APPLICATIONS OF ANALOG RF OVER FIBER OPTICS IN SATCOM, ELECTRONIC WARFARE, AND REMOTE ANTENNA LINKS

Abstract

Optical fiber provides a high bandwidth, low loss link solution for long cable runs connecting antennas and RF signal sources with receivers. Long electrical cable runs result in significant attenuation in the higher frequency (Ku and certainly in Ka) bands, as opposed to virtually no transmission loss with optical fiber. Other advantages are smaller diameter and better flexibility with fiber optic cables for easier installation in confined spaces, such as on aircraft and other vehicles, higher capacity, and reduced size and weight for weight-sensitive applications in aerospace platforms.

APIC Link Hardware Solution and Advantages

Link Components

The major elements of APIC's RF over fiber link solution are the optical transmitter (shown in Figure 1(a)), optical receiver (Figure 1(b)), and the fiber cable linking the first two components (Figure 1(c)). The optical transmitter is available in two versions:

- Micro ATX self-contained analog transmitter for 0.05 to 30 GHz, with configurations optimized for the desired operating frequency range (external dimensions of 13.5 cm × 4.5 cm × 2.5 cm); and

- Smaller form factor direct modulated version for DC to 5 GHz (external dimensions of 6.4 cm × 4 cm × 1.6 cm).

The transmitter is available both with and without a low noise amplifier (LNA). When the LNA is used, there are a number of options depending on desired amplification and operating bandwidth.

(a) (b) (c)

Figure 1 (a) APIC optical transmitters—Micro ATX and direct modulated transmitter; (b) APIC optical receiver; (c) single mode fiber optic cables.

The optical receiver is also available in various versions depending on maximum frequency requirements, with options available for up to 10 GHz bandwidth, 20 GHz, and 40 GHz. The optical transmitter and receiver are designed for analog RF modulation with high signal fidelity.

The link active components provide the interface between the electrical domain signals and fiber optics. Both the optical transmitter and receiver have sufficient bandwidth to enable a very wide instantaneous bandwidth of RF to be converted to the optical signal for transmission over fiber. This capability eliminates the need for down-conversion at the antenna and enables a large slice of RF spectrum to be transmitted without dividing into smaller channels (i.e. “channelization”). Transmission of the raw RF also reduces the amount of electronic hardware necessary at the antenna, where space is often at a premium.

Optical Fiber vs. Copper Coaxial Cable

The APIC RF over fiber link provides an economical and transparent replacement for bulky coaxial cable from the antenna or other RF signal source to a receiver. In addition to easier installation and cable weight savings, fiber does not pick up or emit electromagnetic radiation, is lighter and more flexible than copper coaxial cable, and does not corrode or degrade. Figure 2(a) shows a comparison of a fiber optic cable with a high performance coaxial cable used in high grade RF links.

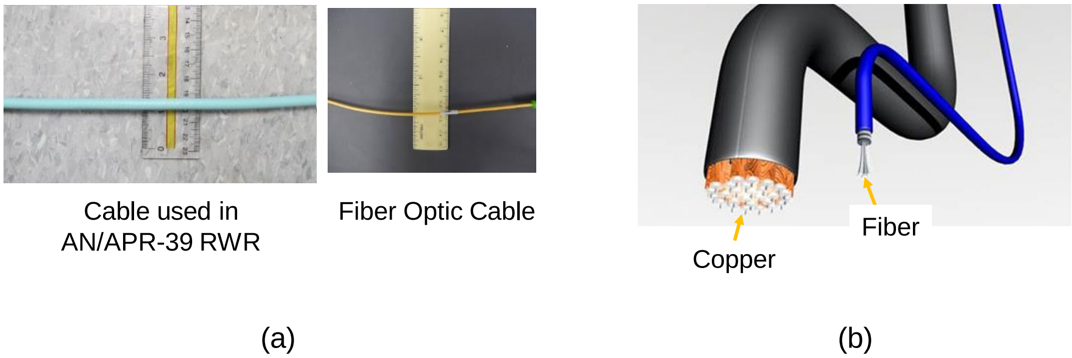


Figure 2 (a) High performance copper coaxial cable (left) compared with fiber optic cable (right); (b) multi-connector cables, both in copper and fiber.

The optical fiber cable consists of the thin fiber encased in a protective jacket. The actual signal-carrying portion of the fiber is a 0.25 mm diameter glass element that is surrounded by Kevlar threads in a durable outer jacket for physical protection. Additional fibers can be carried within the same protective jacket without significantly increasing its overall diameter, while copper coax requires separate cables for each connector so the diameter of the cable grows proportionally with increasing cable count (see comparison in Figure 2(b)). The optical fiber is also non-conductive so it is resistant to electromagnetic interference, for both emission and susceptibility.

Cables meeting aerospace requirements for contamination resistance and flammability are available from vendors such as Carlisle, Amphenol, and Glenair. Examples of such cables installed during an APIC-supported helicopter flight test of fiber optic-linked avionics systems are shown in Figure 3.

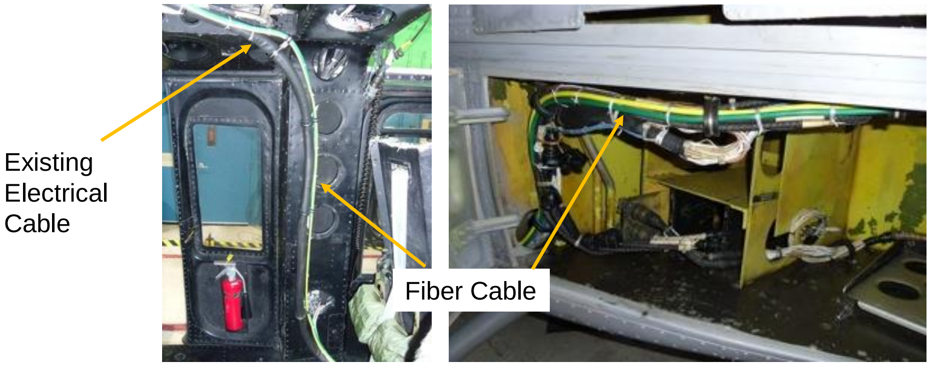


Figure 3 Example of aircraft grade fiber cables installed in a UH-1N for a flight demonstration test of fiber optic links.

APIC Optical Transmitter and Receiver for RF Links

The link is implemented using APIC-developed optical transmitters and receivers as conversion modules to transition from electromagnetic field variations in the RF domain to varying the intensity of light which is then transmitted over optical fiber, as shown in Figure 4. APIC offers a family of products with capabilities of operating from DC to over 30 GHz with low relative intensity noise (RIN) lasers and high dynamic range. The upper figure (Figure 4(a)) shows the baseline copper cable configuration, where one or more low noise amplifiers (LNA's) may be required to compensate for cable loss in the RF signal. Down-conversion to a lower intermediate frequency (IF) may also be used at the source, but this will sacrifice instantaneous bandwidth available for analysis at the processor.

In the fiber optic implementation (Figure 4(b)), a short RF cable is used to connect the antenna to the input port of the APIC analog transmitter, which is available in different configurations depending on the desired frequency range:

- Directly modulated transmitter for DC to 5 GHz, which covers most low band to UHF applications. This provides the most compact solution.

- Externally modulated transmitter for higher frequencies up to 30 GHz, which includes Ku, K, and parts of the Ka band. This transmitter has an optional internal LNA that can be optimized for the desired frequency range to improve the noise figure of the link.

Both transmitters are paired with an analog optical receiver that is available in 10 GHz, 20 GHz, and 40 GHz versions to convert the optical signal back to RF with linearity over a wide dynamic range. Both the transmitter and receiver are matched to 50Ω (input and output, respectively) to match the copper cable impedance for transparent insertion into the link.

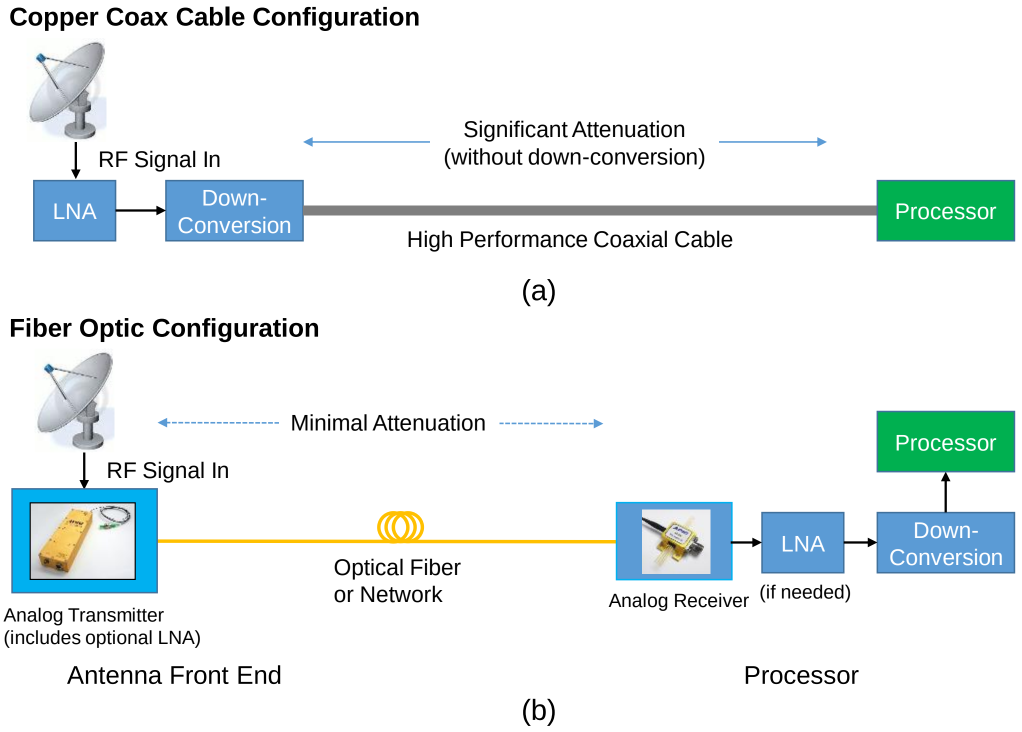


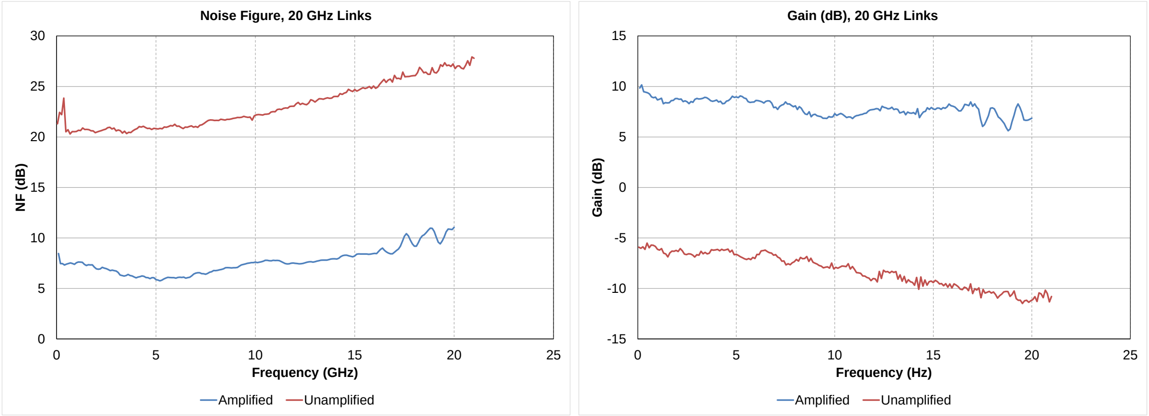
Figure 4 Legacy copper interconnect configuration (top) and equivalent fiber optic configuration (bottom).

Loss difference between copper coax and fiber under various conditions is shown in Table 1. As link length and frequency increases, copper cable suffers from increasing RF signal loss. Optical fiber link losses remain constant with length as the optical fiber adds less than 1 dB per km of loss. The fixed link loss can also be compensated by using a LNA at the input of the link.

The RF link noise figure (NF) and gain measured using the link shown in Figure 4(b) with the Micro ATX optical transmitter and analog receiver are shown in Figure 5(a) and 5(b). Second and third order input intercept point (IIP) and spur free dynamic range (SFDR) are shown in Figures 6 and 7, respectively. Both amplified (with the optional LNA in the optical transmitter module at the RF signal source) and unamplified cases are shown.

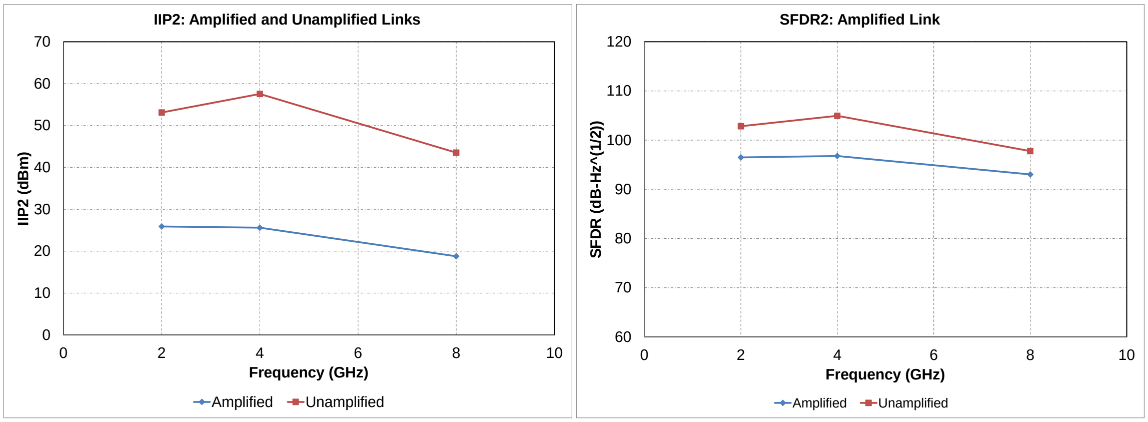
	Copper Cable			APIC Fiber Optic Link		
Link Hardware	Times Microwave QEAM-400 Cable			Micro ATX (unamplified), single mode optical fiber, ARX		
Link Length	30 ft.	100 ft.	200 ft.	30 ft.	100 ft.	200 ft.
RF Attenuation at 10 GHz	6.2 dB	20.5 dB	41.0 dB	8.0 dB	8.1 dB	8.2 dB
RF Attenuation at 18 GHz	14.1 dB	28.1 dB	56.2 dB	11.0 dB	11.1 dB	11.2 dB
RF Attenuation at 21 GHz	15.3 dB	30.6 dB	61.2 dB	11.3 dB	11.4 dB	11.5 dB

Table 1 Loss comparison between copper cable and the APIC RF over fiber optic link.



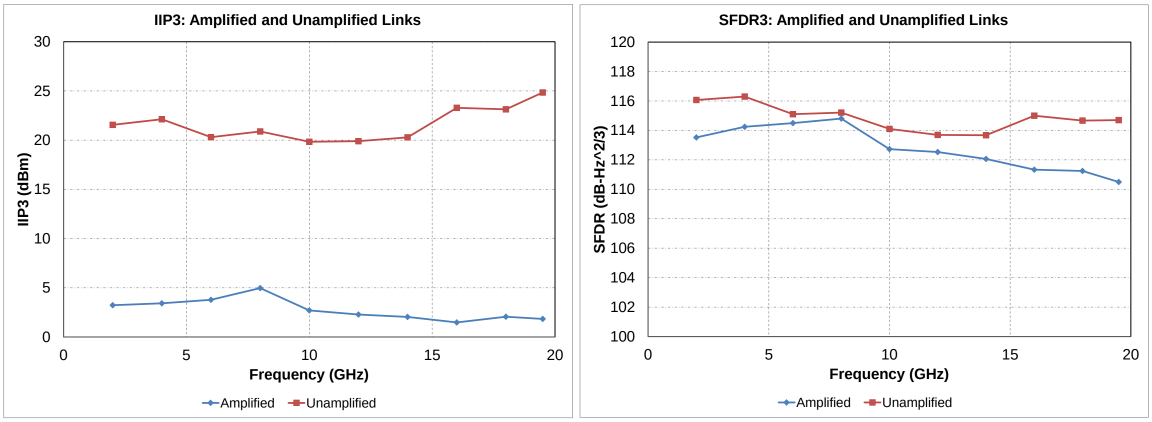
(a) (b)

Figure 5 (a) Link noise figure (NF) for both amplified and unamplified cases; (b) gain for both the amplified and unamplified cases.



(a) (b)

Figure 6 (a) IIP2 for the amplified and unamplified links; (b) SFDR2 for the amplified and unamplified links.



(a) (b)

Figure 7 (a) IIP3 for the amplified and unamplified links; (b) SFDR3 for the amplified and unamplified links.

Size and Weight Considerations

In addition to the performance benefits that are realized by using optical fiber, especially at higher frequencies, implementation of the fiber optic link should also have no negative impact on weight or space requirements as a necessary condition. In most scenarios, significant net weight saving is also realized by using optical fiber as the cable weight savings over lengthy runs exceeds the small additional weight of the interface modules (i.e. the analog optical transmitter and receiver). Two examples are given in Table 2, one for 30 ft representing smaller aircraft and helicopter platforms, and the other at 100 ft for larger transport aircraft-sized applications. As the length of the link increases, the benefits improve. In addition to aircraft, applications on board ships and undersea systems may require even longer links.

	Copper Cable	Fiber Optics	Copper Cable	Fiber Optics
Cable Length	30 ft		100 ft	
Cable Weight per Length	0.22 lbs/ft	0.04 lbs/ft	0.22 lbs/ft	0.04 lbs/ft
Cable Weight	6.6 lbs	1.2 lbs	22 lbs	4 lbs
RF to Fiber Interface Hardware Weight	---	0.7 lbs	---	0.7 lbs
Total Weight	6.6 lbs	1.9 lbs	22 lbs	4.7 lbs
Difference	---	-4.7 lbs	---	-17.3 lbs
% Reduction		71%		79%

Table 2 Comparison of total weight for copper vs. optical fiber, including all interface hardware.

Example Applications

The improved link performance and form factor advantages of the APIC fiber optic link is an enabling factor for applications in areas such as satellite communications (including GPS, broadcasting, and communications links), electronic warfare (EW) and electronic surveillance system links, phase sensitive direction-sensing systems, multi-element radar systems such as phased arrays, and wireless communication systems. Weight and space-constrained applications such as on aircraft and other vehicles are of particular value. Long transmission distances of 100 ft. or more and applications in the Ku and higher frequencies are also advantageous to using fiber optics.

Satellite and Microwave Communications Antenna to Receiver Links

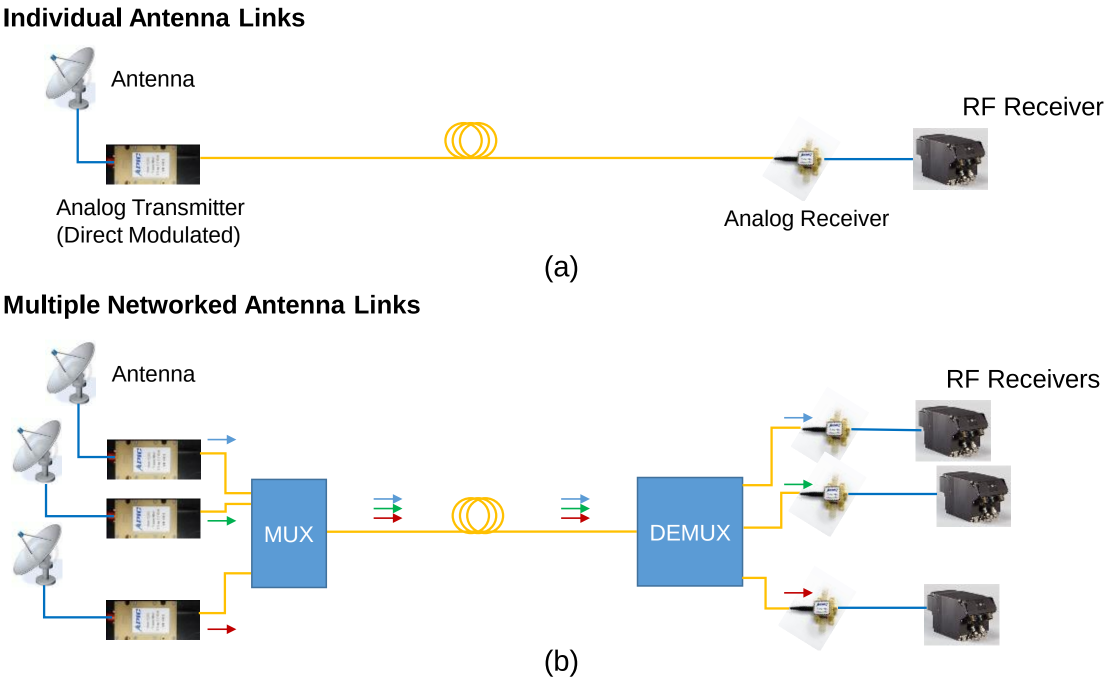
This class of applications is where one or more broadband antennas are located some distance away from the central receiver or processor, requiring lengthy coaxial cable runs for connection. Long cable runs have the disadvantages of:

1. Increasing RF signal attenuation of the link with both distance and frequency, particularly for distances of 100 ft. or more and operation at Ku band and higher frequencies.
2. Increasing cable plant weight and space requirements with distance;
3. Susceptibility of the cable to electromagnetic interference;
4. Bulk of the cable, resulting in cable routing challenges;

Representative system applications where the antenna to receiver distances are significant and therefore prime candidates for RF over fiber implementation include:

- Satellite communications receivers, including global positioning satellite (GPS) operating at 1.228 and 1.575 GHz, and other applications with frequencies up to 30 GHz and extendable to 40 GHz;
- Airliner inflight entertainment (IFE) receivers for live satellite television and radio programming;
- Distribution of video and other types of communication or media signals;
- Satellite direct broadcast satellite antenna to receiver connections;
- Radar and electronic threat warning system antenna links (antenna network to processor);
- Wireless communication network front haul links (i.e. antenna elements on the tower with ground-based transceiver units).

Fiber optics has the advantage of very low attenuation (of a fraction of a dB per km) once the signal is transitioned to the optical domain. Examples of link configurations are shown in Figure 8. The basic single antenna to receiver link implemented using fiber optics is shown in Figure 8(a). For networked or multi-source applications with multiple antennas or signal sources, wavelength division multiplexing (WDM) is used to carry multiple optical signals over the common portion of the path in a single fiber, as shown in Figure 8(b). The individual signals are then separated at the destination to continue on to their intended receivers. With copper cables, separate cables would be required for each connection, resulting in a duplicative bundle of cables along their common path. Combination and separation of the individual signal wavelengths is implemented using a series of optical filters or wavelength selective elements.



(a)

(b)

Figure 8 Examples of RF link configurations for connecting remotely located antennas with the RF receiver.

For frequencies below 5 GHz, which includes GPS signals, the directly modulated analog transmitter (shown in this figure illustration) can be utilized for reduced interface hardware space requirements in the antenna end of the link. Otherwise, the units would be similar to those shown in Figure 4(b).

A similar application, shown demonstrated in Figure 9, uses the RF over fiber link to carry the raw video signals from a thermal infrared imaging camera to the monitor. As the link is analog modulated, it is protocol-independent, being able to transmit a wide range of digital modulation formats as well as raw analog signals.

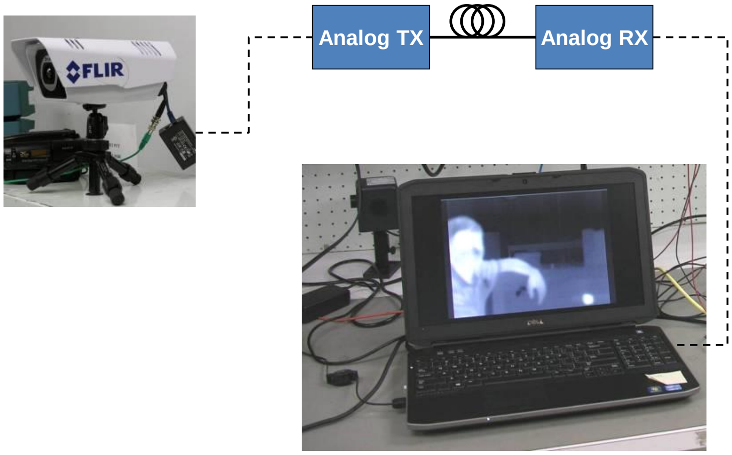


Figure 9 FLIR camera link using fiber optics.

Multi-Antenna Phase Preserving Links for Electronic Warfare (EW) Systems

Electronic Support Measures (ESM) systems such as the AN/ALQ-210 use multiple phase-matched interconnections between the central processor and antenna elements located a different orientations on an airborne platform for threat detection and location. With multiple cable links, the opportunities for cable weight, cost, and installation labor savings are multiplied. These systems also require signal phase control and stability, which is provided by the analog transmitter's support electronics. Figure 10 shows a typical configuration using a system with a total of 16 parallel links, 4 from each antenna element in separate quadrants. Other systems may use different numbers of links so the fiber optic system can be scaled to fit the requirement.

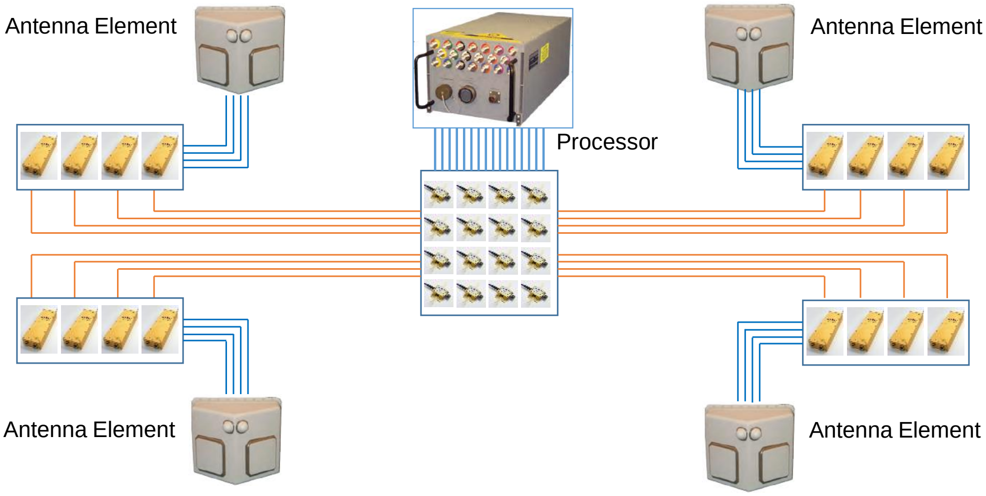


Figure 10 Fiber optic link implementation for a multi-link ESM system with multiple parallel, phase-preserving link requirements.

The weight impact for the example system is given in Table 3, with the baseline copper cable case being 40 feet in length. For 16 total links, there is a significant net weight savings that translates into increased fuel or mission payload. In addition, by combining 4 fibers into a single cable, the weight of one fiber cables is now shared by 4 links, so its weight was allocated over these links (with a small allowance for the additional connectors that will be required). This is shown as Case 2 in Table 3. If the four cables in the copper implementation are bundled and routed along a common path, this combination of fibers in a common cable matches the cable layout of the original installation and there is no change in redundancy as a result of combining the individual fibers in a common cable.

	Copper Cable	Fiber Optics (Case 1)	Fiber Optics (Case 2)
Cable Length per Link	40 ft		
Cable Weight per Length	0.22 lbs/ft	0.04 lbs/ft	0.0125 lbs/ft (4x sharing)
Cable Weight per Link	8.8 lbs	1.6 lbs	0.5 lbs
RF to Fiber Interface Hardware Weight	---	0.7 lbs	0.7 lbs
Total Weight per Link	8.8 lbs	2.3 lbs	1.2 lbs
Difference	---	-6.5 lbs	-7.6 lbs
Difference per Quadrant (4 links)	---	-26 lbs	-30.4 lbs
Difference per System (4 quadrants)	---	-104 lbs	-121.6 lbs

Table 3 Comparison of total weight for copper vs. optical fiber, including all interface hardware.

A similar application is in phased-array radars where multiple links that are phase-matched are required. Fiber optic links are used to carry signals between the processor unit and the radiating elements (Figure 11). For outbound transmissions, the RF power amplifier is located at the antenna aperture as the fiber link is not designed to transmit high power RF.

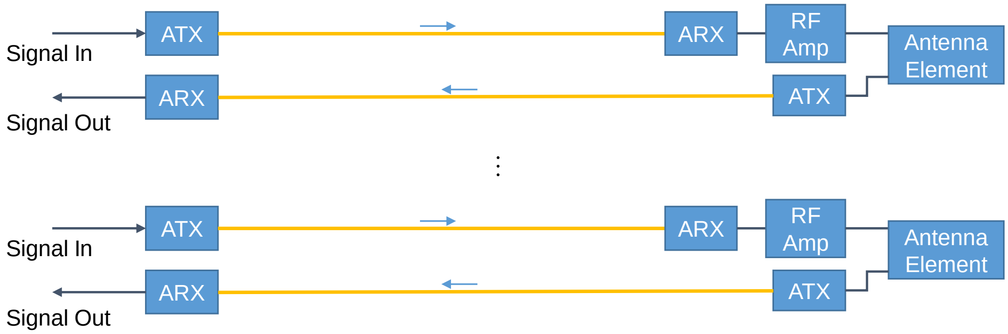


Figure 11 Multiple RF over fiber links with phase matched transmitters for phased-array applications.

Inter-Facility Communications

The RF over fiber link can be used for a number of cases where signals are transmitted within a facility or between buildings where long copper cables (with necessary mid-link amplification being used) would otherwise be implemented (Figure 12). Fiber links can also consolidate parallel copper cables in a single multi-fiber cable (to minimize end to end optical loss) or in a single fiber using wavelength division multiplexing (WDM) if warranted by the link topology. Application examples include:

- Data communications links;
- Microwave and RF antenna links;
- RF test facilities;
- Video distribution.

As the hardware is configured for analog signal transmission, it can accommodate different digital modulation formats (i.e. being protocol independent) as well as raw analog signals.

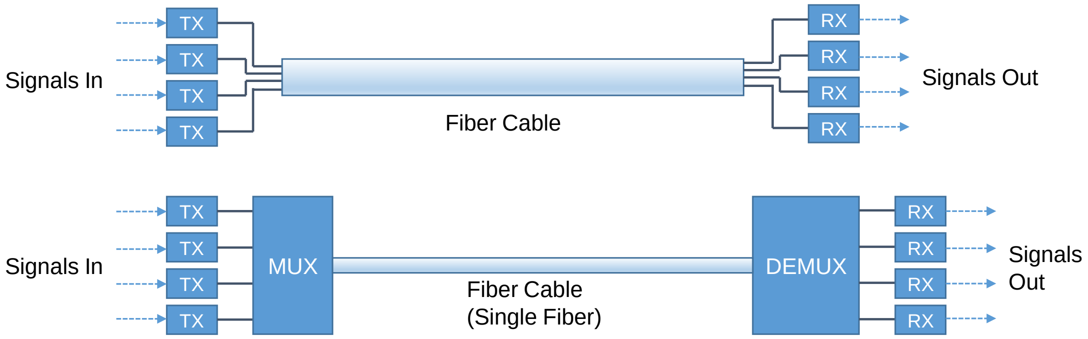
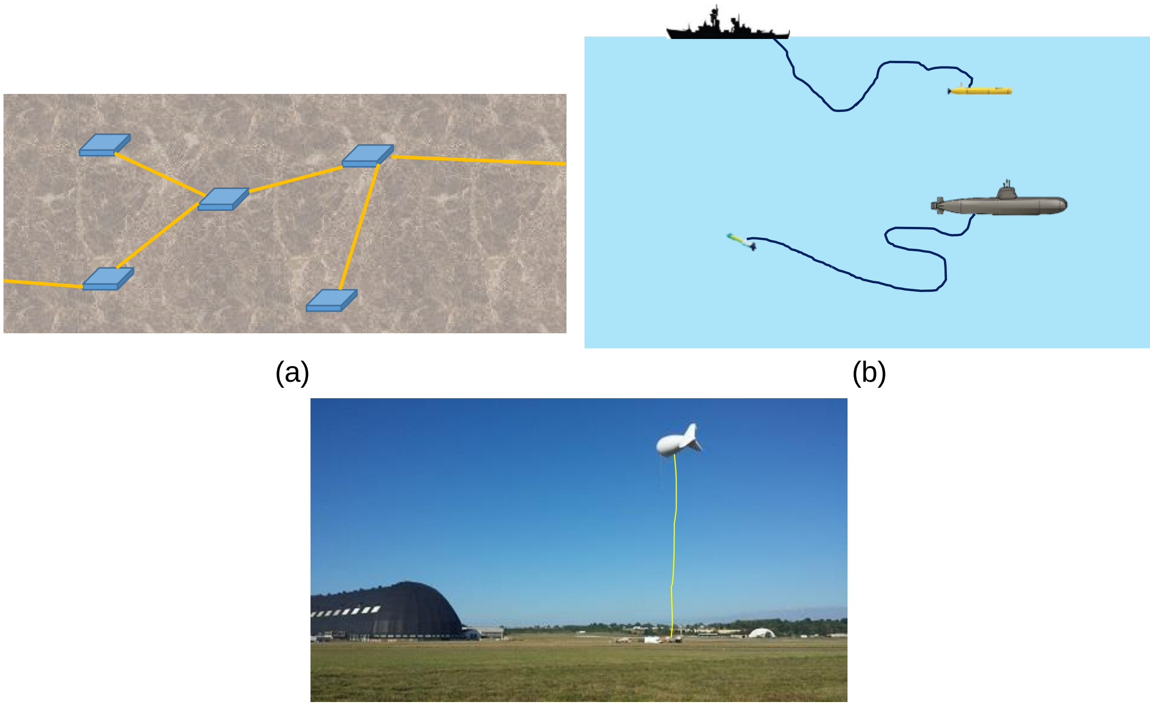


Figure 12 Multiple links for inter-facility communication links, using a multi-fiber cable as well as WDM in a single fiber.

A variation of this application is in remotely located sensors (Figure 13(a)), remotely operated vehicles, such as unmanned underwater vehicles (UUV's, Figure 13(b)), and tethered aerostats (Figure 13(c)). Fiber optics have already been used in undersea communications cables to provide increased bandwidth capacity. Connection topologies can be in a star or ring configuration, or a combination of these depending on system requirements. Connections with towed or autonomously powered vehicles through a fiber umbilical is another application, where the fiber provides much higher bandwidth for exercising control of the remote vehicle as well as transmission and reception of collected data. Aside from the obvious military applications, similar systems have commercial applications in oil and gas exploration systems monitoring and oceanographic surveys.



(a) (b)

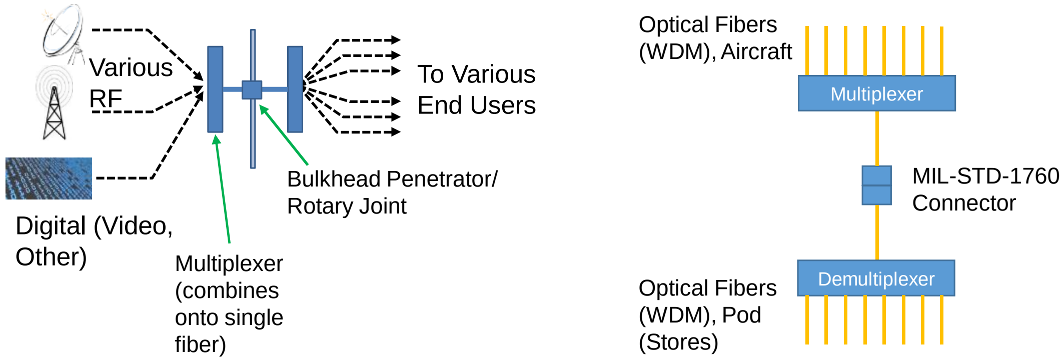
(c)

Figure 13 (a) Undersea network link application for fiber optics; (b) remote underwater vehicle to control vessel link application using a fiber optic umbilical; (c) communications link to and from a tethered lighter-than-air vehicle (aerostat).

A related application is situations where the wiring topology requires passing all of the cables through a single or limited number of termini, such as with a fiber-optic rotary joint for submarine mast applications or a detachable connector (i.e. MIL-STD-1740) for stores or pod-mounted systems (shown in Figure 14(a) and (b), respectively). In this case, WDM is utilized even with the additional multiplexer and demultiplexer components that would be needed because of the requirement that a single fiber be used at the bulkhead penetration or interface point.

Wireless Network Antenna Remoting

The growth of wireless communications and spectral congestion has led to deployment of an increasing number of base station antennas to service a growing number of cells to space-multiplex the limited number of available RF frequency channels. One of the consequences of this trend is the requirement for remote links between the RF transceivers and their antennas, which can be addressed using RF over fiber. Use of fibers enables very low loss links over distances of tens of kilometers to be implemented (Figure 15). This application can also be used in portable military tactical wireless networks for setup in forward operating locations. These stations may be in fixed ground locations or vehicle-based.



(a) (b)

Figure 14 Use of WDM to route multiple signals through a limited number of termini such as a fiber optic rotary joint.

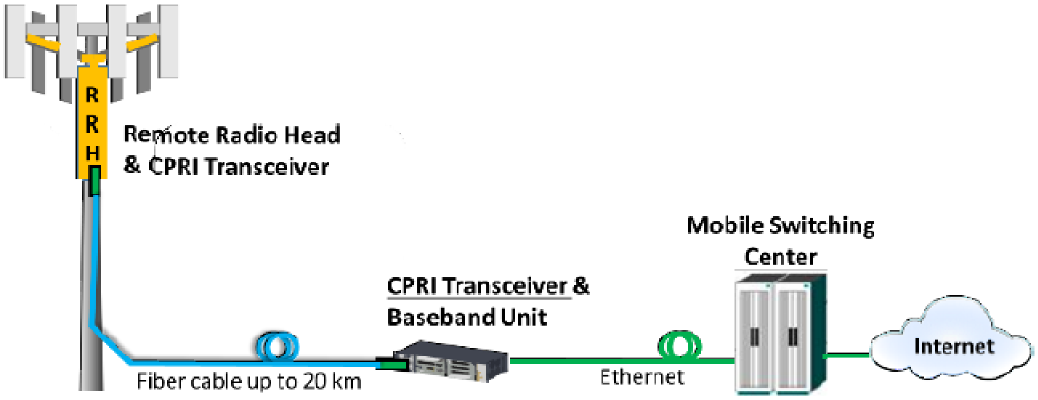


Figure 15 RF over fiber link application for the wireless network remote radio head to base station interconnect.

Summary and Conclusions

APIC's RF over fiber link provides a transparent, efficient, turnkey solution to implementing fiber optic transmission of analog RF signals over a frequency range from DC to 30 GHz. The conversion hardware is self-contained and provides a seamless interface between the RF and optical signals. The extra weight of the hardware is more than compensated by cable weight savings even for short (~10 feet) runs; as the interconnect distances become longer, the greater the weight reduction benefits. In addition, the performance and loss reduction advantages are evident at higher signal frequencies (i.e. above 10 GHz and particularly at frequencies beyond the upper end of the Ku band). Satellite receivers (including GPS), electronic sensor and warfare systems, microwave communication links, wireless data networks, and data communications are some of the many potential application areas.