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Satellite laser communication networks – A layered approach

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Abstract – With high speed space optical crosslink being a reality, the construction of an satellite laser communication network as part of a larger integrated space-terrestrial network is now feasible. The use of multigigabit laser intersatellite links is the enabling factor for routing traffic through the space segment and creating a global space based optical backbone network. This paper examines the characteristics of these networks and a layered approach to satellite laser communication network is introduced that consists of Low Earth Orbit (LEO), Medium Earth Orbit (MEO), and Geosynchronous Earth Orbit (GEO) satellites. The performance of the satellite laser network can be improved drastically if multiple satellite constellations are used in the architecture.

Key-Words: - Optical space communication, satellite communication, satellite networks, wavelength division multiplexing, LEO, MEO, GEO, LASER

1 Introduction

The broadband applications driven by data traffic demand are emerging as the key business driver for satellite constellation [13]. Also data can be routed through the space segment of the network using intersatellite links (ISL), until it reaches the satellite that covers the area where the destination user is located .

This paper builds on the premise that optical space communication at very high rate (> 10Gbps) between satellite is now feasible [1 -16]. Till now the primary links through the atmosphere are assumed to be microwave due to poor optical propagation in bad weather conditions . However we will describe technologies for special applications where optical downlinks from satellite to airborne and ground terminals are viable if absolute all weather availability is not required.

Optical intersatellite links are considered as the enabling technology to satisfy the increasing traffic demand at ISL constellations [14]. At Gbps data rates, optical ISL terminal clearly outperforms their microwave counterparts in terms of required dc power consumption, mass and size which is critical importance for space borne applications .In this case, the constellation can be seen as a fusion of microwave access nodes and a global optical backbone network.

This paper summarizes briefly the state-of-the-art of optical cross link technology examines architecture that combines other technologies to form an integrated space and terrestrial network.

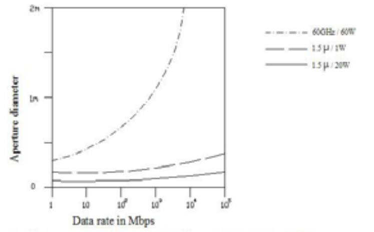


Fig1: Cross link aperture size for RF and optical link with geosynchronous range

The rest of the paper is organized as follows. An overview of optical crosslink technology is presented in section 2. In section 3, the constellation physical topology and traffic demand are presented. Section 4 analyzes a novel solution for the optical satellite network- a multilayered approach. The main conclusions are given in section 5.

2 Optical crosslink technology

The first cross links are microwave systems. The geosynchronous-orbit MIT Lincoln experimental satellites (LES) 8 and 9, launched in 1979, were the first with a 38GHz radio frequency (RF) crosslink . Currently the NASA tracking and data relay satellites systems serves manned space explorations and science experiments with both medium (~300Mbps) and low(~1Mbps) rate access links. The cost of integrating, launching, and deploying a communication antenna or telescope is a strong function of size and is a major design driver for satellite applications.

The design issue is especially important for backbone relay satellites. Since the beam divergence of an RF or optical beam is roughly proportional to λ/D, where λ is the wavelength and D is the aperture diameter. Optics have much higher antenna gain and can project the modest transmitter power into a smaller area at the receiving satellite, allowing much higher data rates. Fig. 1 Compares cross link aperture size for a link distance equal to one time synchronous orbit, taking into account current and reasonable projection of transmitter power amplifier technologies.

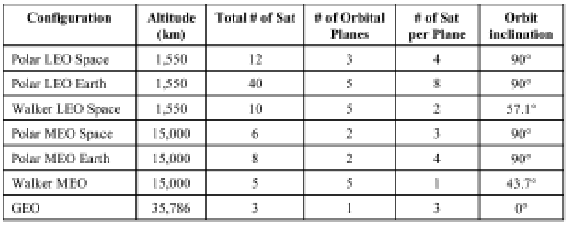
The good Properties of optical cross links with the following general characteristics, for high rates such as 10 Gb/s [16] is given below.

i. Small antenna size (< 30cm), Compared to several feet for RF system.
ii. Less weight (≈ 100 lb) and power (≈100W) compared to several hundred pounds and several hundred watts for RF system.
iii. Easy Multiplexing, demultiplexing, switching and routing for network applications
iv. Much lower cost than RF.

Since the carrier frequencies of optics are very high (≈200 THz), each optical carrier can accommodate very high data rates(≈100Gb/S) without the dispersion effects of fiber, and there is the possibility of using wavelength division multiplexing (WDM) to further increase the data rate per optical beam. Hence the optical cross link technology will greatly revolutionalize space system architecture.

3 Satellite constellation Networks

The use of low, medium and geosynchronous earth orbit for the constellations (LEO, MEO and GEO) ensures very low earth-to-space-to-earth Propagation delay (below 20ms for LEO), enabling satellite networks to offer transmission quality.



Configuration	Altitude (km)	Total # of Sat	# of Orbital Planes	# of Sat per Plane	Orbit inclination
Polar LEO Space	1,550	12	3	4	90°
Polar LEO Earth	1,550	40	5	8	90°
Walker LEO Space	1,550	10	5	2	57.1°
Polar MEO Space	15,000	6	2	3	90°
Polar MEO Earth	15,000	8	2	4	90°
Walker MEO	15,000	5	5	1	43.7°
GEO	35,786	3	1	3	0°

Table 1: satellite constellation

Comparable to that of terrestrial fiber optic systems . To assess the suitability of optical networking techniques, the underlying network physical topology and the network traffic demand have to be analyzed.

3.1 Network physical topology

Satellite constellations follow strict configurations design rules to achieve the desired ground coverage with a desired ground terminal minimal elevation angle using the minimum possible numbers of satellites [15]. Constellation network consists if

- N satellite nodes placed in a grid configuration with 'n' orbital rings and m satellites per orbit (N = m.n). The number of satellites varies from about few in GEO, 10 in MEO to more than 100 in LEO. (See table 1). The satellite motion is deterministic, periodic and therefore predictable.
- ISLs that represent the network links. Usually four ISL terminals per satellite are sufficient to guarantee network connectivity. Two types are distinguished.

i. Intra orbit ISLs interconnect satellites belonging to the same orbit. The ISL range and pointing remain fixed in time.
ii. Interorbit ISLs Interconnects satellites belonging to different orbits, which shift relative to each other. The Interorbit ISL range changes periodically between a minimum and a maximum value. Interorbit ISLs represents the biggest Challenge in terms of ISL terminal implementations, as a continuous and accurate pointing of the counter terminal is required. More over they experience Doppler shift that

has to be compensated for at the receiver [20]. Laser ISLs can be maintained permanently throughout the orbital movement of the satellites. Although satellites move continuously at speeds exceeding 20,000 km/h, the geographic topology of the network changes in a periodic and, therefore deterministic fashion resulting in a network physical topology that appears to be maintained fixed.

The Complexity of the system can be quantified with various parameters; coverage requirements, Constellation altitude, number of orbit, number of satellites required per orbit and number of required ground gateway stations . An interesting benefit of a freespace link is that when the traffic load shifts, the physical connections topology can be easily changed via pointing the telescopes to a new satellite, and load balancing can be implemented more easily.

3.2 Network traffic demand

The traffic demand in satellite constellations changes rapidly due to the rapid motions of the satellites. The connection traffic matrix changes are even more intense since they reflect the geographic coverage changes of both the source and the destination satellites . At present no real traffic data exist. Next some basic parameters for approaching problem are reported.

i. Teletraffic approximation:

The average distance between the network Pair (in number of ISLs) is

$$h_{av} = 1/(N-1) \,.\, \sum_{n=1}^{n=d} h.N_h \qquad (1)$$

Where N_n is the numbers of nodes that can be reached from a given starting node with h ISLs and d is the network diameter. h_{av} represents the average connections length Therefore the average number of satellites traversed by a connection is

$$h_{n-av} = h_{av\ -1} \qquad (2)$$

ii. End node Pair connection band width

The bandwidth requirement of each source –to- destination node pair connection will vary according to the satellites position in the constellation of each time instance and to the traffic type . Unfortunately, no data is available to describe the distribution of Internet traffic (which is expected to represent a large part of the traffic load) served by a global space based system. A recent study of the OECD analyzed the current internet traffic demand for terrestrial systems into member states [17].Based on the report the following general observations can be derived.

- At least 75% of the satellite uplink Capacity is local traffic that will be down linked by the same or neighboring satellites, that is, it does not generate transit traffic.
- At most 25% consists of long distance Connections, which results in transit traffic. The long distance type of traffic is of particular interest since it constitutes a major factor for considering optical networking techniques that allow by-pass of transit traffic. Next, long distance traffic will be considered as uniformly distributed among the nodes beyond the adjacent satellites.

iii. On-board Processor load: The total amount of traffic handled by the On-board processor (OBP), P_{OBP}, will be the sum of the Uplink / downlink capacity $C_{U/D}$ and the bi-directional transit capacity C_{TR}.

$$P_{OBP} = C_{U/D} + C_{TR}$$

$$= C_{U/D} + N_{TR}.C.C_{U/D} / N_{L-D}$$

$$= C_{U/D}\,[1+C.\ N_{TR}/\ N\ N_{L-D}] \qquad (3)$$

Where C is the Percentage of $C_{U/D}$ that generate long distance traffic. The term C. $C_{U/D}$ / N_{L-D} represents the capacity of long distance connections. A Key network design parameter is the percentage of the total OBP capacity that must be reserved for processing the transit traffic (P_{TR}) as a function of C. From equation (3)

$$\alpha = P_{TR} / P_{OBP}$$

$$= C_{TR} / [\ C_{U/D}+ C_{T\,R}]$$

$$= [C.N_{TR} / N_{L-D}] / 1+ C\ .N_{TR} / N_{L-D} \qquad (4)$$

The ratio of N_{TR} / N_{L-D} of the transit connections over the add drop long distance connections is

$$f = N_{TR} / N_{L-D}$$

$$\alpha = P_{TR} / P_{OBP} = f . C. / (1/+f . c) \qquad (5)$$

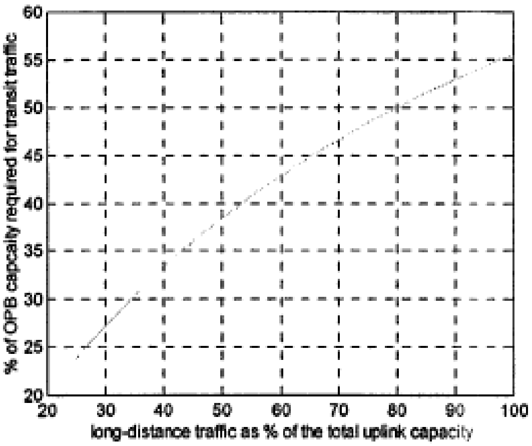


Fig2: Capacity required for processing the transit

Traffic (f = 1.25)

4. Multilayered satellite networks

4.1. Satellite layers

The Multilayered optical satellite network architecture is divided into three layers that each covers the entire globe.

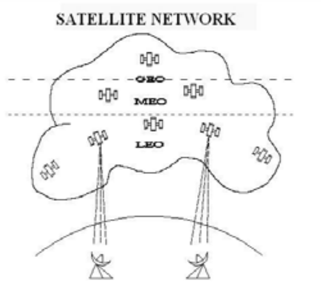


Fig.3 Proposed multilayered optical satellite link

i. GEO Layer: The GEO layer is composed of all GEO satellites in the satellite network. The total number of satellites in the GEO layer is assumed to be N_G, and they are organized as a belt above the equator.

ii. MEO Layer: The MEO Layer refers to the Collection of all MEO satellites in the Network. This layer is positioned at an altitude between the GEO and the LEO system. Assume that there are N_M MEO satellites. The constellation of MEO satellites can be arbitrary as long as global coverage is achieved at all times.

iii. LEO Layer: The LEO Layer consists of all LEO satellites in the network. This layer has the lowest among the three satellite layers. The LEO Layer contains N_L satellites we assume that the LEO satellite form a Walker star type [18] constellations.

Currently GEO, MEO, and LEO satellite Networks exists individually. As stated before, their layered network with light path will increase the capacity, reliability and Performance in global scale communication. A section of the proposed multilayered optical satellite Network is shown in fig3. The terrestrial gateways are covered by LEO, MEO and GEO satellites. Once the packets are sent to the optical satellite network, they are routed to the destination gateways independently over multiple satellite hops in possibly different layers. The routing decision inside the satellite network is isolated from the terrestrial network. Also the number of satellites in a layer decreases with the increasing altitude. Therefore we assume throughout the paper that $N_G < N_M < N_L$.

4.2. Logical location concept and satellite notation

In the satellite network, LEO and MEO satellite move with respect to the earth. In [19], the logical location concept was introduced to cope with the problems caused by the mobility of LEO satellites.

In this approach the entire LEO constellation is divided into grid points. The grid points are placed with equal angular distances. The LEO satellite closest to the center of a logical location is assigned to that logical location. When the satellite assigned to a logical location changes, the successor satellite must take the necessary routing information from its predecessor. The link adjacent to the predecessor LEO satellite is also switched to the new LEO satellite. To have a logical location concept it is necessary to form the satellite groups. The MEO satellite can be organized in an arbitrary manner as long as global coverage is provided at all times.

Similarly it is assumed that there are enough GEO satellites to provide global coverage.

A satellite in the GEO layer is denoted by G_i, similarly $M_{i,j}$ denotes a satellite in the MEO layer which is in the coverage area of the GEO satellite G_i. A LEO satellite $L_{i,j,k}$ is in the coverage area of MEO satellite $M_{i,j}$ and the GEO satellite G_i. In order to keep the notation simple, we will assume that satellites communicate with only one of the satellites of the same higher layer. Hence routing algorithms can be developed and generalized to include satellites maintaining links to multiple satellites of the same higher layer.

4.3. Links in the Network

As we discussed earlier, the satellites maintain three types of links. The communication with in a layer is accomplished over inter-satellite link (ISLs). The communications between satellites in different layers occur over inter-orbital links (IOLs). In our architecture IOLs connect each satellite with other satellites in its coverage area in the lower layers. The satellites in the lower layer maintain IOLs to satellite that cover them.

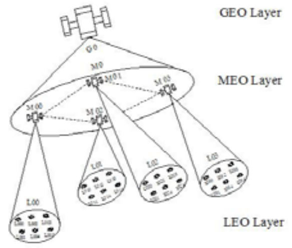


Fig4: Hierarchichal organisation of the optical satellite network

4.4 Satellite groups

In order to reduce the computational complexity in the satellites and the communication load on the network, the satellite network is organized hierarchically.

In this hierarchy, satellites are grouped and their management is given to a satellite in the upper layer. The hierarchical organization is used for routing. The data packets are forwarded independent of this hierarchy.

A sample grouping in the optical satellite Network is shown in fig 3, where a GEO satellite G_0 and satellites in its coverage area are illustrated. In this example, the LEO satellites are organized in four groups of size nine. The LEO and MEO groups have the same subscripts as their manager satellites. The LEO groups $L_{0,0}$ .....$L_{0.3}$ are Managed by the MEO satellites $M_{0.0}$…$M_{0,3}$ constitute the MEO group $M_{0,}$ which is managed by the GEO satellite G_0. Note that satellite in a given layer actually more in circular orbits at the same attitude, which form an imaginary sphere. The satellite layers depicted in fig 3 are projections of the convex surfaces created by the orbits to planar surfaces.

5. Conclusion

Next generation broad band satellite constellation can take advantages of the significant progress achieved in optical networking technologies. Two parameters for evaluating the feasibilities of an optical satellite networking schemes are used.

i. The number of wavelengths to be supported by each ISL terminal (limited Primarily by on board unit complexity).

ii. The total satellite ISL transmitting capacity.

Depending on the topology of the constellation and the above criteria the optical satellite network is designed to provide connections with minimum possible number of light path hops. The capacity of each light path has to be dimensioned according to the number of connections sharing it.

It is possible in clear weather conditions to communicate optically to a user terminal from space, especially if the terminal is located on a high-flying aircraft. It is also the only viable link to the space shuttle during its RF blackout period during reentry. The terrestrial fiber network acts as a backbone to tie together subnets of different modalities and allow the internet to behave as one single network. There may come a time when natural or man made disasters disconnect part of this network can serve as the alternate backbone to reconstitute a fully connected global network.

Hence optical satellite network with multilayered approach will likely be classified as one such transforming technology it its architecture implications are fully exploited. Not only will the layered optical satellite network become economically viable, but also its deployment and the extra-ordinary services it can offer are capable of radically transforming space system architecture.

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