Why photonic systems for space?

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ABSTRACT

Future space-based platforms can and will benefit from the implementation of photonics in both analog and digital subsystems. This paper will discuss potential applications and advantages to the platforms through the use of photonics.

Keywords: Space, Photonics, Signal Processing, A/D Converters, True Time Delay

1. INTRODUCTION

Future spaced-based radar systems will be required to accomplish much more difficult missions than the current state of the art. The need for large bandwidth, light weight antenna structures, and on-board signal processing in the constraint of operating in the space environment places significant demands to improve electronic and material technologies. As the microwave photonics technology matures and system performance improves, it will become practical to use photonics. The benefits associated with using photonics will then drive their implementation.

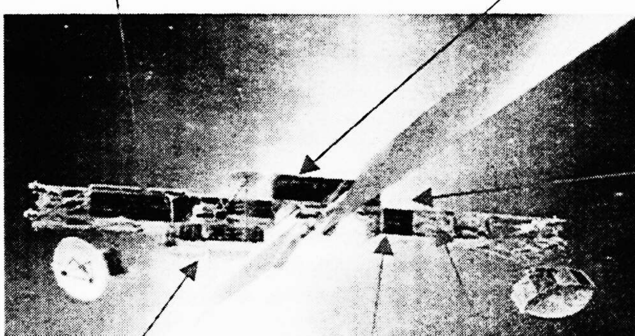

Figure 1. Potential Photonic Applications Areas on Spacecraft

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15. SUBJECT TERMS

Space, Photonics, Signal Processing, A/D Converters, True Time Delay

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In this paper we will discuss some of the potential applications of photonics. These include RF distribution links, true time delay, local oscillator generation, analog to digital conversion photonically implemented signal processing and high speed analog–to– digital signal conversion.

2. RF FIBER OPTIC LINKS

The starting point for discussing the insertion of photonics in space-based platforms is the point-to-point fiber optic link shown in Figure 2. Here we show an externally modulated, direct detection link. Compared to a metallic cable, the photonic link adds a level of complication with the need for devices such as the laser, modulator, and photodetector. The primary benefit of photonics may not be in the RF performance of the link itself. There are, however, rather clear advantages of replacing the traditional metallic cable with a fiber optic cable. **The performance of the optical link is "key" to implementation of analog photonics in space based as well as other application areas.**

Weight and size are critical constraints in the space environment. Launch costs depend strongly on the total payload weight and size. Photonic links, including the associated electronic components, can provide meaningful weight savings. Equally and in some cases perhaps more importantly, weight distribution is a factor. Most of the weight and size of the photonic link are associated with the power supply and laser, which can be located at the base of the satellite. The fiber cable adds significantly less weight and volume than metallic cabling to the antenna structure. For large antennas this is an important design constraint. Also, the flexibility of fiber compared to metallic cabling is advantageous when considering the need for the antenna to be unfolded for deployment.

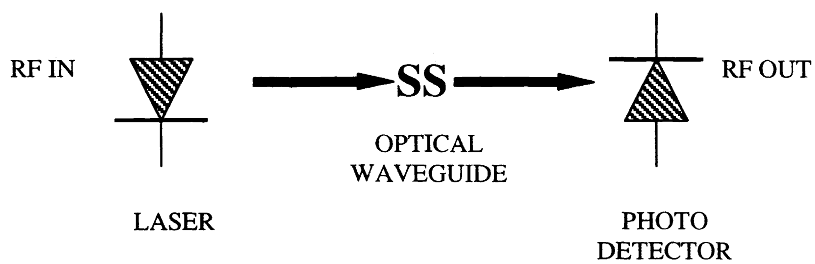

Figure 2. A Directly Modulator Fiber Optic Link

Another important advantage of fiber optic cable is its insensitivity to any form of electronic crosstalk, or electronic interference, unlike metallic cable, which needs to be shielded and results in adding weight. An additional benefit of the electromagnetic effects (EME) insensitivity is that bandpass filters and surge protection devices are not required. This results in a reduced parts count, lighter weight, and improved reliability.

While these benefits of weight, size, flexibility, and EME insensitivity are reasons why photonic systems are suited for space, there are performance issues that need to be satisfied before implementation of a fiber optic link is practical. Although the optical fiber itself has very low transmission loss, the conversion from the electronic-to-optical-to-electronic domain is inefficient. Conversion losses are currently on the order of 20 dB, with a correspondingly large noise figure. For an externally modulated fiber optic link, the link gain G can be expressed as[1]

$$G \propto (P_D/V_\pi)^2 \quad (1)$$

where P_D is the optical power incident on the photo detector and V_π is the half wave voltage of the Mach Zehnder modulator (or the equivalent V_π for other modulator types). Although the RF link performance could be enhanced through increased optical power, this is not a practical option, due to the limited prime power available on a space platform. Improvements must be made in the modulator efficiency. Figure 3 shows the link gain and noise figure as a function of the modulator V_π for typical Mach Zehnder link parameters. Currently available modulators at 20 GHz frequency operate with a V_π of about 10 Volts. As indicated in Fig. 3, in order to obtain a photonic link with less than zero dB loss and less than 6 dB noise figure, V_π needs to be less than 1 Volt. This reduction in V_π is a currently a subject of a Department of Defense Research and Development (R&D) effort through the Defense Advanced Research Projects Agency (DARPA). We believe that this goal can be achieved in the near future.

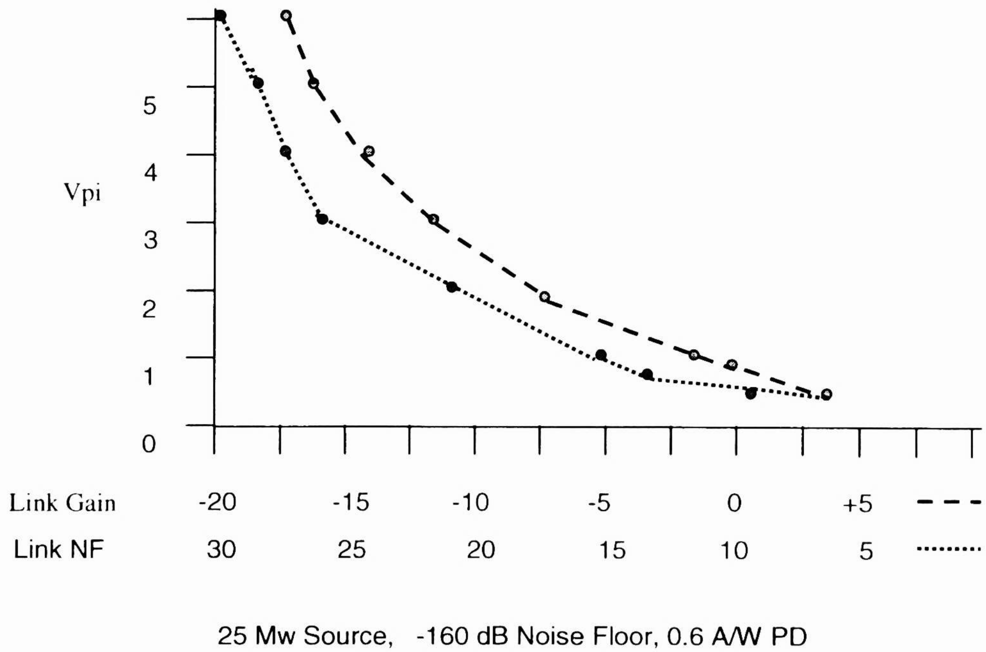

Figure 3. Link Gain and Noise Figure vs. Vpi

The realization of practical fiber optic links will also bring additional benefits to using photonics. Consider the distribution link shown in Figure 4. Here we have shown the presence of a low noise amplifier (LNA) and a compensation network. For the metallic cable the compensation network is necessary for wide band systems, due to the high dispersion of the metallic cable, especially at high frequencies. A current issue in LNAs is to achieve wide bandwidth gain at low operating powers. Since the photonic link is inherently wideband, its use can simplify the constraints on the electronic components. In fact, it is conceivable that the photonic link could provide sufficient RF gain so as to eliminate the need for the LNA. Photonics then would be a technology enabler in the sense that it can provide a bandwidth of operation that would not otherwise be possible.

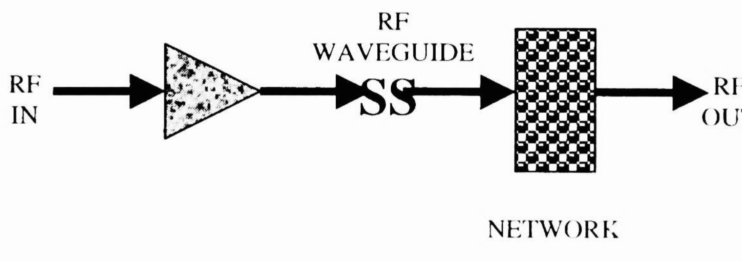

Figure 4. A Metallic RF Link

3. PHOTONIC BEAM FORMING

As electronically steered antennas (ESAs) with multifunctional capabilities move into a space environment, true time delay (TTD) multibeam formation and beam steering will be required, especially for wide bandwidth RF systems and/or wide beam scan angles[2]. TTD overcomes the effects of frequency dispersion that restrict the performance of conventional electronic phase shift systems to narrow band operation. In a phase shift system the energy associated with the different frequencies points in different directions in the antenna's far field as the frequency is changed causing an increase in beam width. This phenomenon known as "squint" doesn't afflict TTD systems in which each of the radiated or received frequencies is properly phased and therefore all frequency components point in the same spatial direction.

The use of photonic links brings with it the ability to implement true time delay functions at little additional system cost. While electronic phase shifters or MEMs may be able to provide small time delays at the element level, photonics techniques can provide course (long) time delays needed for subarrays of large phased array antennas.

Several photonic approaches for generating time delays have been developed based upon emerging technologies such as optical switches, fiber gratings, and dispersive fibers. Our analysis has shown that adding a true time delay function to an existing link adds only a few dB of additional RF loss. This is much less than other electronic alternatives.

4. RF SIGNAL GENERATION

RF millimeterwave (MMW) signal generation is an application for which photonics appears to be well suited for space-based applications. A variety of approaches are under development in which photonic techniques are used to generate a RF carrier, either in the optical or electronic domain. In addition to the well-known technique of optical heterodyning, these techniques include the self-sustaining pulsating diode laser[3] and the opto-electronic oscillator[4] (OEO). These devices are capable of generating tuned RF MMW subcarriers on an optical carrier. In the self-sustaining pulsating diode laser, the RF frequency subcarrier is generated by the laser diode itself under the proper dc biases. The OEO consists of a pump laser and a feedback circuit that includes an optical delay line.

Photonic signal generation techniques are attractive for a variety of reasons. Since the signal can be generated directly in the optical domain, it is conveniently compatible with fiber optic signal distribution and the benefits discussed above. It is important to point out that the signal is generated directly at the desired RF MMW frequency. There is no need to multiply an oscillator output, as is necessary with electronic signal generation. The OEO has already demonstrated excellent spectral purity and low noise, with noise as low as –50 dBc/Hz at 10 Hz offset and –140 dBc/Hz for a 10 Ghz signal[5]. Additionally, the packaging of the self-pulsating diode laser and the OEO are very small, lightweight and require low prime power.

5. PHOTONIC IMPLEMENTED A/D

Analog to digital converters (ADCs) are the critical components in the development of advanced digital receivers and in directly converting analog sensor signals into digital form for advanced processing techniques. However, progress in advancing the electronic ADC modules has been very slow due in large part to the difficulties in fabricating the electronic circuitry required for very high resolution and high sampling rate converters. Wide bandwidth and high resolution ADCs will allow direct sampling of the sensor signal at RF frequencies eliminating the need for analog signal down conversion. Emerging photonic ADC technology can provide revolutionary advances over state-of-the-art electronic ADCs. The ultrafast optical and opto-electronic responses of various photonic devices will also allow for resolutions on the order of 12-14 bits at 10 Gigasamples/sec (GS/s) versus the best current research electronic ADCs operating at 8 GS/s with only 3 bits of resolution.

Revolutionary advances in the development of ADCs can be made by taking advantage of the high-speed and parallelism of photonics. The use of photonics for ultra-fast sampling, clocking, and data processing promises to give rise to ADCs with high resolution and multi-Ghz sampling rates simultaneously. For example the use of an ultra-stable mode-locked laser producing picosecond pulses at multi-Ghz repetition rates allows the analog data to be sampled in an impulse like manner. An electro-optic modulator imprints this sampled data onto an optical pulse train. The analog optical signal can either be converted back into an electrical signal with photodetectors for electronic quantization or the signal can be directly quantized in the optical domain and then converted back into the electronic domain. Realization of photonic ADCs will allow the received analog signal to be converted directly at the RF frequencies eliminating the bulky and often unreliable analog down conversion process. An additional benefit of photonic processing on space-based platforms is that various elements of the ADC can be remoted using advanced photonic links. For example the ultra-stable mode-locked sampling laser can be split and used to sample and clock multiple received signals at various locations on the platform.

6. APPLICATIONS OF PHOTONICS IN PROCESSORS AND DIGITAL RECEIVERS FOR SPACE BASED PLATFORMS

Some on board processing will always be necessary for both space-based and airborne platforms. The degree of on board processing will be determined by a combination of factors such as platform size, platform prime power capability, and - what is most important - the amount of data gathered and the bandwidth and capability for downlinking.

For example, on-board processing may be most critical in earth mapping missions such as the recent NASA radar mapping shuttle project. There the data was gathered and stored on board and then returned to earth for further processing. For most space-based payloads this would not be an option and data transmission bandwidths limit the amount of data that can be downloaded in time critical applications.

Here we consider the utility of photonics based systems for space based platforms. The figure shows the translation of raw sensor data into useful and (hopefully) valuable information. Photonics technology has utility, both as an enhancement assist in the near term, and as a supplement in the longer term, to dramatically improve all-electronic based systems. Photonics technology development falls directly within each of the subregions shown in the data processing and information extraction domain.

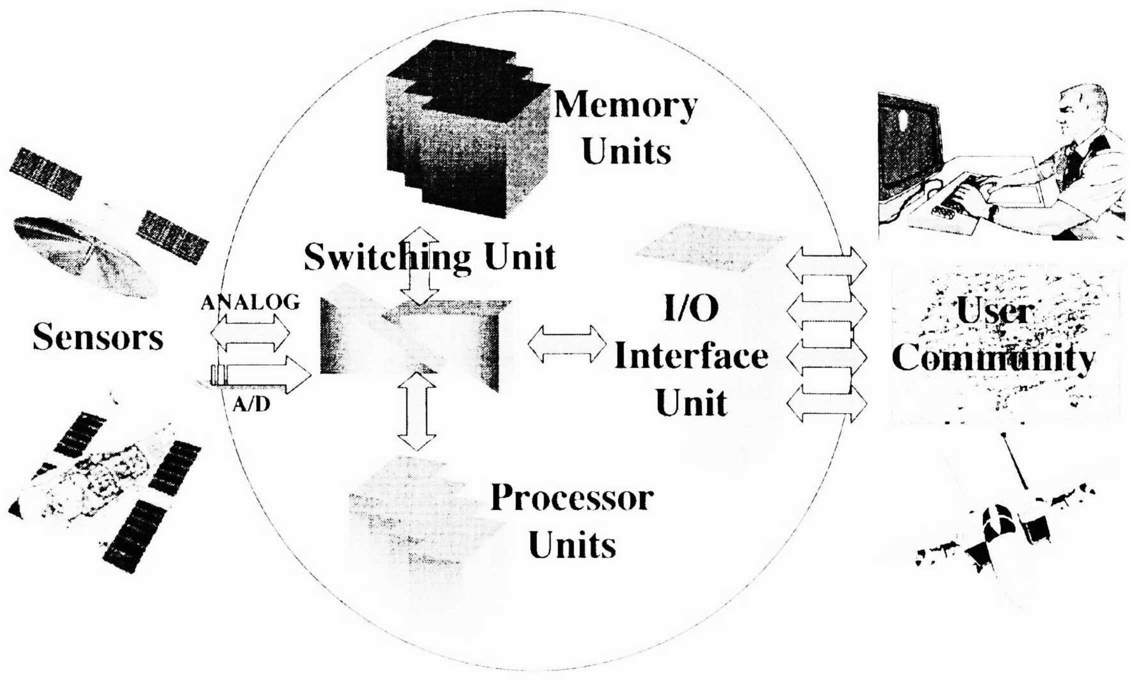

Figure 5. Optical Signal Processing

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Terabits of broadband raw data arriving from a variety of sensor platforms are subject to an increasingly wide array of manipulation and processing. Signal distribution, routing, buffering, storing, algorithm processing, linking, and interfaces must all handle massive amounts of incoming data. All must minimize power, size, and weight, especially on spaceborne platforms. Recent advances in opto-electronic components and RF lightwave integrated circuit technology make this possible on several levels for both military and civilian users.

The problem can be divided into a number of differing regimes. We include long haul communications (up to thousands of kilometers); Local area onboard networks (local signal distribution); intermediate distance data switching (processor card backplane routing), and integrated device to device or on chip processing.

Optical networking has been the subject of intense research by the telecommunications industry the past decade. This has been driven primarily by the ever-increasing demand for more user bandwidth and recently by the exponential growth of the Internet. Recent advances in vertical cavity surface emitting lasers (VCSELs), ultra-fast optical receivers, and both fiber and free-space optical interconnects have dramatically opened the possibilities to implementing integrated opto-electronic circuits. A fundamental limitation of fast electronic processors is the ability to get the processed signal from chip to chip, due to physical limitations in size of connectors and the amount of bandwidth available per channel. Routing of electrical circuitry must take into account issues of latency and contention of signals on a bus interconnect network, such that increasing processor power to handle many GFLOPS results in an overall degraded performance due to decreased intra-network communication capacity. Optical network processor routers, because of their parallel nature and extreme high bandwidth capacity (tens of Terabits/sec), overcome these problems. The result is dramatically improved processing capacity in small, rugged, lightweight, low power consumption packages.

7. CONCLUSION

We have now reached the point in many photonic developments that performance of the photonics can be considered as an adjunct, replacement or enhancement of many electronic systems. As we progress in performance of photonics we see near, mid and far term implementation and integration into space-based systems.

REFERENCES

1. Charles Cox III, Edward Ackerman, Roger Helkey, and Gary Betts, "Techniques and Performance of Intensity-Modulation Direct-Detection Analog Optical Links", IEEE Trans Microwave Theory and Tech, **45**, pp. 1375-1383, 1997.

2. Henry Zmuda and Edward N. Toulghlian, Ed., *"Photonic Aspects of Modern Radar",* Artech House, Boston 1994.

3. Xiaolo Wang, Guifang Li, and Charles S. Ih, "Microwave/Millimeter-Wave Frequency Subcarrier Lightwave Modulations Based on Self-Sustained Pulsation of Laser Diode", J. Lightwave Tech., **11**, 309-315, 1993.

4. X. Steve Yao and Lute Maleki, "Converting Light into Spectrally Pure Microwave Oscillation", Opt. Letters. **21**, 483-485, 1996.

5. Lute Maleki, Steve Yao, Yu Ji, and Vladimir Ilchenko, "New Schemes for Improved Opto-Electronic Oscillator", 177-179, Technical Digest of Microwave Photonics, November 1999, Melbourne.

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