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Laser Satellite Communication: Fundamentals and Applications

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Abstract— **A number of serious consortiums develop satellite communication networking technologies. Such optical communication has a number of advantages from data handling, data relaying, structuring and implementation of complex networking softwares, algorith development, etc. However, the gain of such advanced optical communication systems is reduced due to the noise of optical sources. A lot of distortion may occur due to the presence of laser noise in the optical source. This effects the actual gain as well as the sensitivity of coherent laser communication systems having high bit rates. Noise upto a significant level is also observed in systems with moderate bit rates which can be avoided with proper fabrication of the sources. Different types of noises are observed during the transmission process and various methods are applied in order to minimise them and thus, enhance the networking process. This is an exciting era for space laser communications.**

Index Terms— **Beamwidth, Beam-steering, Heterodyne, Point-Ahead**

I. INTRODUCTION

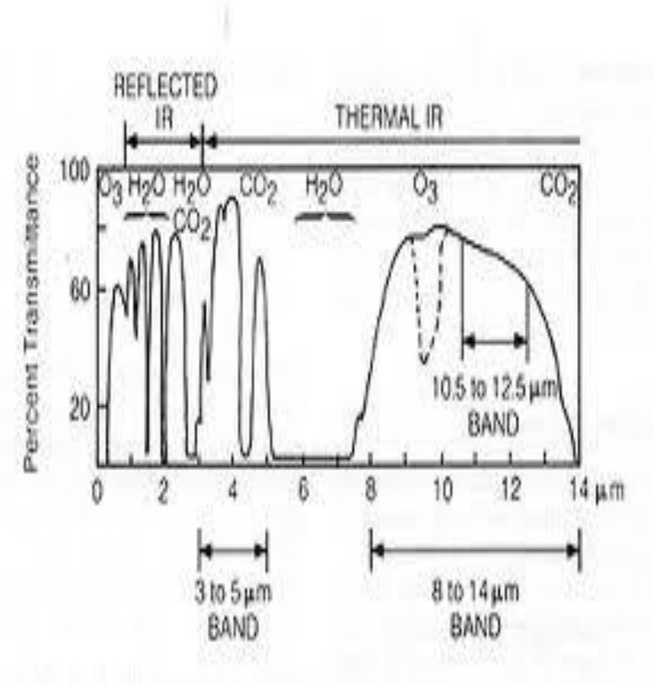
Communication technology is continuously undergoing development to higher transmission frequencies, starting from a few hundred kilohertz at Marconi's time to several hundred terahertz due to the employment of lasers in various complex fiber systems. The main reason for the optimization and development of today's complex networking management systems is the development and alteration in the carrier frequencies. Efficient modulation has led to an increase in the data carrying capacity as well as the transmission between point to point links. The usable bandwidth stands out in accordance to these carrier frequencies. This also allows cross networking of platforms and multiple linking of the transmission and receiving devices. Another important factor comes into picture which is the high bit rate. this allows complex data to be transmitted and with the help of narrow beamwidth, the transceiving process is cut short by adjusting this high value data in the signal bands itself.The large distance for propgation may pose as a hindrance in the wake of efficient communication. As a result of this, laser communications consisting of high bit rates can be easily distorted. However, laser satellite systems find their applications in a number of data transmission methods and link processing networks which make them one of the most advanced techniques in the field of complex communication.

II. LINK ANALYSIS

2.2 ATMOSPHERIC EFFECTS

Earth's atmospheric effects are carefully studied while analyzing the cross- linking. Loss of coherence, field attenuation and transmission losses are some of the losses caused due to the atmospheric boundaries. These can be significantly reduced by using effective linking equipment but they cannot be completely eliminated.

The atmospheric attenuation is dependent on the wavelenght as shown in Figure 1. The beam spreading caused by atmospheric scattering results into weakening of power received at the optical receiver. In clear days the mixing of warm and cool atmosphere strata produces turbulence which may interact with impinging light waves causing the refocussing and reorienting of the impinging beam. This causes the beam to move off-foresight (beam steering)[1] and create optical pointing problems. Similarly the atmosphere also introduces loss in beam front coherence which means that two points on the beam front would no longer be in the same phase. This affects both the direct and hetrodyne optical detection systems.



Variartion of Attenuation with Wavelength

2.2 COMPLETE LINK ANALYSIS

In cases when the effects of atmosphere are considered to be significantly low, optical cross-linking analysis is suitable for assessment. On assuming that the RF link is used for uplinking as well as downlinking transmission towards the satellite and the crosslink between the two satellites is the optical link that uses a direct detection system. As a result of this, direct intensity modulation takes place on receiving the uplink. It should be noted that the upper end of the uplink band should li within the photodetector bandwidth else the uplink should be down connected before carrying out modulation. Thus, the RF uplink waveform may be presented as

$s(t) = u(t) + n_u(t)$

here u(t) denotes the uplink carrier and $n_u(t)$ is the uplink noise/interference. As the laser power signal at the receiving end is intensity modulated so

$P(t) = P_r (1 + Bs(t))$

where P_r represents the Average Power and B denotes the Intensity Modulation Index. The receiving satellite receives the signal of the above equation by photodetecting it. The photodetector detects this intensity modulated signal as

$R [B P_r s(t)] = R B P_r [u(t) + n_u(t)]$

where R is the photodetector responsivity[2]. The photodetected waveform that is actually of the uplink frequency is then translated to the downlink frequency which is then power amplifies and transmitted to the receiving earth station. If P_r represents the available downlink satellite power, A_s and A_n as the signal and noise suppressions and L as the net downlink losses, then the recovered downlink carrier power may be expressed as

$P_s = A_s^2 P_t [(R B P_r)^2 P_{CU}]L$

where P_{CU} is the uplink power of u(t) in the initial equation. Also the total downlink retransmitted noise power (uplink plus total photodetector noise) can be expressed as

$P_{ns} = A_n^2 P_t [(R B P_r)^2 P_{NU} + P_{PD}]L$

where P_{NU} is the uplink noise power and P_{PD} is the combined photodetector noise power (shot, dark current, and thermal) in the satellite bandwidth.

III. OPTICAL SATELLITE LINK TRANSMITTER

A laser source, a modulator, an antenna alongwith some basic data handling electronics are the main constituents of the transmitter part of an optical satellite link. Infact this optical transmitter is quite analogous to its RF counterpart.

3.1 LASER SOURCE SELECTION

A variety of sources used for this type of communication system. Gas lasers, solid state lasers and semiconductor lasers are the ones which are commonly used. Selection of laser source depends upon a number of factors which include propogation medium, link range, data and various platform limitations. Lasers extend from high powered, low efficiency, bulky devices to the smaller light weight GaAs (gallium arsenide)[3] solid state diodes. The satellite crosslink uses preferably the laser diodes because of their light weight. However, these laser diodes are arranged in the satellite payloads to form arrays so that the laser output source power increases as these are low powered devices (output power on the order of tens of milliwatts). During 1977-1980 laser space communication with CO_2 lasers and Nd: YAG laser[4] were also successfully carried out. However, with the advancement in technology it is confirmed that semiconductor laser sources are the ideal light sources for optical space communication due to their small size and weight, high efficiency and reliability. In addition to this, semiconductor lasers are easily modulated by direct current injection. These laser diodes have a long potential life of approximately 10^5 hours. The main advantage of the laser diode is the limited power per diode so that most applications require the use of diode arrays, leading to the beam combing problems. The technique of coherent combining has been developed with the gelp of integrated optics technology, thus increasing the power in the beam while decreasing the beam divergence. Monolithically fabricated laser array designs have further solved the above beam divergence problem.

3.2 LASER MODULATION

In laser space transmission the most preferable mode of modulation is the direct intensity modulation. The driving current of the laser is the varied in accordance with the type of modulation required. Direct modulation of light via the sources drive current causes dynamic effects on the enitted spectrum like those of changes in the peak wavelength and in laser modes. The latter effect is particularly strong in monode laser.

Other light sources (such as gas lasers) may not be capable of being modulated at all. This makes external modulators attractive. Solid state lasers such as Nd: YAG which are capable of achieving a modulation rate of more than 1 Gbits/s also require an external modulator. The external modulators utilize miniature guiding structures (integrated optics) and operate with much less modulating power. A variety of effects such as elctro-optic, acoustic optic, magneto-optic have also been employed in a number of configurations (channel waveguides, planar wave guides,etc.) to realize modulation.

Corresponding to the RF communication systems, laser communication systems also utilize antenna to point the transmitted energy. These are used as conventionally designed telescopes where the size and geometry are taken into account and dictated by the wavelenght and system requirements. As a result of this optical communication systems require narrow light beamwidths (fractions of a degree) instead of antenna gain patterns of several degrees needed by RF systems. Lensing system for beam transmission and focussing is also provided instead of RF antennas. However, in actual practice the optical antenna system design is quite complex. The system combines the diode beams using a focal telescope with the cassegrainian structure[5]. Perfect collimation is achieved with the help mirrors.

IV. OPTICAL SATELLITE LINK RECEIVER

Similar to its RF counterpart, the optical receiver has an antenna, filter, photodetector, and then a conventional receiving electronic system. The main purpose of receiving antenna telescopes is to focus the optical signal on the photodetector and to reject a practically possible amount of background readiation. The interference filters (generally known as receiving optical filters) are required for the elimination of background radiation which is of different wavelength relative to optical. As a amtter of fact, optical wavelength is refered to as that range wavelength which lie in the neighbourhood of the actual laser wavelength. Typical optical filter bandwidths at 1 micron generally range from 10-100 angstroms (1 angstrom= 10^{-4} microns) corresponding to an equivalent frequency bandwidth of about 10^{11}-10^{12} Hz (100-1000 Hz).

Optical detections are mainly of two types, namely the direct detection system and the hetrodyne system. Direct systems are the ones which are most widely used and are in direct association with the signal intensity. On the contrary, hetrodyne systems consist of a local oscillator which combines the laser beam with the signal and then focus it on the detector. These are primarily used in the far-infrared region and they respond to signal amplitude. The photodetector converts quantum mechanically the light radiated on it to into photoelectron current flow. Various lenses focus the received light on the photodetector. The photodetector detects the instantaneous field power of the focussed field on it. Since the amount of field power focussed onto the detector is equal to the amount of field power incident on the focussing lens so the photodetected power can be equivalently computed by determining receiving field power over the lens area instead of focussed field power over the detection area. Photodetector usually used in optical detections may be a PIN diode or Avalanche diode (APD). These are governed by their characteristic properties such as detection efficiency, gain, responsivity, and bandwidth. The fraction of received power is indicated by the detection efficiency. It is wavelength dependent. It also varies in accordance to the material used in photoemmissive surface. Its value lies in the range 0.15- 0.90 for visible frequencies but reduces rapidly at the higher wavelengths (lower frequencies).

The bandwidth of photodetector is different than the optical bandwidth. The photodetector bandwidth actually determines the rate of variation of power which can be detected. It indicates the highest frequency at which the power can be varied and have the variation detected by the output current. Typical bandwidth is usually 1-10 GHz. While using photodetector noise considerations are also to be taken into account. Dark current, shot noise and thermal noise current of the post detection circuitry are taken into account.

In hetrodyne detection system[6], the addition of a strong local field to receiving field(associated to the photonics of the system) takes place. As a result of this the photodetector responds to the inrensity of the combined field (laser plus background plus local field). In this case thelocal laser power is much larger than the received power so the photodetected response current may be given as

$$i(t)= RP_L + 2Rf_s(t)f_L(t)A_r + 2RP_b(t)f_L(t)A_c$$

Here P_L is the laser power over the detector area, $f_s(t)$ and $f_L(t)$ are the received loss and local laser fields respectively over the received area and $P_b(t)$ is the background power collected over the detector area common to both the local and focussed fields. It should be remembered that here A_r is the area corresponding to receive lens and A_c is the area on the photodetector. From the equation it is evident that the local power laser plays quite an important role. It governs the average current and therefore the shot noise spectrum. The detection takes place for the product of incoming (modulated) laser field and the local laser field. This enables the modulation system for the satellite transmitter to use a variey of modulation techniques other than intensity modulation such as phase modulation, frequency modulation and amplitude modualtion. Thus in hetrodyne system a difference frequency term (corresponding to the difference in frequency of transmitting laser and the local laser) is generated which is set to an RF frequency ans further demodulation is carried out by conventional methods. By focussing the local laser, the effective detector area can be reduced that will cause an equivalent reduction in the receiver field of view. Therefore the hetrodyne receivers receive less background noise and compared to that in direct detection receivers. Also the laser power acts like detector gain in reducing the effect of post detection noise. Hence high-gain photomultipliers are not required in hetrodyne receivers. Furthermore, the background noise is also reduced and all these make the hetrodyne system quite apt. However, the overall design is quite complex. It should be noted that it is essential for the amplitude distribution, polarization and phase of the local oscillator beam are matched to the signal beam. Because of these main reasons this system is not usually used in optical laser communication crosslinks.

V. BEAM ACQUISITION, TRACKING AND POINTING

A narrow transmitting beam is required. It would then have maximum power spectrum. However, this extreme narrowness in the beam creates beam pointing problems. It is very important for the beam to be correctly pointed towards the receiving satellite otherwise the communication link will get disrupted. Some pointing error may be allowed (normally in microradians). This problem is not faced with rf systems because their bandwidths are much wider. It is therefore clear that to determine pointing error, the transmitting satellite must illuminate the receiving satellite as accurately as possible. Also, its own altitude should be taken into consideration as accurately as possible so that it may aim its beam at the known direction correctly.

5.1 BEAM POINTING

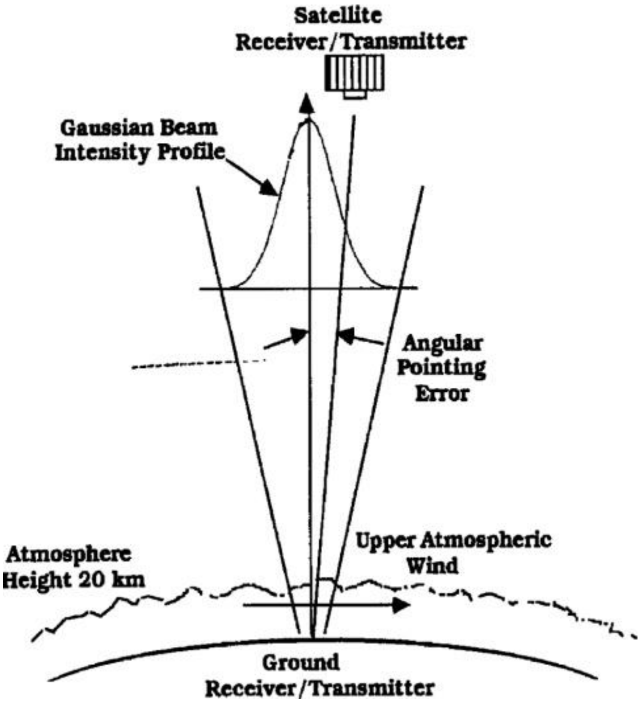
For obtaining the correct required information regarding the receiving satellite's location, the use of an optical beacon which is basically an unmodulated light source, is transmitted from the receiving end.The transmitting satellite first receives the beacon from the receiving satellite and then transmits the its modulated laser beam back to the receiving satellite. Thus the receiving satellite's location can be aptly obtained and the pointing error can be significantly minimized.

5.2 POINT-AHEAD ERROR

However, there might be a situation in which the transmitting satellite has received the beacon but before it could transmit the laser modulated beam, the receiving satellite may move out of the transmitter's beamwidth (transmitted beamwidth is kept nearly equal to twice the pointing error). In such a situation it is necessary to know the angle by which the receiving satellite has moved ahead (or back) of the transmitting satellite. This angle of drifting of the receiving satellite is called point ahead angle.Thus if the tangential velocity of the receiving satellite is V_T meters/sec, then the point ahead angle is given as

$$A = V_T / 150 \text{ micro radians}$$

In case the above point ahead angle exceeds the one half of the laser modulated beam's beamwidth then the use of this angle is being made. It is clear from the above equation that the point ahead angle is independent of the the distance of optical satellite cross-link. For velocities at earth orbiting speeds, the point ahead angle is approximately equal to 200 micro radians.



5.3 TRACKING METHOD

In case the optical beacon is to be used both the transmitting as well as the receiving satellites would have optical transmitters and receivers. Tracking of the arrival of the beam direction and adjustments are made in the transmitted beam direction. A number of different wavelengths are put to use in this case. Here, there is no requirement for the point ahead knowledge and the receiving optics of the signal is handled by the transmitted beam itself. However, in some cases point ahead angle comes into play in which the command control needs to be utlized in order to alter the direction of the transmitted beam in accordance with the receiving beam. This requires an accurate satellite attitude control.

With above discussions it is evident that before proper optical data transmissions, the transmitting antenna must acquire the beacon from the receiver. This beacon is transmitted from the receiving end with a beamwidth wide enough to cover the uncertainty angle of the beacon-receiving satellite. Once the beacon has been acquisitioned the satellite continuously tracks LOS (line of sight vector) of the arriving beacon since the latter may vary due to the relative motion. In case the point ahead is needed, the satellite laser transmitter must point ahead by the proper angle and direcion. In many cases commands for the point ahead are delivered from the earth stations through RF or microwave links.For this it is essential that the earth station accurately knows the instantaneous V_T and also it is accurately transmitted to the satellite. The satellite returns the position of the reverted beam after the LOS is tracked and the ddetermination of the point ahead angle is complete.

Though the above steps may be carried out carefully and efficiently, even then some errors might be present. These might be due to altitude reference errors in the satellite, mechanical and structural variations, boresight errors, etc. However, the contributions of these errors are quite small. The contribution due to vibration and boresight errors is generally below microradians but the error due to altitude control may be high. It is therefore important to have proper altitude control in order to eliminate altitude errors upto a significant amount and to achieve greater pointing accuracy.

VI. CONCLUSION

With the significant error reduction in point ahead angles and the elimination of laser noise, laser satellite technology provides a vast scope for improvement in the data transmission sectors. Effective transmission techniques such as point-to-point transmission, mass transmission, etc. have also been enhanced due to the introduction of laser communication. Another important characteristic of this method is that the big data can be handled with care. Large and complicated data signals such as high quality picture transmissions and audio signals with higher frequencies can also been received due to the high beamwidth of the laser. A number of modulation techniques are being used to conjust the big data in the form of laser transmission signals.

Furthermore, the work in this sector also lays emphasis on laser divergence problems and beam pointing problems. As discussed earlier, the beamlength is kept twice the pointing error. This reduces significant effects of divergence and tries to concentrate the maximum part of the beam on the receiver. However, research is still under progress in completely removing divergence problems.

Even after the elimination of these errors, some errors might be present. These might be due to altitude reference errors in the satellite, mechanical and structural variations, boresight errors, etc as discussed earlier. However, the contributions of these errors are quite small. It is therefore important to have proper altitude control in order to eliminate altitude errors upto a significant amount and to achieve greater pointing accuracy. A number of research organizations use high altitude laser transmission devices and tackle these problems with the help of complex equipment. For example, the transmission end might have a long metallic tube around the laser source and it may extend up to a few meters in order to make the beam focus on the receiver.

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