FIBER-OPTIC NETWORK ARCHITECTURES FOR ON-BOARD RADAR AND AVIONICS SIGNAL DISTRIBUTION[1]

Mohammad F. Alam, Mohammed Atiquzzaman and Bradley B. Duncan
University of Dayton, Dayton, Ohio, USA

Hung Nguyen and Richard Kunath
NASA Glenn Research Center, Cleveland, Ohio, USA

Abstract

Future avionics systems will require high-bandwidth on-board communication links that are lightweight, immune to electromagnetic interference, and highly reliable. Fiber optic communication technology can meet all these challenges in a cost-effective manner. Recent advances in fiber optic technology, especially wavelength division multiplexing (WDM), have opened a number of possibilities for designing on-board fiber optic networks for radar and avionics RF signal distribution. In this paper, we investigate a number of different novel approaches for fiber-optic transmission of on-board VHF and UHF RF signals using commercial off-the-shelf (COTS) components. The relative merits and demerits of each architecture are discussed, and the suitability of each architecture for particular applications is pointed out.

1. Introduction

Recent advances in avionics applications in both civil and military aircrafts require high-bandwidth on-board microwave and millimeter-wave radio-frequency (RF) communication networks. A number of RF systems with their interconnection network based on coaxial cables and waveguides increase the complexity of the RF communication network on board modern civil and military aircrafts with increasing problems related to electromagnetic interference (EMI). A simple, reliable, and lightweight communication system that is free from the effects of EMI, and capable of supporting the broadband RF communications needs of the future on-board avionics systems can not implemented by existing coaxial cable based systems easily. Fiber-optic communication systems can meet all the challenges of modern avionics applications in an efficient and cost-effective manner where a single fiber has the potential to replace dozens of RF cables [1]. In addition, a number of optical fibers can be bundled in a single fiber-optic cable, which has the potential to reduce the weight of the communication hardware significantly. Also, fiber-optic components for airborne applications which are capable of withstanding the adverse environmental conditions on-board an aircraft are already under development [2-6].

Presently, two different optical wavelength regions are used for modern optical communication in optical fiber. These wavelength regions are around 1.31 and 1.55 micron (1310 and 1550 nm, respectively). For both of these wavelengths two methods can be used for fiber-optic transmission: analog and digital. Analog signals are continuously varying signals where the exact waveform of the RF signal needs to be preserved when transmitted over a fiber optic link. This requires the analog fiber-optic transmitter and the analog fiber-optic receiver to be extremely stable, linear, and to have a large dynamic range. On the other hand, digital signals are composed of ones and zeros as in computers. The digital signal does not require preserving the exact waveform of the transmitted signal as long as the transmitted signal is not distorted to the extent that ones and zeroes can not be distinguished from each other. For these reasons, digital fiber-optic communication equipment can perform well even when noise and distortion of the optical signal is present.

Fiber-optic communication networks onboard aircrafts for digital data communication has recently become an active area of research and development [7-11]. However, the systems under development today are digital fiber-optic communication systems which are capable of carrying digital data only, but are not capable of transporting radar and avionics RF signals. Analog fiber-optic links can be employed to transport microwave and millimeter-wave RF signals on board an aircraft. These analog fiber-optic links take as input an RF signal, transports it over fiber, and reproduces at the output an exact replica of the RF waveform fed to it at the input. The RF signal itself may be modulated by a baseband signal by any of the analog or digital modulation techniques. Figure 1 shows a typical RF signal (modulated by analog or digital modulation techniques) being transported by an analog fiber-optic link.

An optical transmitter launches the optical signal into an optical fiber. At the other end of the fiber, we need an optical receiver that converts the optical signal to RF again. Usually a single fiber can carry information in one direction only (simplex) which means that we usually require two fibers for bi-directional (duplex) communication. However, recent advances in wavelength division multiplexing make it possible to use the same fiber for duplex communication using different wavelengths.

In this paper, we will discuss a number of architectures for RF signal distribution with traditional hybrid RF-optical as well as modern all-optical approaches using commercial off-the-shelf (COTS) components. The rest of the paper is organized as follows. In Section 2, we introduce the principles of some of the novel fiber-optic communication techniques based on recent advances in fiber optic systems. Section 3 discusses some generalized fiber-optic distribution networks including all-optical solutions, whereas Section 4 describes fiber-optic architectures for multiple-source multiple-destination networks. We conclude this paper in Section 5.

2. Traditional And Modern Fiber-Optic Systems

We first show how a simple system can be implemented using both traditional and modern all-optical approaches. Figure 2 shows such a simple system where an on-board VHF system communicates with a VHF antenna, and an on-board UHF system communicates with a UHF antenna.

2.1 Traditional Approach

In the traditional fiber-optic approach, separate optical fibers are used for each point-to-point link. Thus, one pair of fibers connects UHF antenna 1 with UHF system 1, and another pair connects VHF system 2 with VHF antenna 2. Each point-to-point link requires a fiber-optic transmitter (Tx), a fiber-optic receiver (Rx), and a continuous fiber-optic light path from each transmitter to the corresponding receiver. This system requires three cable segments: the left segment requires a cable with two fibers, the middle segment requires a cable with four fibers, and the right segment requires two fibers. For the two fibers connecting the UHF antenna 1 with UHF system 1, splicing is required at every cable junction: once at the junction between the left and the central cable segments, and again at the junction between the central and the right cable segments.

This architecture is simple, economical and easy to implement when few systems need to be interconnected. However,

[1] This work is supported by NASA Grant NCC3-703

)-7803-5776-0/00/$10.00 © (2000 IEEE)

IEEE INTERNATIONAL RADAR CONFERENCE

as the number of systems that need to be connected becomes higher and complex, it becomes almost impossible to use fiber cables with multiple fibers. If cables with multiple fibers are used, then they have to be spliced at many locations, making the system lossy and unreliable. On the other hand, using many single-fiber or twin-fiber cables reduces the advantage of weight reduction which could be obtained if fiber cables with multiple fibers could be used. One solution to the problem, which addresses signal-loss at each splice, can be solved by using a fiber-optic receiver and a transmitter at each node where a fiber has to be spliced. This solution, which we call the *hybrid RF-optical approach* is discussed in Section 2.2. Another modern approach, where a number of different wavelengths are carried by the same optical fiber using the *wavelength division multiplexing (WDM)* technology is discussed in Section 2.3.

2.2 Hybrid RF-Optical Approach

In this approach, one fiber carries all the RF signals from left to right, and another fiber carries all the RF signals in the opposite direction. These fibers are, however, split at every node where an RF channel needs to be added to the fiber, or a node where an RF channel needs to be dropped from the fiber. In addition to fiber-optic transmitters and receivers, we also need RF power combiners and RF demultiplexers for this approach. RF power combiners multiplex a number of different RF channels onto a single RF transmission line, while the RF demultiplexer separates an RF channel from a band of RF frequencies. Each transmitting/receiving node must have a channel add-drop subsystem, which, for the simple network of Fig. 2, requires only two add-drop subsystems for VHF antenna 2 and VHF system 2.

The advantage of this system is that only a single pair of fibers running from the nose section to the tail section of the aircraft acts as the fiber-optic trunk line. At any point in the aircraft, if a new channel need to be added to the fiber optic trunk line, the channels coming from the upstream fiber are converted to RF by an optical receiver, the local RF signal is multiplexed with the channels from upstream, and the multiplexed RF signal is again sent out to the downstream optical fiber using an optical transmitter. Although this approach saves some fiber as compared to the traditional approach discussed in Section 2.1, additional fiber-optic transmitters and receivers, as well as RF power combiners and demultiplexers increase weight and power consumption of the system.

2.3 All-Optical Approach

The method of sending more than one wavelengths through an optical fiber is called wavelength-division multiplexing (WDM), which is a new and evolving technology. Using WDM technology, it is possible to share a single fiber for carrying two or more optical channels at different optical wavelengths simultaneously. Thus, a single fiber carries a number of optical wavelengths, and each of the wavelengths carry a number of multiplexed RF channels. In this approach, we need optical power splitters, optical power combiners, and optical wavelength demultiplexers. Optical power splitters split the optical power received from an incoming optical fiber into two or more equal or unequal fractions, and each fraction is transmitted to a new outgoing fiber.

In order to implement the system in Fig. 2, we can choose the wavelength 1330 nm for the UHF system, while the VHF system will communicate on 1280 nm. (Both a splitter and a combiner have the same physical construction. So, a single component can work either as a combiner or as a splitter depending on the way it is connected). We still require two fibers, one for transmission in each direction. However, we do not need four fibers in the central segment as in Fig. 2. For the fiber carrying signal from left to right, optical signals from two transmitters, one from the UHF system 1 and the other from the VHF antenna 2, are combined by an optical power combiner. One of the transmitters transmit at the wavelength 1280 nm, while the other transmitter operates at the wavelength 1330 nm. The combiner at the VHF antenna 2 combines the two wavelengths and launches the combined power onto a single fiber, which runs up to the point where the VHF system 2 is located. At that point, a power splitter splits the total power into two equal halves. The receiver for the VHF system 2 at 1280 nm will receive its channel from VHF antenna 2 via one of the ports of the splitter. The other port of the splitter transmits half of the signal which is received by the UHF antenna 1. The receiver at UHF antenna 1 receives its channel from the UHF system 1 on 1330 nm. Both of these receivers (VHF system 2 and UHF antenna 1) should have the capability to choose the right wavelength from the two wavelengths (1280 and 1330 nm). The right wavelength can be easily separated by an optical wavelength demultiplexer at the receiver. For communication in the reverse direction, we need another fiber running in the opposite direction, and two more combiners/splitters.

The advantage of this method is that it is an all-optical solution where an optical signal injected into the system by an optical transmitter remains in optical form until the optical signal is received by the corresponding optical receiver. Thus, a complete light-path exists between an optical transmitter and an optical receiver for every wavelength that is present in the system, and there is no optical-to-RF and RF-to-optical conversion (as in the solution of Section 2.2) which may degrade the signal-to-noise ratio of the RF signal being carried by the optical signal. Also, the ability to carry many RF signals on different wavelengths over the same fiber means savings in weight. In addition, the use of wavelength multiplexers and demultiplexers, which are passive components requiring no power supply, reduces the power consumption compared to hybrid RF-optical systems.

3. Fiber-Optic Signal Distribution Systems

In this section, we discuss the problem of designing a fiber-optic signal distribution network which distributes an RF signal originating from a single source (e.g., an antenna) and distributes it to a number of points on an aircraft. Figure 6 shows the distribution system design problem in detail. Here, a single VHF antenna receives RF signals which need to be distributed to a number of on-board systems (1, 2, 3 etc.). We can adopt either a hybrid RF-optical approach as in Section 2.2, or an all-optical approach as in Section 2.3. Both these approaches to implement the system in Fig. 6 are discussed next.

3.1 Hybrid RF-Optical Approach

In this method we extend the idea of Section 2.2 to multiple nodes. There is only one pair of fibers running from the nose to the tail of an aircraft. At each point (called a *node*) the incoming optical signal coming from the left side is converted to RF, the local RF channel is extracted, and a new optical signal is transmitted by a fiber-optic transmitter to the outgoing fiber-optic link. Figure 7 shows the implementation details of this approach, where each node is a receiving node. The details of each node are described in Figure 8.

This solution is simple and requires only a single fiber running over the length of the aircraft. However, each node requires a fiber-optic transmitter as well as a receiver in this approach.

3.2 All-Optical Approach

A *fiber-optical splitter* is a device which splits the optical power received from a single fiber into a number of fractions and then transmits each fraction to a separate fiber. It is usually a passive device which is simple and light-weight in construction. Using one or more levels of splitters, it is possible to generate a distribution tree from a single source of fiber-optic signal.

Figure 9 shows the all-optical solution to the signal distribution problem of Fig. 6. In this approach, we first convert the RF signal into an optical signal using a fiber-optic transmitter. Then it is split into eight by a one-to-eight optical splitter. Each of the split optical signals may go through repeaters (where the weak optical signal is first converted to RF, and then re-transmitted by a fiber-optic transmitter, as in Fig. 10). Each of these optical signals is then again split into eight by another level of optical power splitters. If repeaters are not used, then each receiver receives only 1/64 of the optical power transmitted by the optical transmitter at the antenna.

This system is highly advantageous because the optical signal is distributed by an all-optical network (except for repeaters, if needed) and the overall design of the system is simple and easy to implement.

4. Systems With Multiple Transmitters And Receivers

Finally, we describe the design methodology for an on-board system where multiple nodes are transmitting, and each of the systems on board the aircraft must be capable of receiving the transmission from any one of the transmitters.

Figure 11 shows a communications architecture with three antennas from where optical signals are transmitted, and these signals should be transported to any of the on-board systems (three shown in Fig. 11). As in the earlier sections, we can take either the hybrid RF-optical approach, or the all-optical approach.

4.1 Hybrid RF-Optical Approach

In this approach, we use two fibers running in opposite directions throughout the length of an aircraft. At the location of each (transmitting) antenna or (receiving) system, the optical signal is first converted to RF, and then either a new RF channel is added in case of a transmitting node, or the received signal is retransmitted in case of a receiving node. Figure 12 shows the block diagram of such a multiple-transmitter multiple-receiver system. The antenna nodes are transmitting (Tx) nodes, while the system nodes are receiving (Rx) nodes. The details of each of the transmitting and receiving nodes are shown in Figs. 13 and 14, respectively. At each of the transmitting and receiving nodes, the optical signal is converted to RF, an RF channel is added or extracted, and then a new optical signal is transmitted from the RF signal.

This solution has the advantage that the optical signal is being amplified at each of the nodes, so signal loss at connectors is not a problem. In addition, this system utilizes only two counter-running fibers. However, this system has the disadvantage that many fiber-optic transmitters and receivers are required. Also, a signal which was injected to the fiber at the leftmost end reaches the rightmost end after a large number of optical-to-RF and RF-to-optical conversions, which may cause the RF signal to degrade considerably, and the RF signal may have an unacceptable signal-to-noise ratio.

4.2 All-Optical Approach

In this approach, we use dense wavelength division multiplexing (DWDM) technology, where a number of wavelengths, which are separated by only a few nanometers, are transmitted over the same fiber. Different transmitters transmit optical signals at different wavelengths. Just like earlier solutions, we need two counter-running fibers for carrying optical signals in two directions. From each antenna, two separate transmitters are used to transmit the optical signals into the two fibers carrying signals into two (opposite) directions. Each receiving system receives optical signals from an antenna either from the upper fiber or the lower fiber, but not from both fibers from the same antenna (whether the receiving system is located to the left or to the right of the antenna determines whether the signal is received via the upper fiber or the lower fiber). Figure 15 shows the block diagram of an all-optical multiple-transmitter multiple-receiver system.

Each of the transmitting nodes adds a new wavelength (W_1, W_2 etc.) to the set of wavelengths being carried by the optical fiber with the help of an optical power combiner. Each receiving node uses a optical splitter to split the incoming signal and take out a fraction of the optical signal being transmitted through the optical fiber. Each of the receiving systems receives more than one wavelengths. By using wavelength demultiplexers, each of the wavelengths (W_1, W_2, W_3 etc.) can be separated. From each of the separated wavelengths, separate receivers can retrieve the separate RF signals transmitted by different transmitting nodes (antennas).

This system has the advantage that the system uses only two fibers to interconnect a large number of transmitting and receiving nodes. The solution is all-optical, and a light-path is established between every optical transmitter and receiver. Since there are no optical-to-RF and RF-to-optical conversion, the problem of signal-to-noise ratio degradation is eliminated which is a substantial problem in the hybrid RF-optical solution of Section 4.1. Also, by choosing proper power-splitting ratios at the power splitters, the signal strength may be kept at a high level at each point despite the losses at the connectors. Since most of the components are passive, the weight and power requirement for this approach are also less than the hybrid approach of Section 4.1.

5. Conclusion

In this paper, we investigate a number of different novel approaches for fiber-optic transmission of on-board VHF and UHF RF avionics and radar signals using commercial off-the-shelf (COTS) components.

The hybrid RF-optical approach has the advantage of low signal loss due to repeated re-generation of the RF signal, and requires less number of fibers. However, the use of too many fiber-optic transmitters and receivers increases the weight and cost of the hybrid system, and also increases EMI.

The all-optical approach, on the other hand overcomes all these difficulties by ensuring a continuous light-path from a fiber-optic transmitter to one or more fiber-optic receivers while sustaining a strong optical signal. Also, an all-optical approach has the potential for replacing multiple-fiber cables by carrying a number of RF signals on different wavelengths on a single fiber simultaneously, thereby reducing the weight. In addition, all-optical solutions use a number of passive components, and an all-optical solution requires less power than hybrid RF-optical solutions.

References

[1] C. A. Bedoya, "Fly-by-Light Advanced Systems Hardware (FLASH) program", *Proc. SPIE*, vol. 2467, pp. 2-13, 1995.

[2] M. W. Beranek, E. Y. Chan, H. E. Hager, Q. N. Le, and J. S. Wilgus, "Emerging opportunities for applying COTS optoelectronics in avionics fiber-optic networks," *Microprocessors and Microsystems*, vol. 22, no. 8, pp. 439-451, 1999.

[3] M. W. Beranek, E. Y. Chan, H. E. Hager, and Q. N. Le, "Status of optoelectronic module packaging for avionics/aerospace applications," *1998 11th Annual Meeting, IEEE Lasers and Electro-Optics Society*, Orlando, FL, USA, pp. 329-330, December 1-4, 1998.

[4] D. Horwitz, "COTS fiber optic interconnect solutions for mobile platforms," *1998 48th Electronic Components & Technology Conference*, Seattle, WA, USA, pp. 395-403, May 25-28, 1998.

[5] A. G. Lubowe, T. P. Million, E. G. Sayegh, and F. Baumann, "Multifiber optical connectors for avionics," *Proc. SPIE*, vol. 2840, pp. 14-22, 1996.

[6] E. Y. Chan, M. W. Beranek, K. W. Davido, H. E. Hager, C. S. Hong, R. L. St. Pierre, "Challenges for developing low-cost avionics/aerospace-grade optoelectronic modules," *Proc. Electronic Components & Technology Conference*, pp. 1122-1129, 1996.

[7] J. Zhang, "High-speed avionic optical fiber CDMA networks," *IEEE Aerospace & Electronic Systems Mag.*, vol. 14, no. 6, pp. 15-21, 1999.

[8] J. Zhang, "Optical fiber data bus modulation techniques for military avionics," *IEEE Aerospace & Electronic Systems Mag.*, vol. 14, no. 4, pp. 31-37, 1999.

[9] G. L. Nelson, N. M. Rao, J. A. Krawczak, and R. C. Stevens, "Design process for a photonic network for military platforms," *Proc. SPIE*, vol. 3541, pp. 179-190, 1999.

[10] E. M. Drogin, and A. M. Leopardi, "High speed data link concepts for military aircraft," *National Aerospace Electronics Conference*, Dayton, OH, USA, pp. 136-143, July 13-17, 1998.

[11] D. Halski, "Fly-by-light flight control systems," *Aerospace Engineering*, vol. 16, no. 9, pp. 11-18, 1996.

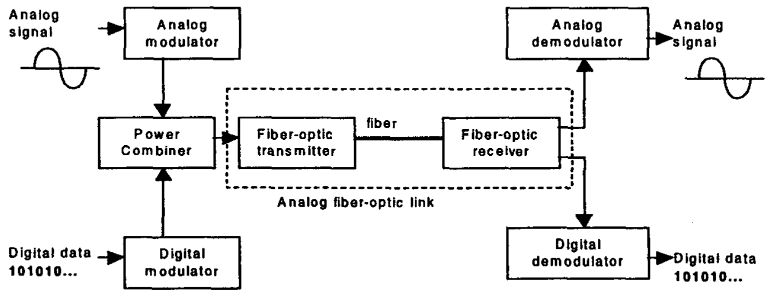

Figure 1: An analog fiber-optic link transports RF signals where the RF signal may be modulated by an analog or a digital modulation technique.

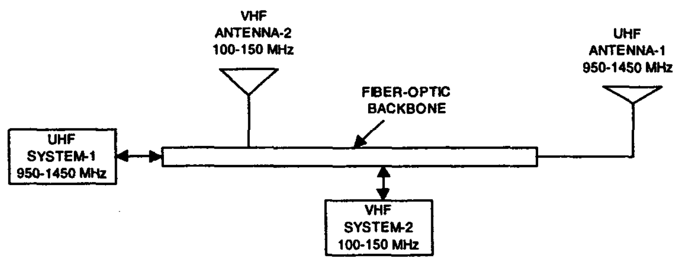

Figure 2: A simple fiber-optic communication system. The VHF antenna communicates with the VHF system, and the UHF antenna communicates with the UHF system.

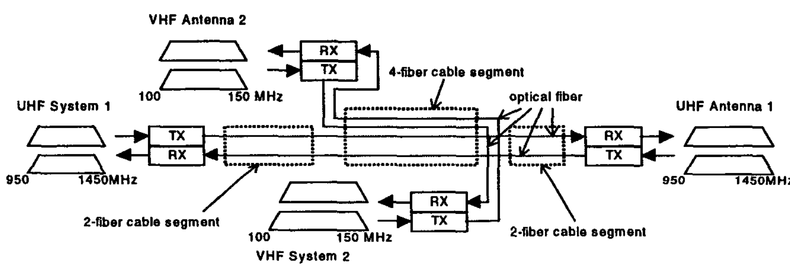

Figure 3: Traditional fiber-optic network solution to the interconnection problem of Fig. 2. RX represents fiber-optic transmitters, and TX represents fiber-optic receivers.

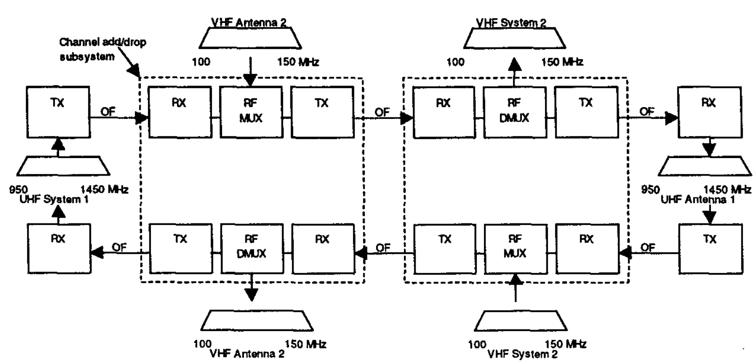

Figure 4: Hybrid RF-optical approach for Fig. 2. OF represents optical fiber. MUX represents RF power combiner (multiplexer). DMUX represents RF demultiplexer. TX represents fiber-optic transmitter and RX represents fiber-optic receiver.

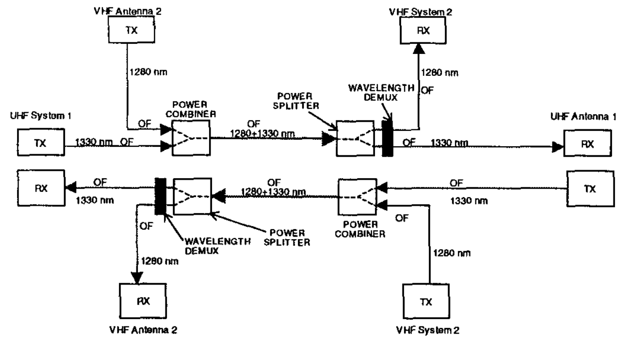

Figure 5: All-optical solution to the problem of Fig. 2 using wavelength division multiplexing. TX represents optical transmitter and RX represents optical receiver. OF represents optical fiber. Wavelength demultiplexer (DEMUX) separates two or more wavelengths from a combination of wavelengths.

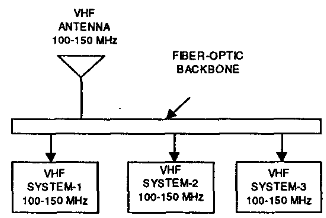

Figure 6: A fiber-optic signal distribution system for a signal originating at an antenna.

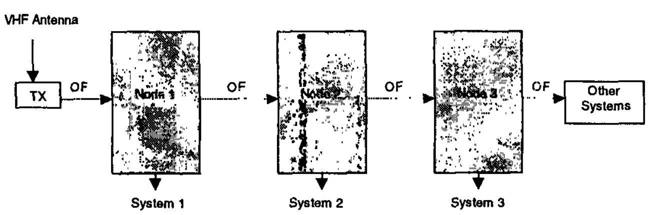

Figure 7: Schematic diagram of hybrid RF-optical solution of the problem in Fig. 6. TX is a fiber-optic transmitter. OF is optical fiber.

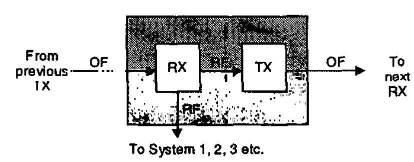

Figure 8: Detailed schematic of a receiving node in Fig. 7. RX is a fiber-optic receiver, and TX is a fiber-optic transmitter. OF is optical fiber, and RF is radio-frequency cable.

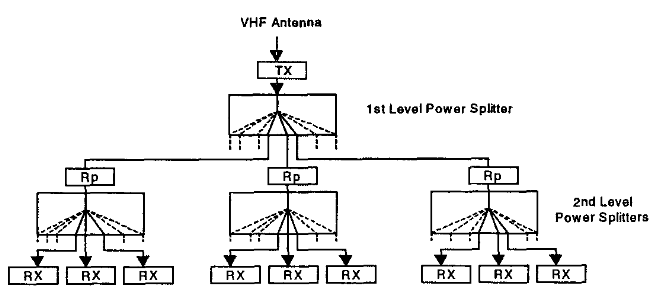

Figure 9: Schematic diagram of all-optical solution to the problem of Fig. 6. There are two rows (levels) of power splitters. Not all branches are shown for clarity. TX represents fiber-optic transmitter, and RX represents fiber-optic receiver. Rp represents optional repeaters which may or may not be required depending on the signal strength at the final receivers. After the top TX, all signals are optical.

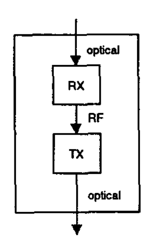

Figure 10: Detailed schematic of a Repeater (Rp) in Fig. 9, which consists of a single fiber-optic receiver(RX) followed by a single fiber-optic transmitter (TX) to increase the strength of the optical signal.

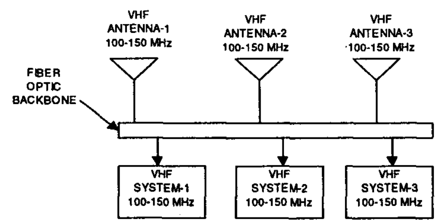

Figure 11: A fiber-optic communication network architecture with multiple transmitters (antennas) and receivers (systems).

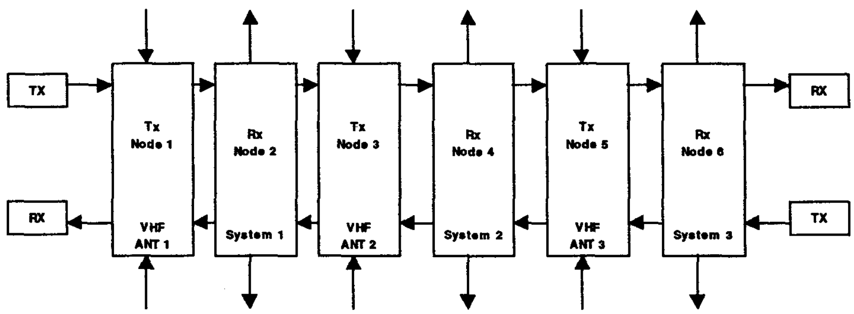

Figure 12: Hybrid RF-optical solution to multiple-source multiple-destination problem. TX is a fiber-optic transmitter and RX is a fiber-optic receiver. In this example, all antennas are transmitting (Tx) nodes, and all on-board systems are receiving (Rx) nodes.

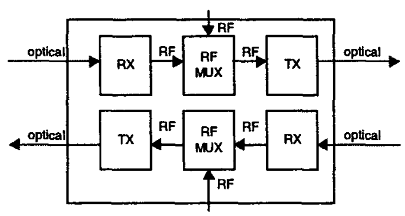

Figure 13: Detailed schematic diagram of a Transmitting (Tx) node in Fig. 12. In each direction, the optical signal is first converted to RF by a fiber-optic receiver (RX), and then a local RF channel is multiplexed with the received RF signal by and RF multiplexer (RF MUX). The combined RF signal is then converted to optical by a fiber-optic transmitter (TX).

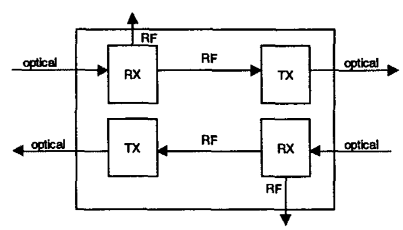

Figure 14: Detailed schematic of a receiving (Rx) node in Fig. 12. In each direction, the optical signal is converted to RF by a fiber-optic receiver (RX), and then the RF signal is re-transmitted by a fiber-optic tranmitter (TX) in optical form. A fraction of the RF signal is also fed to the local RF receiver.

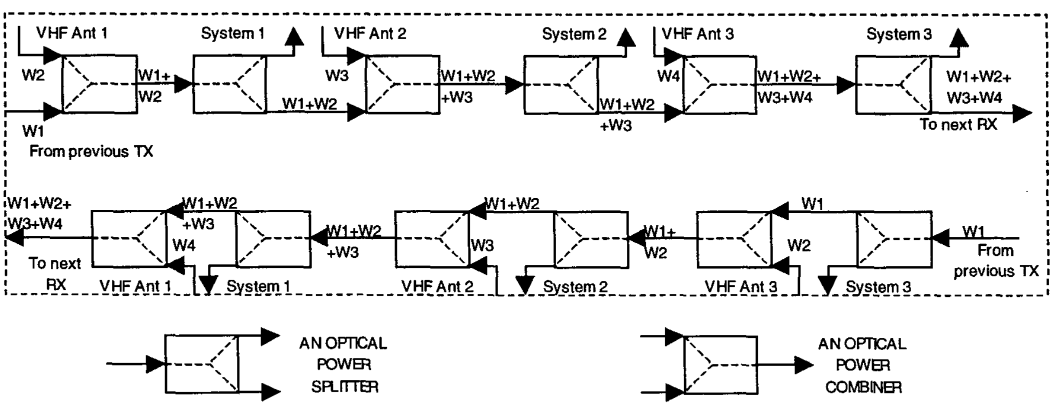

Figure 15: All-optical solution using dense wavelength division multiplexing for implementation of multiple-source multiple-receiver network architecture. The fiber-optic transmitters and receivers are not shown here for clarity. Each of the up-going arrows on the upper row as well as each of the down-going arrows on the lower row supply optical signal to a fiber-optic receiver in systems 1, 2, 3 etc. Each receiver requires a wavelength demultiplexer to separate all the wavelengths present. Optical signals are transmitted from VHF antennas 1, 2, and 3 to optical power combiners.