization for multiplexing of two channels.

The intensity distribution of a laser beam, as a function of angle with respect to the maximum intensity, follows a Gaussian law. The on-axis gain is given by:

$$G_{T\,max} = \frac{32}{(\theta_T)^2} \qquad \text{--- (7)}$$

Where θ_T is the total beamwidth at 1=e^2 where e = 2.718. The choice of θ_T depends on the pointing accuracy. With imprecise pointing, a large θ_T is better but gain is lost. If θ_T is reduced, there is benefit in gain but the pointing error loss increases. It can be shown that, if the pointing error is essentially an alignment error, the (maximum gain x pointing error loss) product is maximum when θ_T =2.8^o (pointing error) (Kaitzman, 1987). In general, for a pointing error of any kind, the beamwidth may be adapted to the pointing error.

In addition to losses due to pointing error, transmission losses and degradation of the wave front in the emitting optics occur.

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Table 3: Typical values of transmitted power for lasers

Types of Laser		**Wavelength**	**Transmitted power**
	AlGaAs	0.8 to 0.9 µ	About 100mW
Solid state	InPAaGa	1.3 to 1.5 µ	About 100mW
(laser diode)	Nd:YAG	1.06 µ	0.5 to 1 W
	Nd:YAG	0.532 µ	100mW
Gas Laser	Co_2	10.6 µ	Sever tens of Watts

Transmission Loss

Transmission loss reduces to the free space loss:

$L = (\lambda/4\pi R)^2$;

Where L is the wavelength and R is the distance between transmitter and receiver.

3.4. Reception

The receiving gain of the antenna is given by:

$$G_R = (\pi D_R/\lambda)^2 \quad \text{--- (8)}$$

Where D_R is the effective diameter of the receiver antenna.

The receiver can be of a direct detection (Figure 5) or a coherent detection receiver (Figure 6). With direct detection, the incident photons are converted into electrons by a photodetector. The subsequent baseband electric current at the photo detected output is amplified then detected by a matched filter. With coherent detection, the optical signal field associated with the incident photons is mixed with the signal from a local laser. The resulting optical field is converted into a band pass electric current by a photodetector and is subsequently amplified by an intermediate frequency amplifier. The demodulator detects the useful signal either by envelope detection or by coherent demodulation.

The receiving losses include optical transmission losses and, for coherent detection, losses associated with the degradation of the wave front (The quality of the wave front is an important photodetector front end). Filtering, to reject out-of-band photons, also introduces losses, since the transmission coefficient reduces with bandwidth. A typical filter width is from 0.1 to 100 nm.

The signal-to-noise power ratio at the detector output depends on the type of detection. For direct detection (Figure 5):

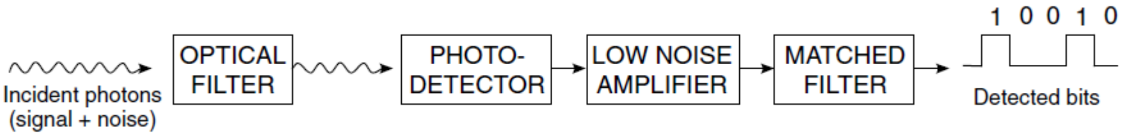

Figure 5: Optical direct detection receiver

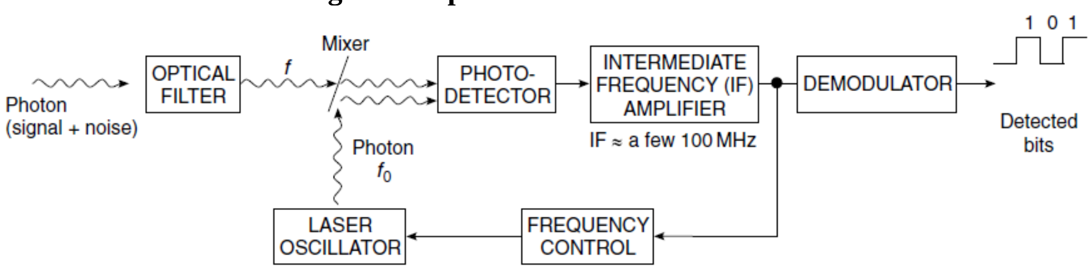

Figure 6: Optical coherent detection receiver

$$\frac{S}{N} = \frac{I_{Sdd}{}^2}{i_{dd}{}^2} \quad \text{--- (9)}$$

The quantity $I_{S\,dd}$ represents the signal current intensity:

$$I_{Sdd} = (P_s/hf)\eta_p eG \quad \text{--- (10)}$$

Where:
P_S is useful optical signal power (W),
h is Planck's constant = 6.6 x10^{-34} J/Hz,
f is laser frequency (Hz),
η_p is quantum efficiency of the photodetector, typically 0.8 for an avalanche photodetector (APD),
e is electron charge =1.6x10^{-19} C,
G is photodetector gain, of the order of 50–300 for an avalanche photodetector (AP) and 10^4 to 10^6 for a vacuum tube photomultiplier.
Also (P_s/hf) represents the number of photons received per second, and K = $\eta_p e/hf$ represents the sensitivity of the photodetector (A/W). Hence:
$I_{Sdd} = KGP_s$ (A)
The quantity i_{dd} represents the root mean square noise current intensity:
$i_{dd}{}^2 = i_{nS}{}^2 + i_{nB}{}^2 + i_{nD}{}^2 + i_{nT}{}^2 \quad (A^2)$
$i_{nS}{}^2 = 2eKP_S G^2 f(G) B_N$ *is the signal shot noise,*
$i_{nB}{}^2 = 2eKP_n G^2 f(G) B_N$ *is the background shot noise,*
$i_{nD}{}^2 = 2ei_o B_N$ *is the dark current shot noise,*
$i_{nT}{}^2 = N_o B_N$ *is thermal noise of electronic amplifying circuits.*
In these formulae, P_n is the received background optical noise power (W), $f(G)$ is a multiplying factor taking into account the noise generated in the photodetector by secondary electrons (typically $f(G) = a + bG$ where a=2 and b=0.01), i_0 is the dark current intensity (A), N_0 is the electronic amplifier thermal noise spectral density (A^2) Hz and B_N is its noise bandwidth (Hz).
If all sources of noise besides the signal shot noise could be eliminated (i_0 = 0; P_n = 0; N_0 = 0; f(G) = 1, one would achieve the quantum-limited S/N value, given by:
$(S/N)_{ql} = \eta_p P_s/2hfB_N$ --- (11)
For coherent detection
$\frac{S}{N} = I_{S\,cd}{}^2/(I_{dd}{}^2 + I_{LO}{}^2)$ --- (12)
The quantity $I_{S\,cd}$ represents the signal current intensity:
$I_{S\,cd} = KG\eta_m L_p (2P_s P_{LO})^2$ --- (13)
Where:
η_m *is* mixing efficiency,
L_p *is* loss due to polarisation mismatch.
The local oscillator power i_{dd} represents the root mean square noise current intensity for direct detection, as determined from equation (12); i_{LO} represents a supplementary source of noise, i.e. the local oscillator root mean square noise current intensity:
$i_{LO}{}^2 = 2eKP_{LO} G^2 f(G) B_{IF}$ --- (14)
Where B_{IF} is the noise bandwidth of the intermediate frequency amplifier (Hz).
The quantity P_{LO} can be increased to the point where i_{LO} is the predominant source of noise:
$\frac{S}{N} \approx \frac{I_{S\,cd}{}^2}{i_{LO}{}^2} = \frac{\eta_m L_p \eta_p P_s}{f(G) B_{IF} hf}$ --- (15)
Coherent detection confers a higher value of S/N than direct detection. In theory, one could achieve the quantum-limited S/N value, $(S/N)_{ql}$, given by equation (11), considering
$\eta_m = 1,\ L_p = 1,\ f(G) = 1$ *and* $B_{IF} = 2B_N$. However, in the case of alignment error between the local oscillator and the beam signal, mixing efficiency is degraded. This type of detection cannot therefore be used both for acquisition and tracking. Unless high data rates are involved, there is no advantage in weight or power from using coherent detection techniques for communications along with a separate direct detection receiver for acquisition and tracking, compared to the situation where a direct detection receiver is used for both. For high data rates (typically greater than 1Gbit/s), the power required for direct

detection is excessive, and one may consider resorting to coherent detection for the communications function.

Conclusion

The choice between radio and optical links depends on the mass and power consumed. In general terms, it can be said that the advantage is with radio links for low throughputs (less than 1 M bit/s). For high capacity links (several tens of M bit/s) optical links command attention. For a link involving one uplink, one or more optical intersatellite links and one downlink, the overall station-to-station link performance should be established in the same way as the overall link performance for regenerative satellites. Indeed the implementation of intersatellite links at radio frequency or with optical technology, is mainly of interest when on-board demodulation is available, so as to provide flexible on-board switching.

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