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LAMP
SERIES REPORT
(Laser, Atomic and Molecular Physics)

OPTICAL SPACE COMMUNICATION:
AN OVERVIEW

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MIRAMARE-TRIESTE

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OPTICAL SPACE COMMUNICATION: AN OVERVIEW

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ABSTRACT

In this paper, importance of the optical space communication has been highlighted. Its merits and demerits over the conventional microwave system has been presented. In contrast to coherent systems, use of an optical preamplifier in direct detection system has been emphasized. Status of some of the ongoing/future space communciation projects has been given.

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Preface

The ICTP-LAMP reports consist of manuscripts relevant to seminars and discussions held at ICTP in the field of Laser, Atomic and Molecular Physics (LAMP).

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1. Introduction

With the advent of laser in 1960, unguided optical communication systems were the subject of a great deal of research and development activity between 1960 and 1970. In the year following 1970, major efforts were directed towards the guided propagation of optical signal through the optical fiber and the study of unguided systems remained somewhat neglected. The main reason for this neglect was that scientists were not hopeful of a significant role that these unguided system could play in future terrestrial and space communication systems. These unguided systems will have an advantage over the guided systems when one or both of the terminals has to be mobile. Also in short links between buildings or over difficult terrains where cable can not be run conveniently. For these applications, optical channel for communication has been the atmosphere. With the development of interest in high capacity long distance links, communication in free space by optical means has become more and more attractive. At present, several projects on space communication around the world are underway and shortly such links are expected to be operational [1].

In this paper, potential applications of optical space communication system have been highlighted. Various space communication techniques have been described and a comparative

study with the currently used microwave technique has been made. Some results on the use of an optical preamplifier in optical space communication has been presented. Finally, status of some of the ongoing/future optical space communication projects has been given.

2. Potential Applications

The potential applications of optical space communication are following (refer to Fig.1):

(i) Intersatellite Link (ISL) - It is used for a link between two geostationary earth orbit (GEO) satellite/spacecrafts. Most of the time, these satellites are communication, TV broadcast or data relay satellite (DRS).

(ii) Interorbital Link (IOL) - It is used when two satellites/spacecraft are on different orbits; in practice one orbit is the geostationary one and the other is a low earth orbit (LEO). The forward link (GEO - LEO) only demands telemetry data rates of about 25 MBPS, while the return link (LEO - GEO) requires high data rates of the order of 500 MBPS. The maximum distance involved is about 84,000 kms (defined by the geometry), but a more practical value is 45,000 kms for ISL and 42,000 kms for IOL.

(iii)Deep Space Mission (DSM) - It provides high capacity data transmission link between planets such as Mars or Saturn (78 million and 1278 million kms from the earth respectively) to a geostationary earth satellite.

3. Space Communication Techniques

There are two techniques for optical space communication: direct detection and coherent detection. Direct detection (DD) optical systems, though poorer in sensitivity are quite easy to implement. Because of this, majority of optical communication systems currently operational employ direct detection/noncoherent detection technique. However, recent advances in optical technology have made the concept of coherent detection feasible. The required optical power level for a given data rate and performance depends upon the receiver structure which, in turn, depends upon the type of modulation and demodulation scheme used. If it is intensity modulation, a simple receiver structure known as noncoherent or direct detection can be used. However, if the digital modulation schemes like PSK, FSK etc. are employed, coherent receivers viz. homodyne (for PSK) and heterodyne (for PSK and FSK), which are much more complex than the direct detection receiver has to be used. Coherent receivers have significant advantages over the noncoherent receivers in regards to the receiver sensitivity, data rate, transmission distance. But their practical implementation is quite difficult. In view of this, direct detection systems are still considered to be more suited for space communication inspite of rapid development in the coherent technology during the last decade.

Most of the differences between an optical and a microwave space links are due to difference in the wavelengths. As shown in Fig.2, the much shorter optical wavelength results in a very small beamwidth and a very small spot size. The spot size of an optical beam transmitted from planet Mars is only about 10 percent of the earth's diameter, whereas in case of microwave beam, it is about 100 times of the earth's diameter. The small spot size of an optical beam results in an increased received power and, therefore, improvement in the receiver performance. Further, higher antenna gain achieved at the optical frequency ($\approx 1/\lambda^2$) allows to (i) decrease the antenna (telescope) diameter, (ii) increase the data rate and (iii) increase the transmission distance which can, for example, reach millions of kms in space.

The use of a coherent system offers the receiver sensitivity gain of more than 10-15 dB. It may be noted that a sensitivity improvement of 6 dB doubles the transmission distance (for example 30 million kms with a direct detection system becomes 60 million kms with a coherent system). The great improvement in transmission distance is particularly attractive for the long-range space links in deep space missions. In addition to this, a coherent optical system requires much less power than a direct detection system for a given requirements. Therefore, it offers the power consumption of satellite, which is quite important. Further, the influence of background noise (example of such sources are : stars, planets, sun etc.) in coherent system is lower than a direct detection system.

Clearly, in choosing a satellite communication system, minimization of the overall weight and power consumption is of utmost importance. Thus, the narrow beamwidth which can be obtained with an optical system using antenna of modest aperture may be thought to give an advantage. At present, microwave links (at wavelength of 5-10 mm) are used for space applications because of their proven reliability, their high transmitter efficiency and low receiver noise level. However, both frequency - double neodymium and carbon dioxide lasers have been considered for the intersatellite links and must be possible contenders for future systems.

Unfortunately, the small beamwidth as the main advantage of optical space communication system is also

responsible for main disadvantage. As seen in Fig.2, small satellite vibrations can result in a total optical link break. The very small beamwidth complicates pointing, acquisition and tracking. Therefore, high accuracy and high speed pointing acquisition and tracking (PAT) subsystems are required to reduce the influence of satellite vibrations. In coherent optical communication system, doppler frequency shift (≈ GHz) as a result of the relative motion of two linked satellite is a problem. This problem can be tackled by including a tuneable local laser with a tuneable range of about 20 GHz and a automatic frequency control (AFC) in the receiver circuit. The other problem associated with the direct detection and coherent receivers is the availability of the components at the low optical wavelengths used in optical space communication systems (for example 532 nm wavelength).

The microwave channel differs from the optical channel because of the quantum nature of light. A microwave transmitter produces about 10^{24} photon/s, each with an energy of about 4×10^{-24} J whereas an optical transmitter produces about 10^{15} photon/s, each with an energy of about 2×10^{-19} J. The thermal background noise at the receiver is described by the distribution

$$N_{\upsilon} = \frac{h\nu}{\exp(\,h\nu\,/kT_{\upsilon}\;-1)} \qquad (1)$$

where h is the Plank's constant, ν is the operating frequency, k is the Boltzmann's constant and T_0 is the reference temperature.

Since $h\nu \ll kT_0$ in the microwave receiver, the noise spectral density from (1) will be kT_0 or about 4×10^{-21} W/Hz. Thus, each microwave photon has considerably less energy than the background thermal noise. In the optical receiver, since $h\nu \gg kT_0$ energy of each photon is very much greater than the thermal noise. As a consequence, the thermal noise is a limiting factor in microwave channels, but it is not in optical channels [3].

Block diagrams of microwave and optical communication systems with typical values of the transmitting power and antenna gain are shown in Fig.3. The intermediate frequency (IF) signal-to-noise ratio (SNR) for microwave receiver is given by

$$\frac{S}{N} = \frac{P_R T}{kT_0} \qquad (2)$$

where P_R is the received signal power, T is the bit duration. The corresponding expression for a coherent (heterodyne) optical receiver is given by [5]

$$\frac{S}{N} = \frac{P_R T}{h\nu} \qquad (3)$$

A comparison of (2) and (3) reveals that the thermal noise kT_0 in microwave system corresponds to the quantum noise $h\nu$ in optical system. This analogy is not surprising. It is well known from thermodynamics that kT_0 and $h\nu$ are the two limiting forms of the power spectral density (psd) of an oscillator at frequency ν and at temperature T_0. When $kT_0 \gg h\nu$, thermal noise dominates and when $h\nu \gg kT_0$, quantum noise dominates [5].

In optical communication systems, thermal and other noise like optical preamplifier noise may become comparable with the quantum noise. In that case, an additional parameter, F called noise figure (NF) of the receiver will come in the denominator. It varies from 1 to ∞. Lesser is the NF, better is the receiver performance. Effect of an optical preamplifier in an optical receiver in terms of change in NF (decrease in NF implies improvement in the receiver performance and vice versa) has been described in section 4.

Variation of antenna aperture diameter and terminal weight with data rate for microwave and optical communication systems are shown in Figs.4 and 5 respectively. It is infer from these figures that use of optical technology in space communication offers a tremendous reduction in antenna diameter and weight as compared to microwave system. This is quite promising for satellite communication [6].

4. Optical Amplifier In Space Communication

In space communication, strength of the received signal can become considerably small due to increase in the transmission distance. In such cases, use of a semiconductor (SC) optical preamplifier in the receiver may be of great help. The SC optical amplifiers are of two types: Fabry-Perot amplifier (FPA) and travelling wave amplifier (TWA). In a FPA, the amplifier output consists of a central longitudinal mode at a certain wavelength - the amplified signal - surrounded by a dozen or so weaker components of amplified spontaneous emission (ASE) 0.5 to 2.0 nm apart created by the other longitudinal mode resonances within the cavity. When the amplifier output is detected by a photodetector, it will produce signal - ASE and ASE - ASE beat noise components. In a heterodyne receiver, there will be an additional LO-ASE beat noise component. In a TWA, ASE-ASE beat noise component is spread over a wide continuum instead of being concentrated in discrete modes [7].

The author has carried out a detailed analysis of optical preamplifier in direct detection and coherent (heterodyne) receivers [8]. For the analysis, power associated with different beat - noise components has been evaluated and these are used to

determine the receiver NF. Variations of NFs in terms of change in the amplifier gain (for a fixed background noise) and back - ground noise (for a fixed amplifier gain) have been studied. Some of the important results of the analysis are following:(i) Use of an optical preamplifier in a heterodyne receiver will not give any advantage unless local oscillator power is low. Whereas in a direct detection receiver, it may improve the receiver performance considerably. The level of improvement will depend upon the received signal power level and it may be more than 20 dB, (ii) The NF of a heterodyne receiver is always better than the NF of a direct detection receiver irrespective of background noise and use of an optical preamplifier in the direct detection receiver and (iii) Background noise degrades the performance of both heterodyne and direct detection receivers. Degrading effect of background noise is relatively more in a direct detection receiver.

6. Present Scenario

Status of some of the ongoing/future optical space communication projects is as follows:

(i) LITE 'Laser Intersatelite Transmission Experiment'. This project is being executed by MIT - LL /Airforce, USA. The aim of the project is to establish a GEO-

Earth optical link at 860 nm (GaAlAs) wavelength. It will employ 4-FSK modulation scheme and coherent heterodyne receiver. The data transmission rate is 110 MBPS. The link was originally planned to be operational in 1991. But due to some reasons, it has got delayed.

(ii) LCE 'Laser Communication Equipment'. This project is to be executed by PTT Japan. The objective of the project is to establish a bidirectional optical link between ET6 (GEO)-Earth. The forward GEO - Earth link will operate at 830 nm, while the return Earth - LEO link at 510 nm. It will use OOK signalling scheme and direct detection receiver. The data transmission rate is 1 MBPS. It is likely to be operational in 1993.

(iii) SILEX 'Semiconductor Intersatellite Link Experiment'. This is to be executed by European Space Agency (ESA) and the aim of the project is to establish a bidirectional optical link between the French earth observation spacecraft SPOT - 4 (LEO) and ESA's technology mission spacecraft ARTEMIS (GEO). The link will operte at 850 nm and employ OOK signalling scheme and direct detection receiver. The data transmission rate is 50 MBPS. It is likely to be operational in 1994 [9].

(iv) SOLACOS 'Solid State Laser Communication System'. This project is to be executed by different German companies and research organizations. It is in continuation of the ESA's project Nd:YAG Systems which has been cancelled. The project intends to build up a coherent optical 50 MBPS breadboard system ready for future GEO - LEO applications

7. Conclusions

Optical space communication systems show many advantages over the conventional microwave space systems. In near future, it will be feasible to design high capacity long - range optical communication links and optical technology will enter in a big way in space communication.

8. Acknowledgement

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Figure Captions

Fig.1: Applications of optical space communication systems.

Fig.2: Beamwidth of microwave and optical signal transmission from Mars to earth.

Fig.3: Block diagram of microwave and optical communication systems.

Fig.4: Variation of antenna aperture diameter with data rate for microwave, direct detection and heterodyne receivers.

Fig.5: Variation of weight with data rate for microwave and optical communication systems.

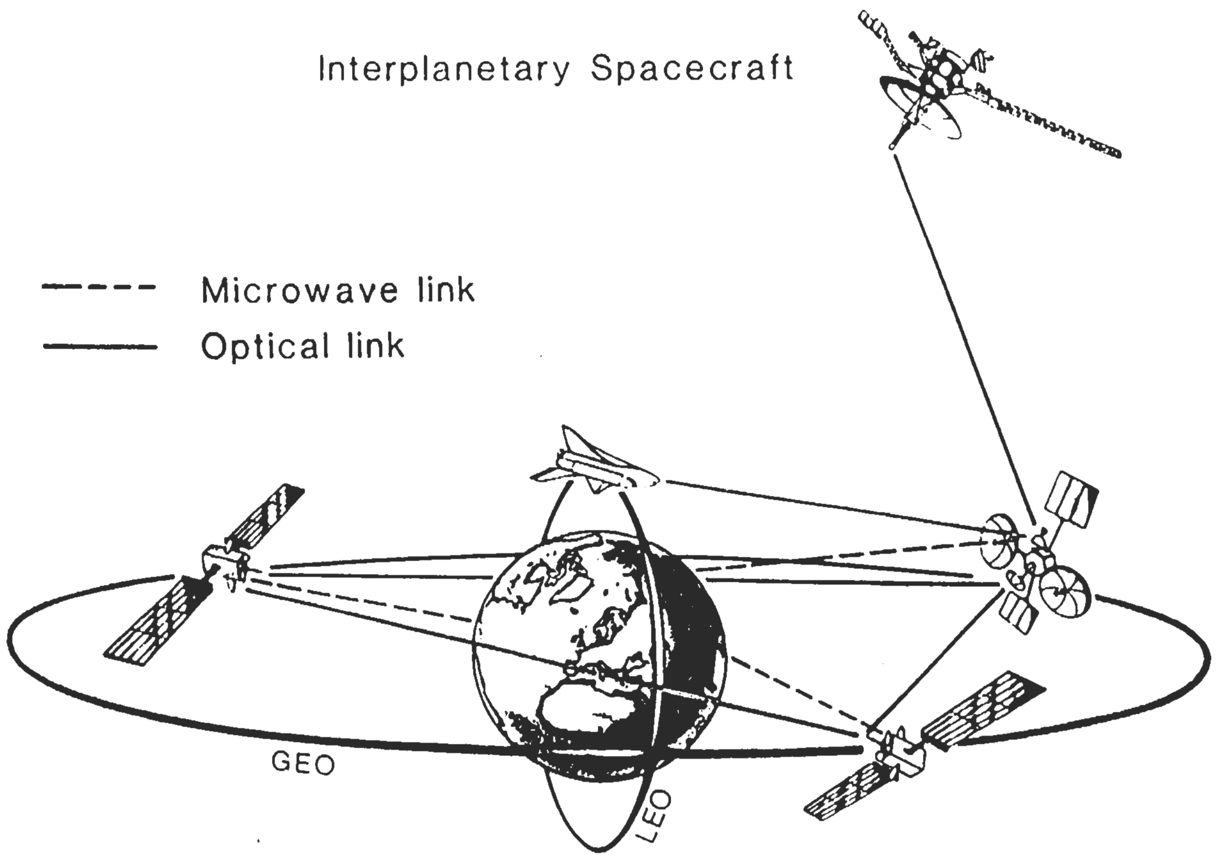
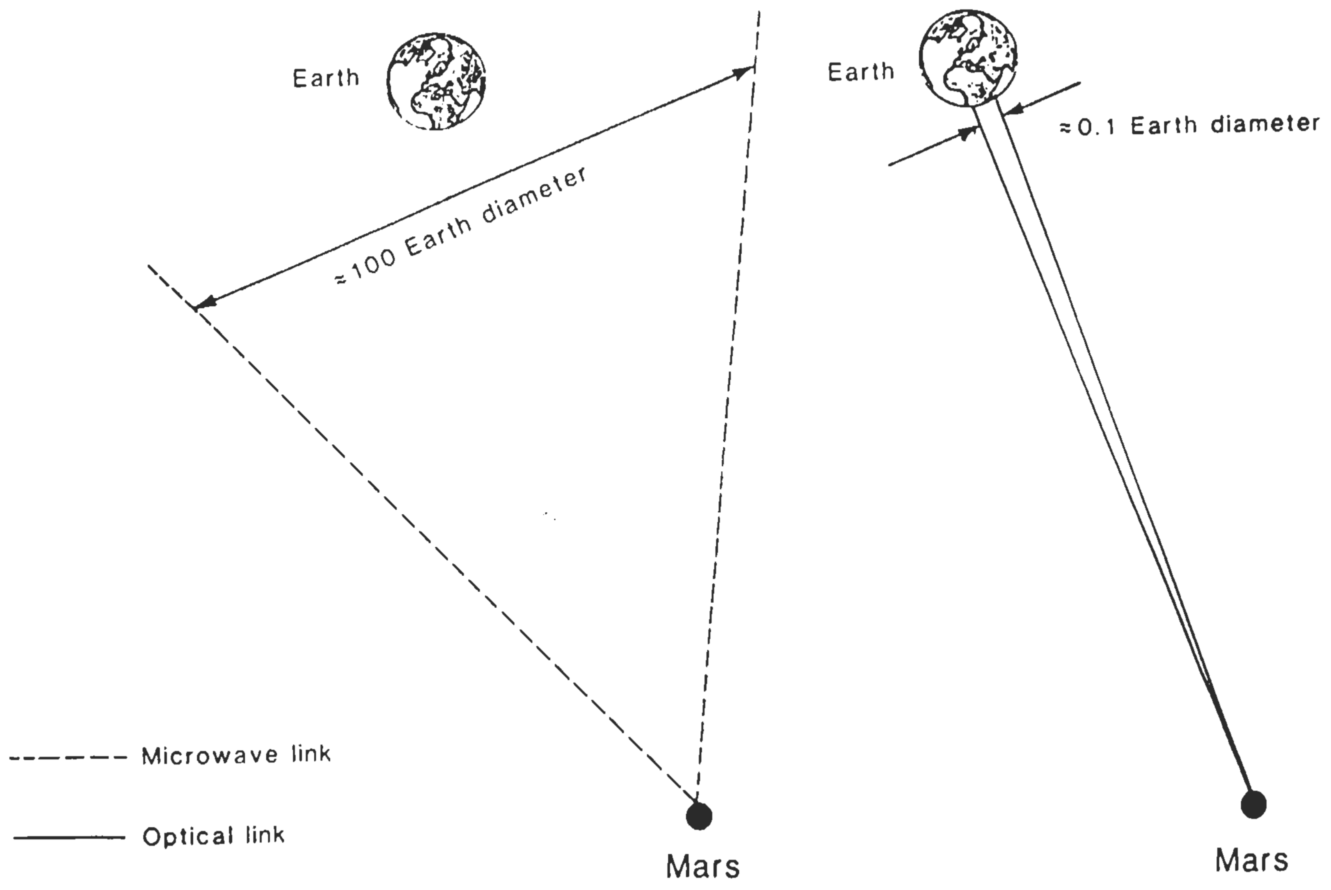

Interplanetary Spacecraft
Microwave link
Optical link
GEO
LEO

Fig.1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≈100 Earth diameter
Earth
≈0.1 Earth diameter
Microwave link
Optical link
Mars
Mars

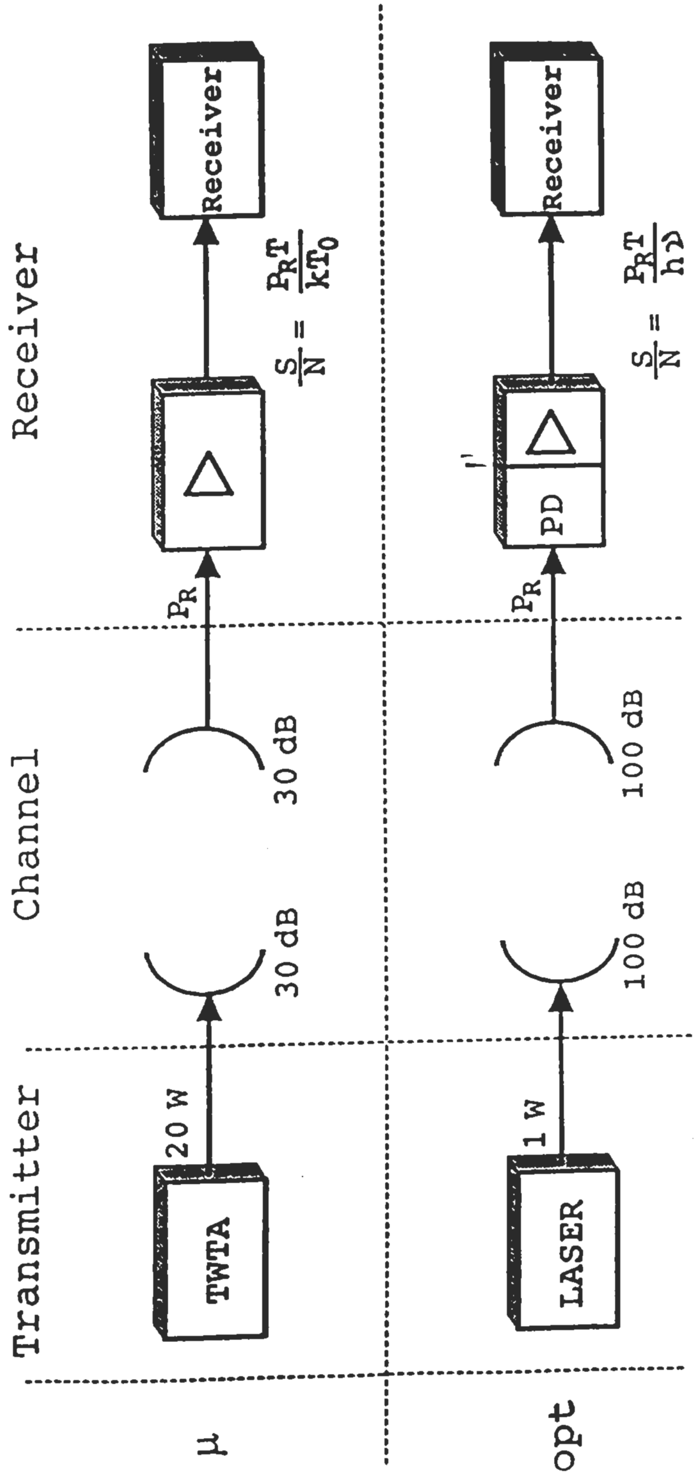

Fig.3

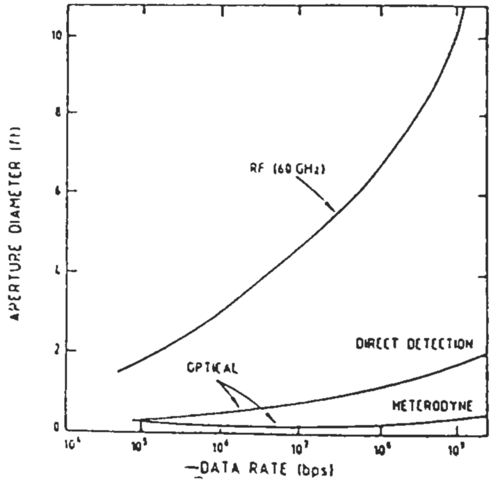

Fig.4

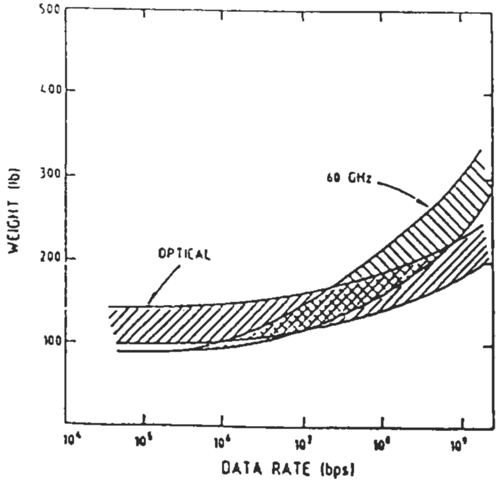

Fig.5