OPTICAL SPACE COMMUNICATIONS AND NETWORKS

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ABSTRACT

Optical space communications is now a reality. It will be a key building block for wide-area space data networks of the future. This new technology will provide quantum-leap improvements to satellite network performance and cost and have profound transforming effects on space system architectures and applications.

1 INTRODUCTION

Optical free space communication will be a key building block for wide-area free space data networks of the future. Figure 1 illustrates the general concept of an integrated space-terrestrial network. Optical communication links can be used in satellite to satellite crosslinks, up and down links between space and aircraft, ships and other ground platforms and among mobile and stationary terminals within the atmosphere. This paper examines network architectures from the Physical Layer to the Application Layer that combine other communication modalities to form an integrated space and terrestrial network and explores the space of possible revolutions in network performance and applications that are enabled by such a key technology innovation.

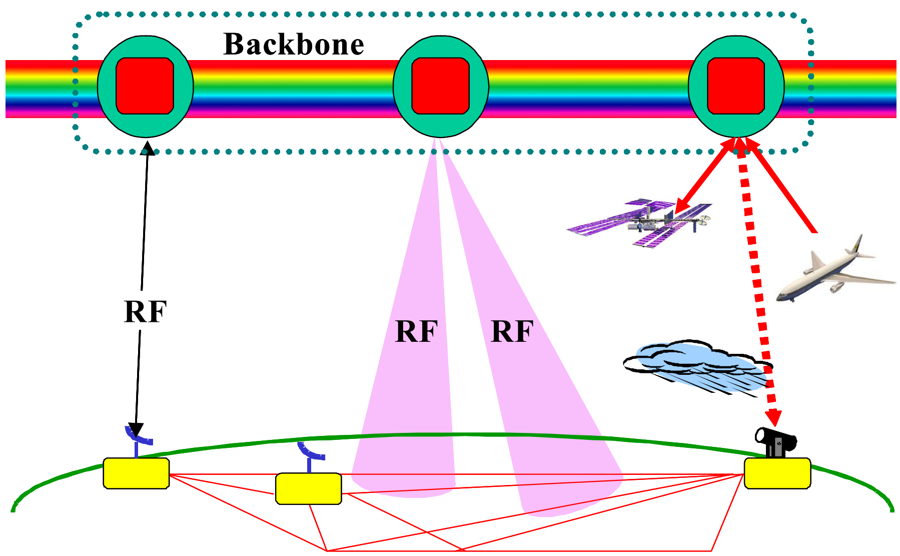

Figure 1. Integrated space-terrestrial network with intersatellite optical crosslinks and optical up and down links between satellites, ground and aircraft through clear air turbulence.

Figure 2 depicts logically the different optical and RF links that will be integrated together to form the space-terrestrial network of the future. The intersatellite link is a vacuum link with no channel impairments other than propagation loss. Error statistics are due to background and detection (including quantum) noise and are independent from symbol to symbol. The channel is predictable and can be treated as deterministic for the design of crosslinks.

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However, when the link includes part of the atmosphere, clear air turbulence (plus boundary layer turbulence in the case that one end of the link is on an aircraft) induces serious phase distortions and fading to the link. The channel must be treated as random with a significant memory for the design of the optical communication system and the integrated network. In addition, the propagation times are long compared to those of terrestrial links and the delay-rate product of these links will be very large compared to terrestrial links for which the Transport Layer Protocol, TCP, is designed. As a result, the network throughput can become very low (~1%) making the system not cost effective and competitive. Thus, the overall network architecture must be redesigned.

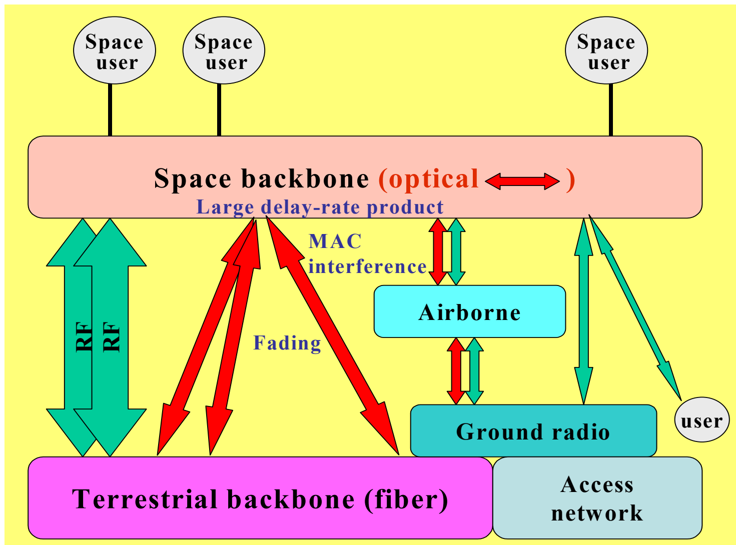

Figure 2. Logical network connection of different links in an integrated space-terrestrial network with major link properties that affect network performance and drives network architectures.

2 ENABLING OPTICAL CROSSLINK TECHNOLOGY

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 gains and can project the modest transmitter power into a smaller area at the receiving satellite allowing much higher data rates. Figure 3 compares crosslink aperture size for a link distance equal to one time synchronous orbit (44,000 Km).

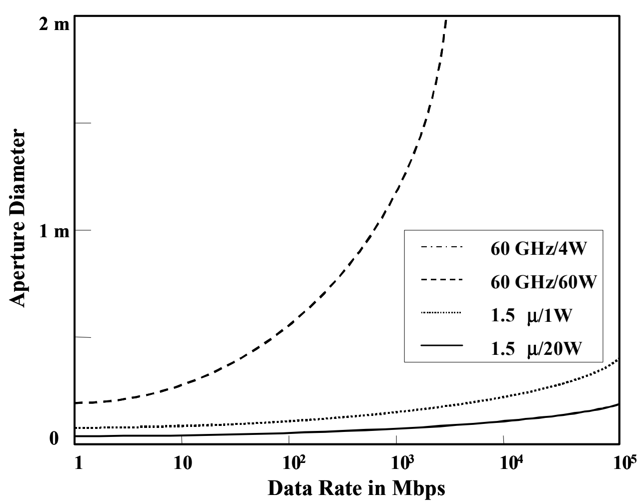

Figure 3. Crosslink aperture size for RF and optical links with geosynchronous range.

Optics have a clear advantage when the rate is high. An optical space communication system has many high precision subsystems that are intimately coupled and interacting (often not weakly). It can be partitioned into three interacting subsystems, (Figure 4):

(1) Opto-mechanical-thermal subsystem

(2) Spatial acquisition and tracking subsystem

(3) Communication subsystem.

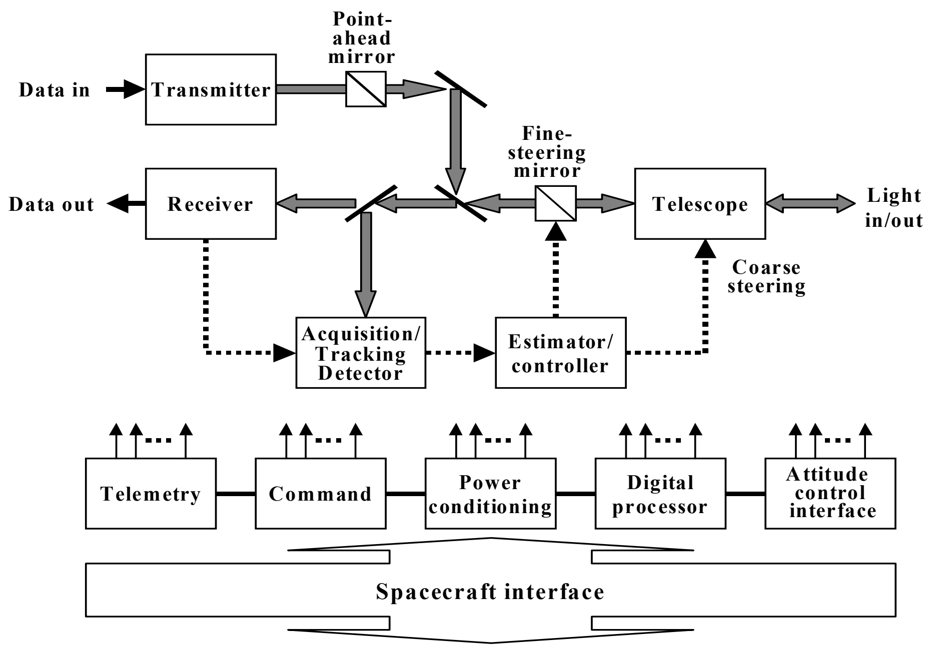

Figure 4. High-level block diagram of an optical space communication system.

2.1 Opto-mechanical-thermal subsystem

The opto/mechanical/thermal subsystem must be weight and power efficient. Specifically, the optical subsystem must minimize optical throughput losses (~3db), provide high wave-front quality (>λ/10), and maintain accurate beam pointing and alignment (~1/20 beamwidth). The subsystem must also survive harsh launch loads and its performance must be maintained over on-orbit thermal environment and in the presence of spacecraft mechanical disturbances. The main design principle is:

"***Optically lock to a beacon from the receiving platform, via sensors and steering mirrors and use a common optical path for the transmit and receive beams while allowing the structure to flex with the mechanical disturbances and thermal distortions".***

A potential big 'quantum' leap over current systems would be to reduce the telescope to a small enough size (~10 cm) and light enough weight via sensitive receivers, high power optical amplifiers and lightweight materials such as graphite epoxy so that one can steer it at high enough speeds (~500 Hz) to track out all the platform disturbances using only one mirror yielding lighter, less power consuming and cheaper designs.

2.2 Spatial acquisition and tracking subsystem

A typical optical space communication system points its transmit beam by tracking a beacon from the receiving satellite with a point ahead angle. Before this happens, each terminal must acquire the other satellite's transmit beam or beacon by performing a spatial search of its angular uncertainty range to locate the other satellite.

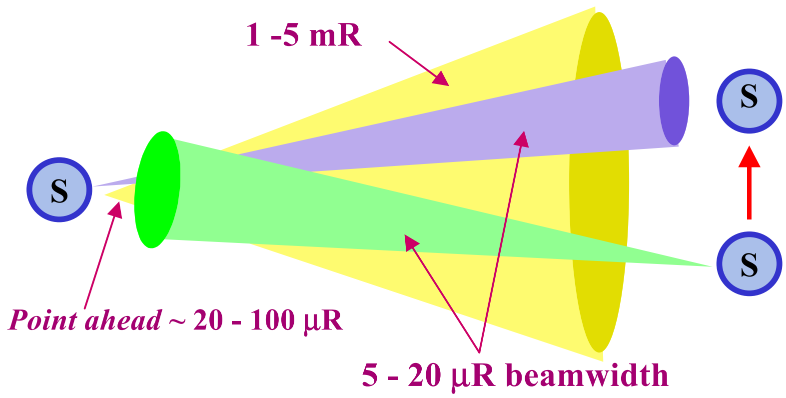

Figure 5. Spatial acquisition geometry.

Figure 5 illustrates the spatial acquisition geometry. The number of spatial uncertainty cells is typically ~10^6. Acquisition strategies can be classified into serial and parallel searches and hybrids such as zooming. After acquisition, the system will enter the coarse and then fine tracking phases. Isolators are used to dampen jitters from the satellite platform. The spatial error sensor detects the beacon and estimates its angle of arrival. The signal is used to track out with a slow outer loop (~10 Hz) via the telescope coarse pointing mirror and a fast inner loop (~1 KHz) via a high-speed fine tracking mirror. The transmit beam shares the same optical train as the beacon and thus its jitters are reciprocally tracked out by added to the outgoing beam. The transmitter and receiver can be decoupled and remoted via the use of fiber couplers.

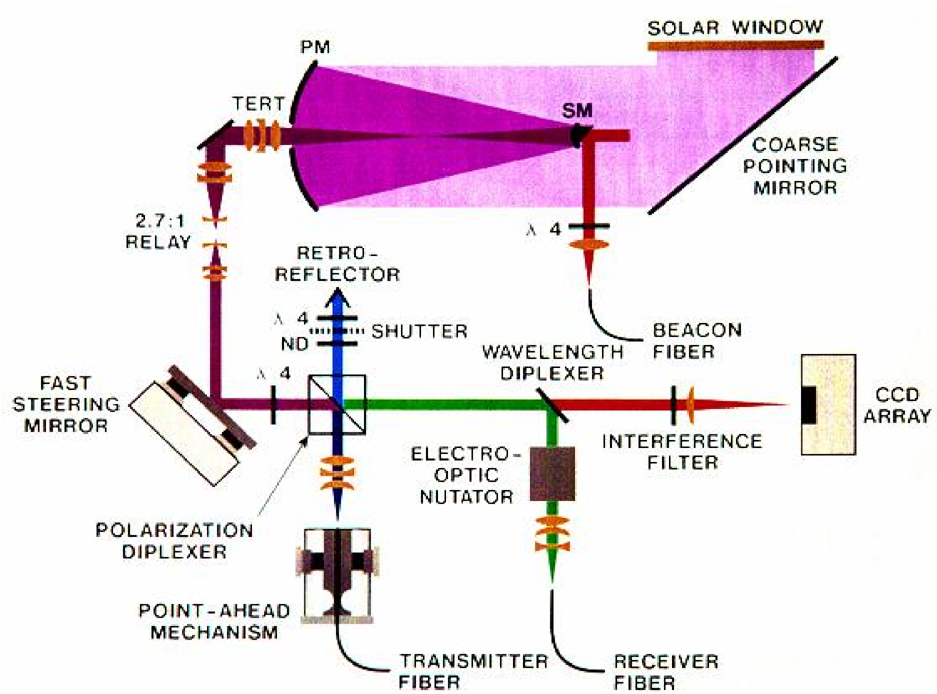

Figure 6. Optical subsystem.

2.3 Communications subsystem

A typical block diagram of a multi-Gbps space optical communication system, Figure 7, includes an optical power amplifier since the link distances are long. The communication performance should be as close to the fundamental limit of quantum detection as possible.

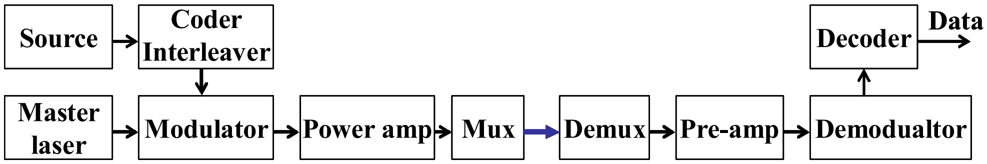

Figure 7. Communication subsystem

At the transmitter, a low power master laser is used to give the optical signal low phase and amplitude noise and good frequency control. A separate external modulator is used to reduce chirp and allow higher bandwidth modulation, reducing crosstalk. A 1–20 W optical power amplifier is used to reduce telescope size. Figure 8 shows a design for very high power EDFAs by using a double clad fiber. With a 10 W amplifier one can close a 40 Gbps link for 44,000 Km with 10 cm apertures. Higher data rates can be realized by using wavelength division multiplexing.

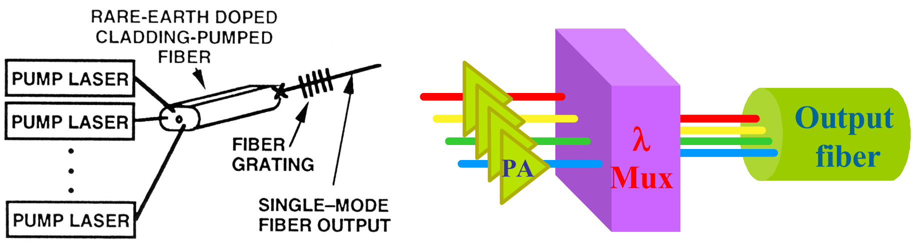

Figure 8. Double-clad erbium amplifier and multiplexer.

The faint optical fields at the receiving satellite exhibit significant quantum behavior and an optimum receiver is necessarily quantum-limited in nature. Quantum optimum receivers are often unrealizable with known techniques or their implementations, even if known, are very complicated. Thus, simpler receiver realizations, called 'structured receivers', are used as near optimum compromises. The detection schemes used can be incoherent (direct) detection or coherent (heterodyne or homodyne) detection. Figure 9 shows the ideal binary signaling performance for structured and quantum receivers.

Signal Set	Direct Detection	Heterodyne Detection	Homodyne Detection	Quantum Optimum
On-off Signal	$2N_s$	$N_s/2$	N_s	$2N_s$
Orthogonal Signal (PPM, FSK)	N_s	$N_s/2$	N_s	$2N_s$
Antipodal Signal (PSK)	Not Applicable	N_s	$2N_s$	$4N_s$

Receiver performance comparison; probability of detection error, Pr[ε] for binary signaling

[1] Exponent θ of tightest exponential bound, $Pr[\varepsilon] = e^{-\theta}$

[2] N_s = average number of detected photons per bit

Figure 9. Ideal receiver performance

Improvements with highly efficient optical links

If the optical communication link sensitivity is increased, substantial improvements to the opto-mechanical-thermal system are possible. When the system is not background noise limited, the photon counting receiver is singular and is believed to have 'infinite' capacity per photon. While that limit is correct in principle, it is achieved when very large symbol size pulse position modulation (PPM) is used at the expense of very low spectral efficiency and the energy per photon approaches infinity. For free space optical systems the average transmitter power is the critical parameter and the relevant quantity to optimize upon is not the capacity per photon but the capacity per unit energy. For a specific target nontrivial transmission rate R_g, the optimum efficiency of the direct detection photon counting channel is finite. In a non-zero data rate system the design problem must be set up as a constrained optimization problem as follows,

$$\max_{\Delta\upsilon,\upsilon,T} C_e = \frac{\log 2\Delta\upsilon T}{h\upsilon}$$

$$\textit{subject to} \quad \Delta\upsilon \le 2\upsilon, \quad \frac{\log 2\Delta\upsilon T}{T} \ge R_g \quad \rightarrow$$

$$\max_{\Delta\upsilon,\upsilon,T} \frac{\log 2\Delta\upsilon T}{h\upsilon} + \lambda\left(R_g - \frac{\log 2\Delta\upsilon T}{T}\right) + \kappa[\Delta\upsilon - 2\upsilon]$$

where υ=frequency, $\Delta\upsilon$ =modulation bandwidth, T=symbol time and λ and κ are Lagrange Multipliers.

The optimum occurs when the modulation uses the entire bandwidth 2υ, with $\upsilon^* \sim e(\ln 2)R_g/4 \sim R_g/2,\ T^* \sim 1/\upsilon^*$ and,

$$C_e^* \sim \frac{1}{h\upsilon^* \ln 2} = \frac{4}{e(\ln 2)^2 hR_g} \sim \frac{2}{hR_g}$$

and

$$C_e^* \sim \frac{2\alpha}{hR_g}$$

if $\Delta\upsilon / 2\upsilon$ *is constrained to* $\alpha \le 1$.

Thus, the capacity per unit energy is upper bounded and does not approach infinity and the optimum symbol size is closer to 2 and 4 as opposed to a very large value.

2.4 Atmospheric channel model and diversity mitigation techniques

The atmospheric optical channel is susceptible to fading due to refractive index fluctuations induced by clear air-turbulence. Spatial diversity is an attractive technique to mitigate fades of the received signal. To capture the significant memory effects of the channel, the *outage probability*, (the probability that the bit error rate of the channel is higher than an outage threshold bit error rate) should be used as a parameter for the link. Other related parameters are the outage duration and the inter-arrival time of outages. Figure 10 shows a generic optical spatial diversity transmitter and receiver. In many application scenarios, it is also reasonable to assume that the transmitter subapertures are separated by more than a coherence length.

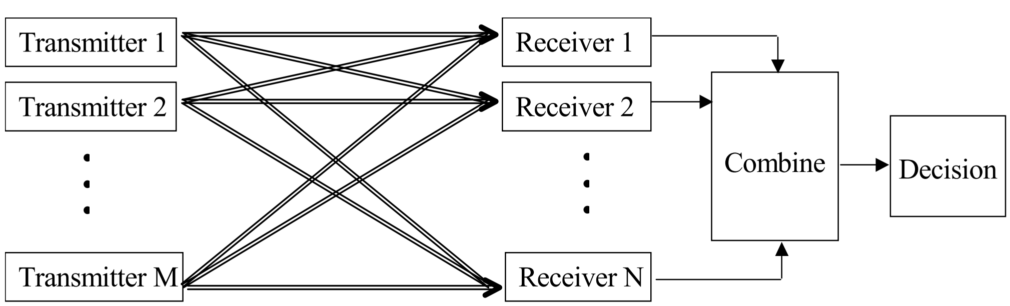

Figure 10. Generic Spatial Diversity Transmitter-receiver.

A continuous-time Markov Process Model can be used to capture the statistics of the memory of the channel's fading process, Figure 11.

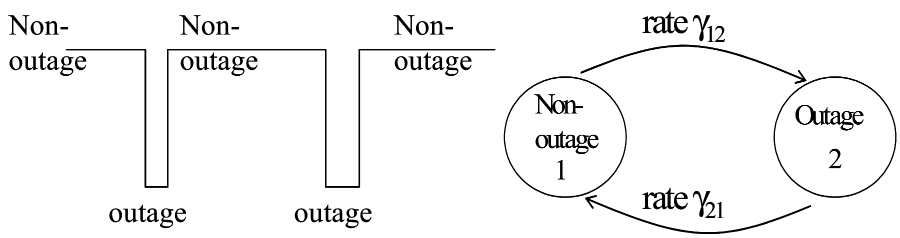

Figure 11. Outages due to atmospheric turbulence and two-state Markov statistical model.

Packets received during an outage are assumed to be lost, and packets received during a non-outage are assumed to be received correctly. Typical outage durations are shortened from a few mS to a fraction of a mS when diversity is used. The inter-arrival times of these outages are of the order of 100 mS. Figure 12 shows typical expected outage probabilities and Figure 13 outage lengths over a short range for spatial diversity direct detection receivers for fairly strong turbulence.

For large diversity degree N and margin m, the outage probability is given by,

$$P_{outage} \sim c_3 e^{-c_2 N (\ln m)^2}$$

The expected outage length is given by,

$$E[outage\ length] \sim c_1 e^{-c_2 N (\ln m)^2}$$

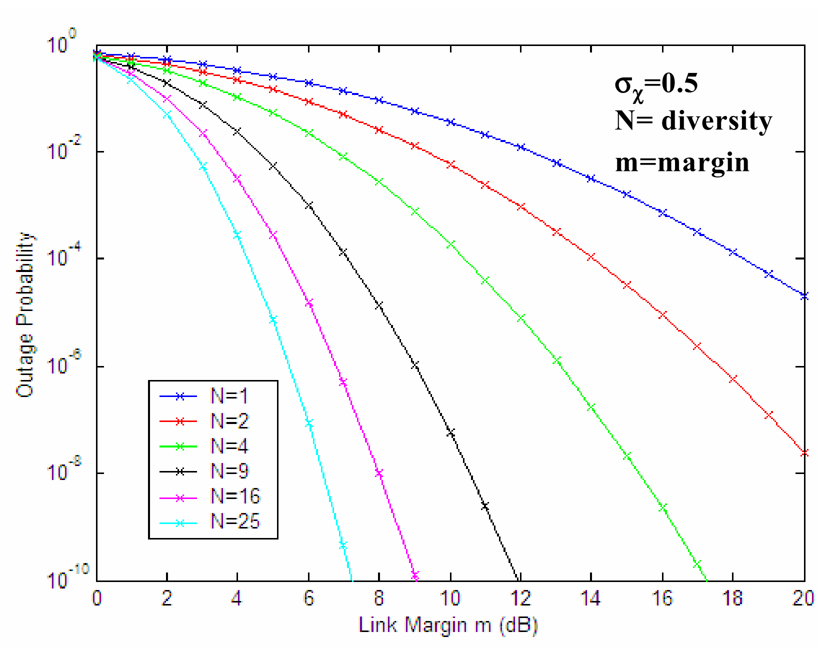

Figure 12. Outage probability for different degrees of diversity; log-amplitude standard deviation, σ_χ=0.5 (strong turbulence), transverse wind speed of 10 km/hr (moderate), and cutoff wind speed of 100 km/hr (nominal).

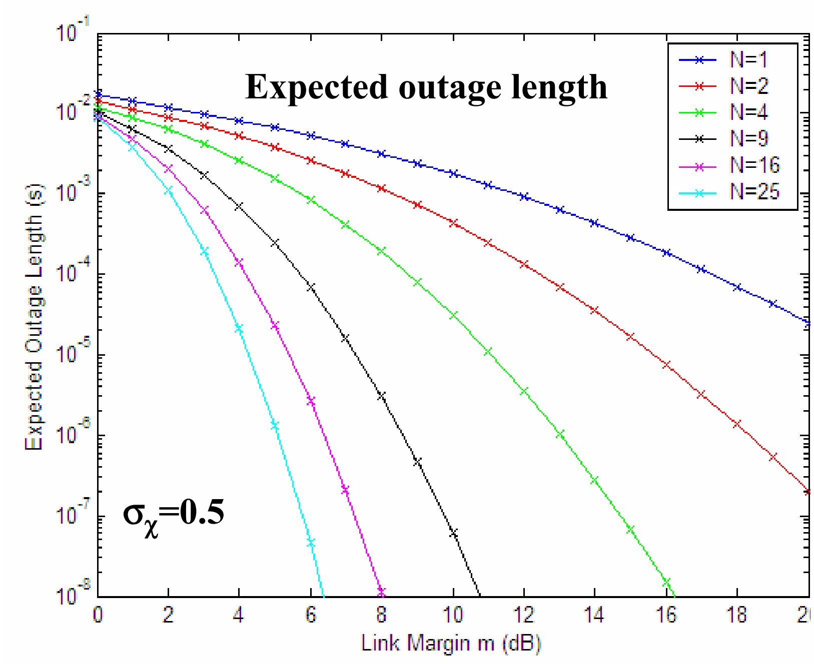

Figure 13. Expected outage length for different degrees of diversity; σ_χ=0.5 (strong turbulence), transverse wind speed of 10 km/hr (moderate), and cutoff wind speed of 100 km/hr (nominal).

Figure 14 and 15 show the magnitude of the power gain of a diversity direct detection system for moderate turbulence. Substantial gains (~10db) can be realized using a moderate to high degree of diversity. The above results are based on incoherent receivers and thus suffer the combining of multi-mode noise of such a system, which is of the order of $\sqrt{N}$, where N is the degree of diversity. Coherent systems with phase control can recover this factor of $\sqrt{N}$.

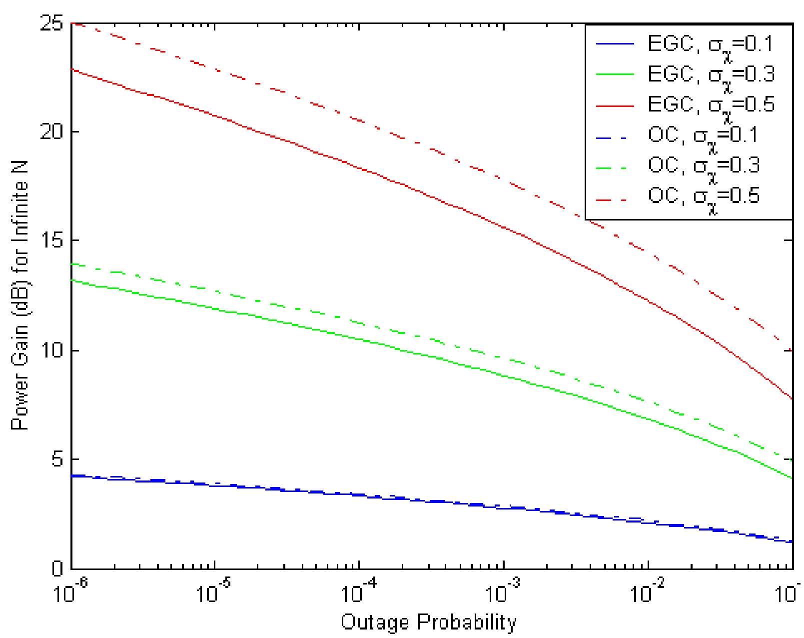

Figure 14. Power gain of direct detection diversity optical communication systems for moderate turbulence and optimum receivers (OC) and equal gain combining (EGC) receivers – infinite number of diversity receiver asymptote.

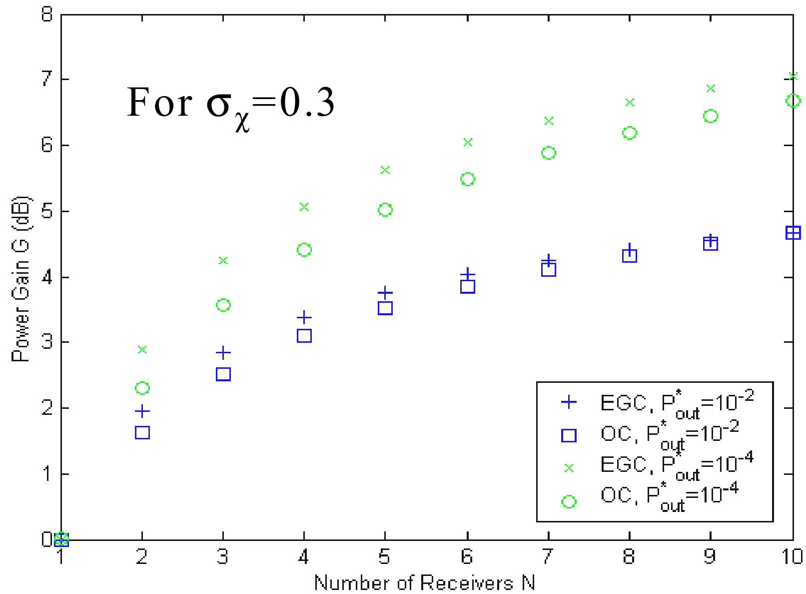

Figure 15. Power gain of direct detection diversity optical communication systems for moderate turbulence and optimum receivers (OC) and equal gain combining (EGC) receivers – finite number of receivers.

3 OPTICAL SATELLITE NETWORK ARCHITECTURE

There can be two reasons an optical satellite network is economically viable. The first reason is that for long distance intercontinental transmissions, it can be cost-competitive with under sea fiber systems and can become an alternative for terrestrial networks. The second reason is that the optical satellite network may provide unique services to space missions and open-air-interface access such as voice and data communications over microwave satellite systems for mobile platforms and remote users with no broadband infrastructure, and satellite and terrestrial distributed sensing read-out. The economical viability of such a network will heavily depend on its architecture.

3.1 Physical network topology

The primary goal of a backbone constellation is to provide the coverage as required by the users. The complexity of each individual satellite can be quantified by the number of apertures required, the size required of each aperture, the slewing rate required of each aperture, and any obscuration issues which arise from the placement of apertures on the satellite. Figure 16 provides a comparison of typical satellite network configurations. GEO constellation has the drawback of the ¼ second propagation delay that affects voice and video conferencing. However, though LEOs may alleviate the delay problem, its constellation is complex and requires all ground user terminals to have a tracking antenna. Since most of the traffic of a high rate satellite network will be data-based, provided a suitable MAC protocol is used, the effects on user quality of service of the GEO delay can be minimized. In addition, pass-through traffic in a satellite constellation, which increases crosslink capacities, is a strong function of constellation architecture. For example, for a LEO or MEO constellation with m planes and n satellites per plane and all satellites are connected to their neighbors, the ratio of pass-through traffic to add-drop local traffic in their coverage area is ~ $(m+n)/4 - 1$. This pass-through traffic can become a burden to the crosslink resources of the optical satellite network and drive the system cost up. Thus, it is prudent to minimize pass-through traffic with a small GEO constellation. The traditional notion of connecting GEO nodes into a ring topology needs to be revised. To minimize pass-through traffic a higher degree of connectivity (mesh) network topology should be used. An interesting benefit of a free space link is that when the traffic load shifts, the physical connection topology can be easily changed via pointing the telescopes to a new satellite and load balancing can be implemented easily.

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°

Figure 16. Satellite network constellation configurations for space or space/earth users.

3.2 Spacecraft node switching architecture

Figure 17 shows the different processing architecture options for a backbone satellite network node. The minimum configuration is to have transponders only and an analog switch to cross-connect input and output links. This can be done if the RF access links are analog-modulated onto optical links at the expense of link efficiency. Since space resources are precious, a better architecture will be to also have on-board demodulation and modulation together with switching and even routing, albeit not necessarily for all the traffic. Since a substantial fraction of the traffic at each node can be high-speed pass-through traffic, optical or electronic (O-E-O) switching/'routing' via WDM techniques can be used to eliminate a significant fraction of expensive regeneration and electronic processing resources (such as packet by packet routing by a high speed router) at the expense of losing some link performance (only if there is no regeneration).

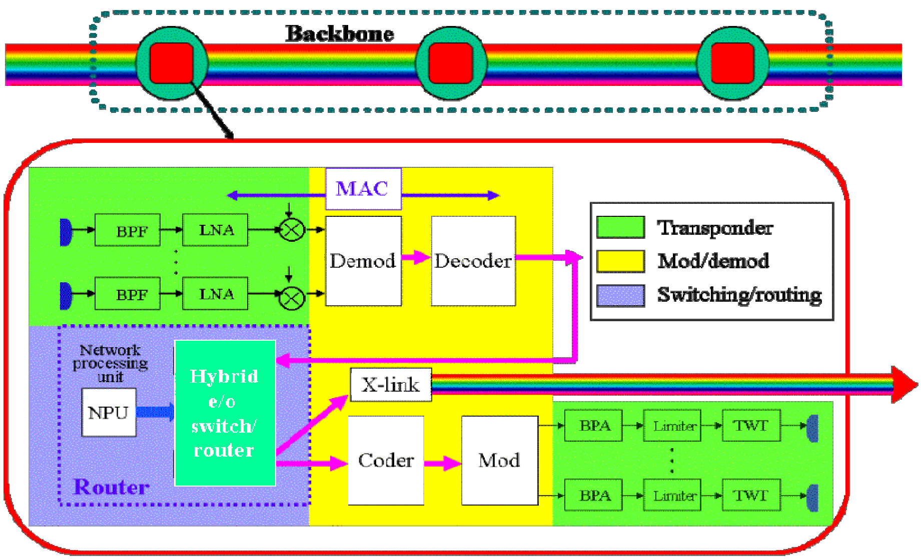

Figure 17. Different processing architecture options for a satellite network node.

3.3 Optical multiple access

In a number of specialized applications, multiple users can be within the same field of view of the satellite receiving telescope. From geosynchronous orbit, users more than 100m apart can be resolved by multiple focal plane detectors of a modest telescope of ~10cm in diameter. However, for many lower rate random access users, such as those on airliners, it is prohibitively costly to assign one optical receiver per user even if it is dynamically scheduled. Thus, a multiple access receiver combining the signals of a larger group of users at the same detector makes sense, Figure 18. The messages from the individual users are extracted via traditional decoding schemes. Each user can gain the attention of decoding resources by sending a unique preamble. Since each user laser will not be coherent with other users' lasers, the modulation scheme will have to be energy and not phase modulated. For lower rate users, there should be plenty of bandwidth available and hence M-ary PPM is a good signaling scheme. It can be shown that if there are on the average K users active in the same optical channel, the capacity of the multi-access channel is given by: $C \sim \log M - \log K$ bits per use of the channel. As the number of users becomes large the capacity approaches $\ln 2$ bits per time slot.

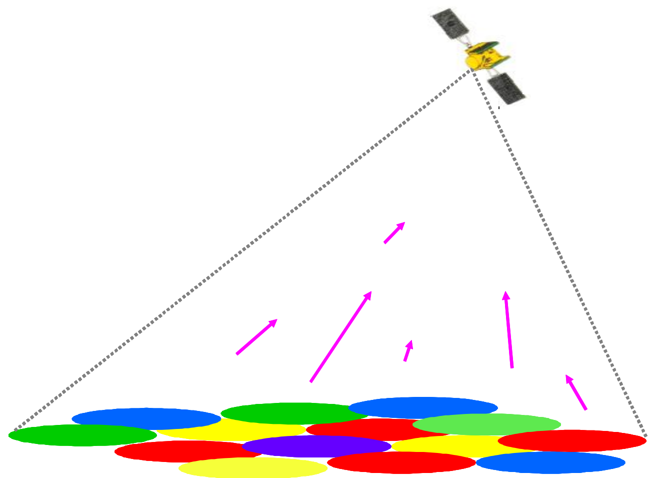

Figure 18. Optical multiple access.

3.4 Network and Transport Layers

Networking over a satellite network is very different from terrestrial networking. At the Physical Layer, independent symbol errors occur due to RF and optical receiver noise and in the case of good optical receivers that are readily implementable, quantum uncertainties. In addition to the independent errors induced by the detection process, the satellite channels also can suffer time varying degradations much longer in duration by comparison to a symbol time. The capacity of the microwave channel can vary over two orders of magnitude. Adaptive modulation and coding can keep the links operating at or close to capacity. This gain is of little use for circuit services since the link capacity may change over seconds and thus cannot be conveniently allocated to additional users. For data-oriented services, these gains can be utilized effectively for bursty accesses. It will appear to the users as a less loaded network with faster response not unlike a lightly-loaded or faster Ethernet. However, current upper layer protocols such as the Network Layer routing protocols are designed to change slowly (as long as a time scale of minutes) to mitigate undesirable effects such as oscillations of network flows. Thus, new Network Layer Protocols will have to be designed to avoid network instabilities due to fast adaptation and prevent network oscillations. Also, with the long link delays, especially over geosynchronous distances, and the high data rates possible with optical links, there will be typically many packets in flight. If traditional protocols such as TCP (Transport Control Protocol) are used, the network will be very inefficient. TCP's throughput is near optimal over very short ranges, since the number of packets in flight is small and the time it takes to increase the window size after an outage causes window closing is not appreciable. Over medium range optical atmospheric links, TCP's throughput can be made high if a moderate amount of diversity and/or high link margin is used Over long ranges (100-72,000 Km) atmospheric links, TCP's throughput is poor for direct detection even for large diversity and link margin. This is because the loss in throughput due to Transport Layer Protocol mismatch to the channel, exhibiting two detrimental behaviors called 'window closing' and 'slow start', substantially decreasing throughput. For moderate to long distances the throughput ranges from poor to practically nil. Figure 19 shows the end-to-end throughput of an ultra high speed 100Gps space to ground link. This problem of the Transport Control Protocol (TCP) is recognized as a major impediment for high speed space-terrestrial networks. There are several proposed 'fixes', but none is totally satisfactory since they create other mismatches to problems in the network that the unmodified protocol are designed for. In order to maintain high throughput efficiency over long atmospheric links, a Transport Layer Protocol whose transmission rate is relatively independent of round trip delays should be utilized. Moreover, the Transport Layer should not react to packet losses due to outages by reducing the transmission rate and ramping up the window slowly. The key design principle is to provide feedback from the network to distinguish congestion packet losses and outage losses. Thus, more intimate handshaking between Physical and Transport Layer has to be employed.

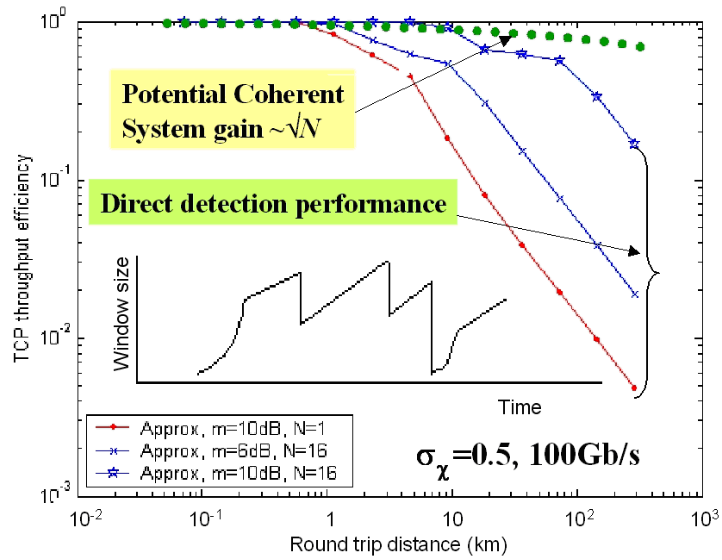

Figure 19. Transport layer throughput efficiency of incoherent and coherent 100 Gbps optical systems as a function of link distances, showing improvements due to spatial diversity and potential gains with coherent detection.

3.5 Coherent Systems

Coherent detection will improve the Physical Layer architecture by providing communication performance gains. One can also make use of the temporal, polarization and frequency dimensions to provide even more diversity. The throughput gain of a coherent system over that of a direct detection system is about $\sqrt{N}$, where N is the total diversity available in the system. If the number of telescope array elements for the transmitter and the receiver are both M, the temporal diversity is T, the number of orthogonal frequency is F (must be separated farther than the frequency coherence bandwidth of > 50 nm), the total diversity available is $N = 2M^2TF$. For moderate values of these parameters (between 2 and 25), the available diversity N can be very large. Figure 20 shows some of the essential blocks of a transmission system that exploits several techniques to improve link and network performance including phase pre-distortion via feedback to tune near-field optical field patterns for turbulence compensation and interference rejection.

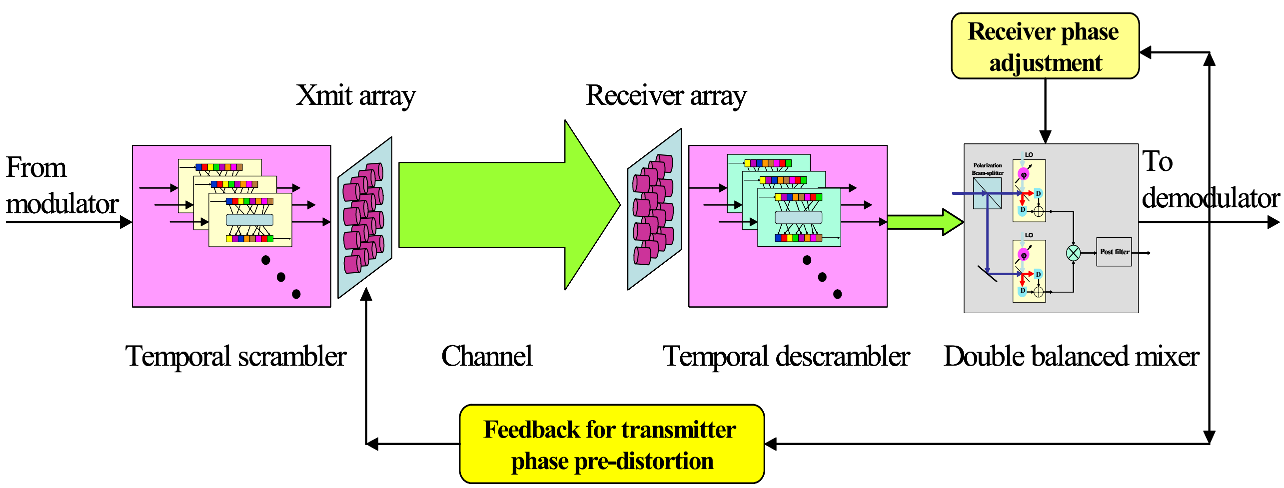

Figure 20. Transmission system block diagram; not all subsystems shown (including: modulator/demodulator, coder/decoder, frequency shifters, optical amplifiers etc.).

4 INNOVATIVE SPACE ARCHITECTURE IMPLICATIONS OF A HIGH SPEED OPTICAL SATELLITE NETWORK

Optical crosslinks provide satellite networks with a quantum-leap in capacity and lower cost. It allows the creation of a cost competitive space network. However, the implication of an optical satellite network in space goes far beyond economics and rates. It is an enabling technology that permits the creation of new application architectures. Innovative ways of using this network may revolutionalize satellite communications and space missions such as remote sensing.

4.1 Optical satellite network as an enabling technology for shared spaceborne processing

With an ultra-high rate and economical optical satellite backbone in place, one can think about the concept of using shared space-borne processing (Figure 21), to compress the amount of data to be sent earth-bound and thus reducing the requirement for very costly high RF down links. Modest RF down links can then be used for the processed and compressed data, substantially lowering the overall system cost and raising the resolution and coverage rate of sensors and other space missions. Besides enabling the sharing of a massive processor farm, the concept also allows the easy periodic upgrade and replacement by simply launching new processing satellites. The most advanced commercial (non-radiation hardened) processors can be used with radiation damaged processor satellites replaced more frequently than the primary mission satellites.

4.2 Multi-platform multi-static sensing

A sensor's performance can be improved if the sensing function can be distributed over more than one satellite. For example, for geo-location, two satellites can form the arm of a long baseline interferometer provided the two sensed signals can be brought together for coherent processing, Figure 22. In general, a distributed satellite system can substantially improve image oriented sensing and object identification from space. "Coherency" between the sensors has to be maintained using either sampling at very high resolution and high rate digital crosslinks or high fidelity analog links bringing the data to a common processing platform.

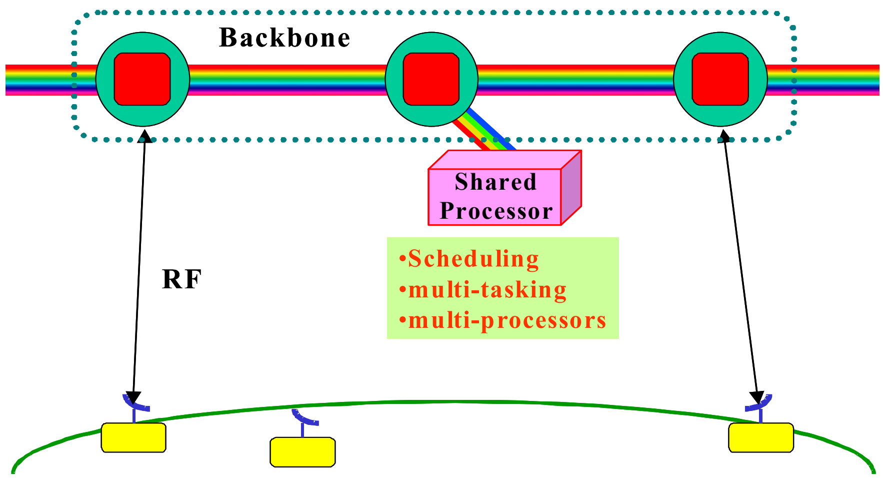

Figure 21. Shared processing in space.

4.3 On-orbit upgradeable satellite communications

The RF section and the baseband processing section of a satellite transmitter and receiver have different life cycle durations. The antenna and RF front-ends usually stay at near state-of-the-art longer than the processing segment. If, for example, the raw RF analog signal or the digitized waveform is sent to a processing satellite to perform the rest of the receiver function via software processing by general processors, both the processors and the software can be reprogrammed or upgraded to adopt new or better modulation, coding and MAC protocols, Figure 23. Similar changes can be made to the transmitter.

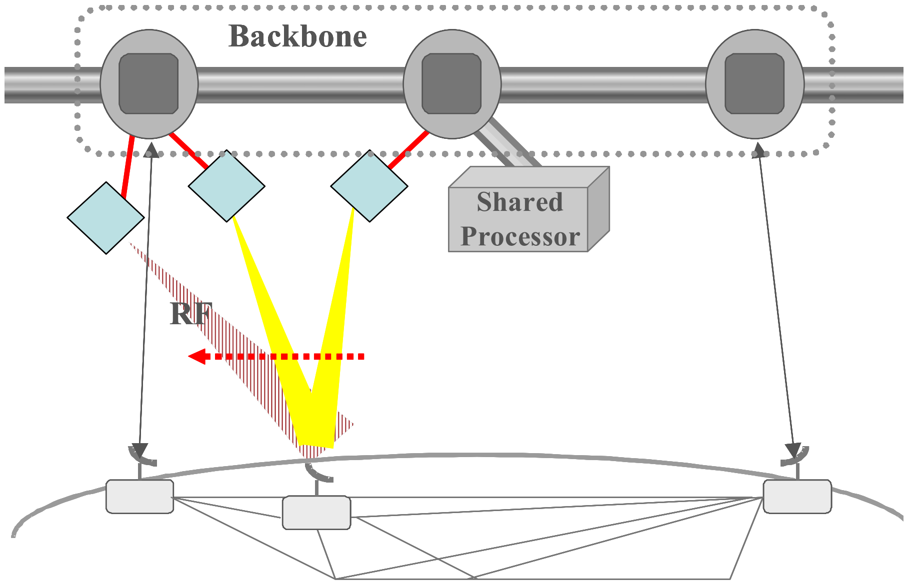

Figure 22. High resolution multi-platform distributed sensing.

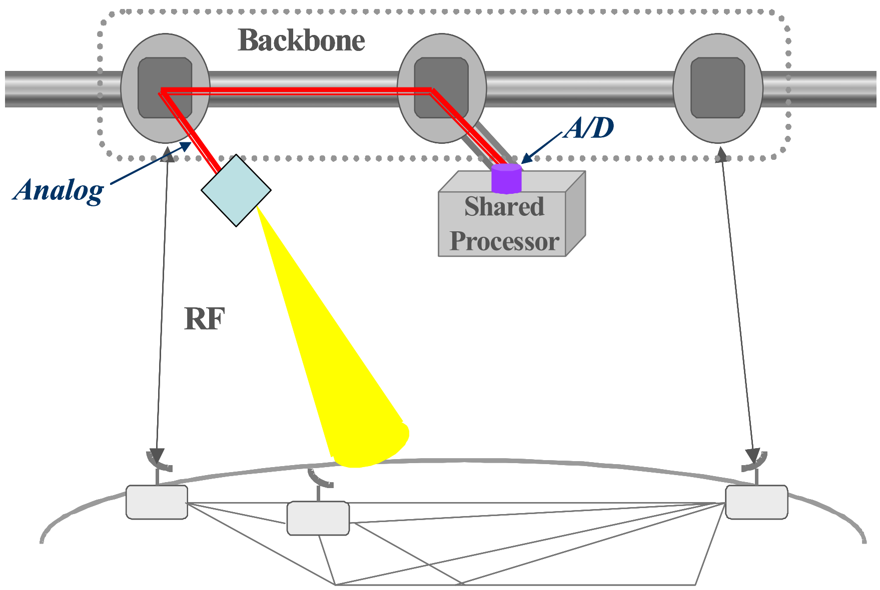

Figure 23. Reconfigurable and upgradeable RF satellite access network.

4.4 Multi-platform high performance data satellite communications

Just as for multi-platform multi-static sensors, the optical satellite network enables the realization of a multi-platform satellite communication system, as illustrated in Figure 24. The multi-platform system can be viewed as a traditional satellite communication system with a multi-element antenna array distributed over multiple satellites as a very large albeit "thinned" (as in not filled) aperture. This arrangement can improve communication performance to small and low power terminals by forming an electronic antenna pattern with significant gain on the user and placing nulls on strong interfering users to suppress their signals. With a powerful and modern processor farm on the processing satellite, this can be done dynamically in rapid response to bursty user demands and orchestrated by a MAC protocol.

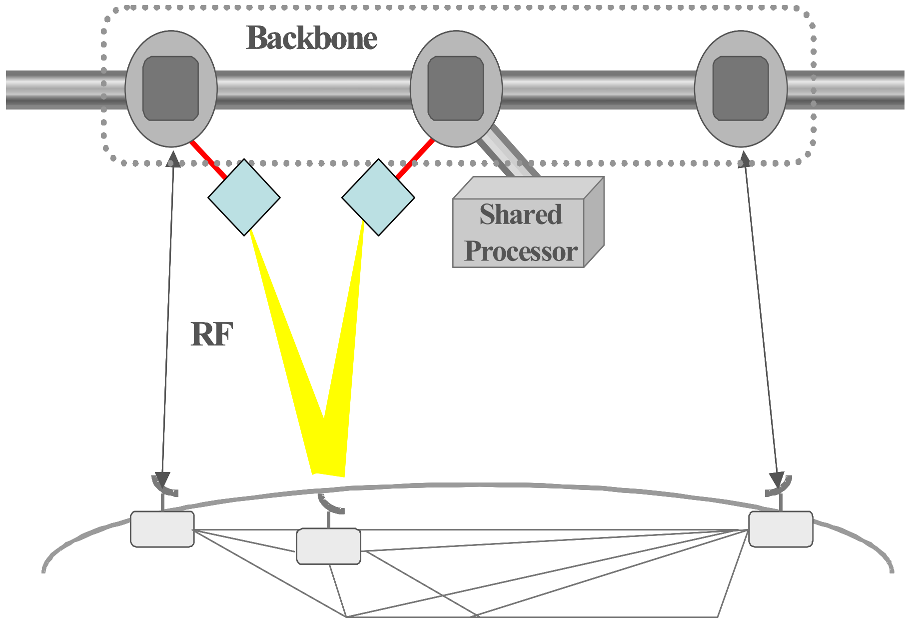

Figure 24. Multi-platform distributed space communications

5 SUMMARY

There is no doubt that free space optical communication technology is ready for real life applications. While successful experiments have shown that there are no Laws of Physics against such systems, their estimated system costs are still much too high for serious consideration. There are a few research forefronts that will yield high payoffs:

1. *high sensitivity receivers*
2. *efficient high power amplifiers*
3. *lightweight construction*
4. *techniques to deal with turbulence*
5. *highly efficient network architectures specific to the properties of space systems.*

Not very often in the history of communications and networking have there been truly transforming inventions that result in quantum-leaps in the nature of services or costs to the end users. The router and connectionless IP packet network is one such example. Optical satellite communications and networks will likely be classified as another such transforming technology if its architectural implications are fully realized. Not only will the satellite network become economically viable, its deployment and the extraordinary services it can offer are capable of radically transforming space system architectures.

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