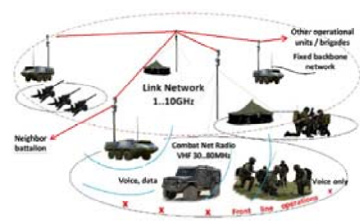
APPLICATIONS OF ANALOG RF OVER FIBER OPTICS:

ANTENNA LINKS

Long distance, high-frequency RF interconnects between the antenna and receiver are well-suited for implementing RF over optical fiber technology, where the RF signal is used to modulate light for transmission over compact optical fiber for long distances with little loss. This approach results in significant performance, weight, and space advantages over using copper cable. Copper cable also has significant disadvantages in signal loss with increasing distance and frequency; lack of flexibility in routing the cables; electromagnetic signal leakage; and cable weight. Fiber optics is compact, very low loss over long distances, and presents significant opportunities for weight and space savings, particularly in harsh environment and vehicle applications shown in Figure 1. Longer distance, high bandwidth links are especially useful for radio astronomy, satellite ground stations, and wireless network antenna links.

Radio Astronomy and Satellite Ground Stations

Aircraft Antenna to Receiver Links



Military Tactical Networks

Vehicle Networks

Ship-Borne Networks

Building Networks (i.e. DAS)

FIGURE 1 Example link applications that are candidates for RF over fiber replacement.

IMPLEMENTATION OF RF OVER FIBER LINKS

LINK CONFIGURATION

The fiber optic link replacement for copper cable uses two conversion modules, one at the ends of the link to interface between the RF signal with the modulated light that is carried over the optical fiber (Figure 2). At the antenna (RF signal source), an amplitude modulated optical transmitter is used to transfer the RF signal onto the optical carrier for transmission over single mode optical fiber. At the signal destination, a photodetector is

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used to convert the signal back to RF format. The small size and flexibility of the optical fiber provides added flexibility in cable installation and routing over larger copper cable. In addition, fiber has the advantage of reduced electromagnetic interference (both emission and susceptibility) over copper cable.

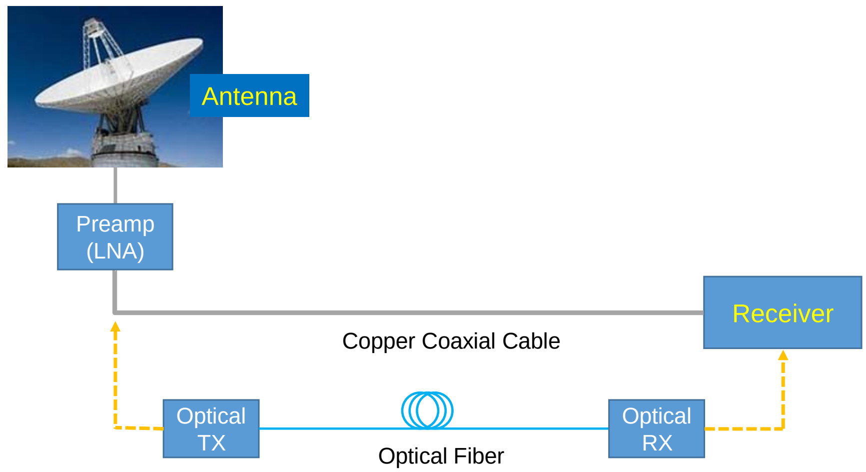

FIGURE 2 Copper cable link replacement using RF over optical fiber.

For transmit/receive links, where two-way RF traffic is carried over the link, the transmitting link is configured as shown in Figure 3, with the RF power amplifier moved to near the antenna as RF over fiber does not efficiently transmit high power. The most efficient configuration is for the downlink and uplink signals to be transmitted in separate fiber strands within a common cable, where the additional fiber adds very little additional weight as most of the cable is sheathing and protective layers. Transmission in a single fiber is also possible, but requires a fiber circulator to combine and separate signals at the ends of the link.

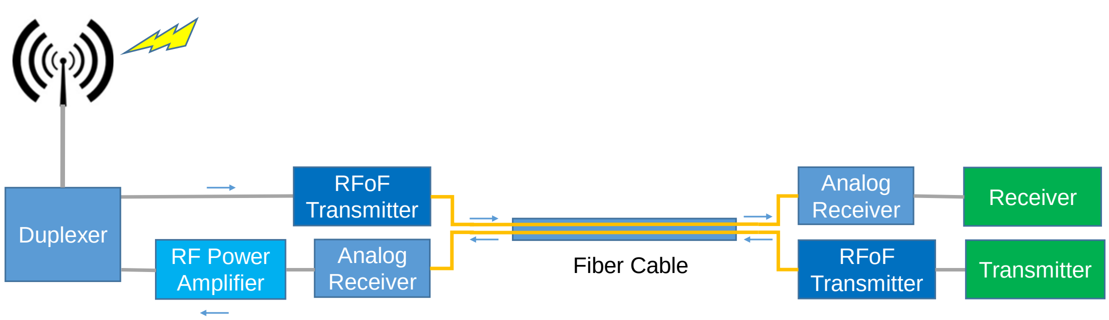

FIGURE 3 Bi-directional link configuration with fiber optic transmission of the received and transmitted RF signals, with the RF power amplifier moved to the end of the link.

Fiber optics is particularly advantageous for transmission of multiple signals over a common path or when a substantial portion of their paths overlap. The most

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straightforward solution is to use a multi-fiber cable, shown in Figure 4(b). Additional fiber strands can be added to the cable assembly with little incremental increase in weight and cable diameter. For cases where only a single fiber is available or feasible, then wavelength division multiplexing (WDM) where all of the signals are combined into a single fiber is used (Figure 4(c)). WDM implementation requires a few additional optical components for optical channel combining and separation.

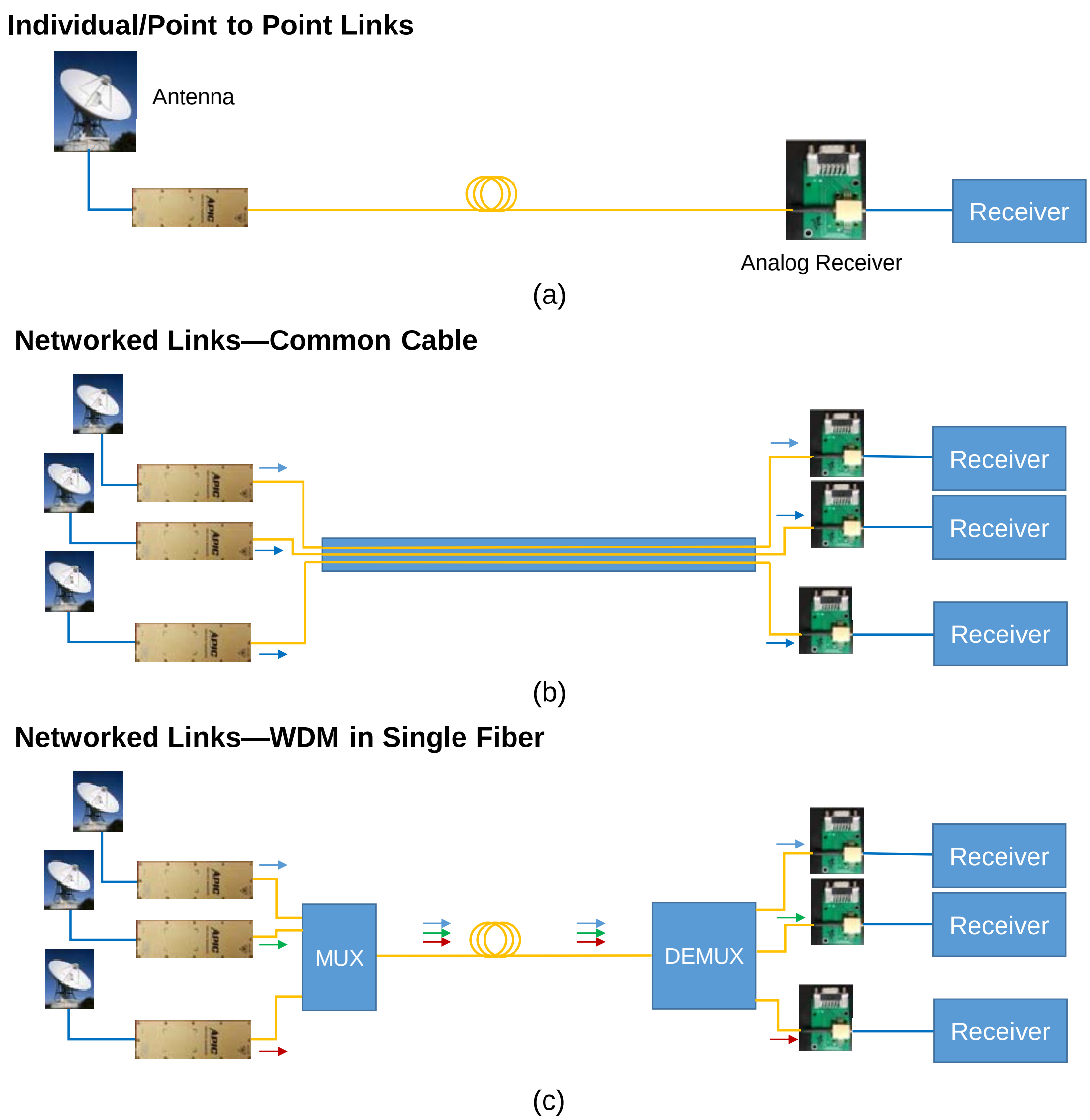

FIGURE 4 (a) Individual link for a radio telescope observatory or ground station to a remote receiving location; (b) multiple antennas networked over a common cable with multiple fiber strands; and (c) multiple channels transmitted over a single fiber using WDM.

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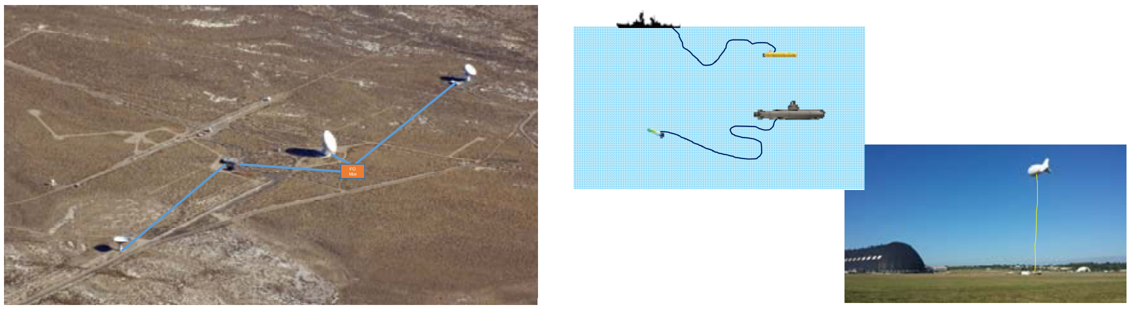
Figure 5 illustrates examples of fiber optic networking for fixed ground stations as well as tethered vehicles and platforms.

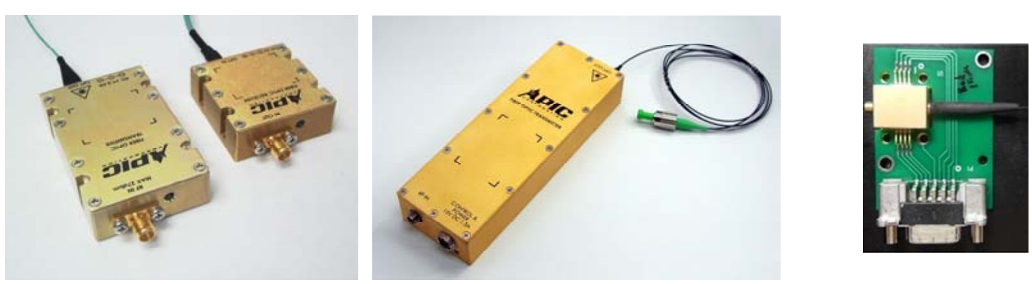


(a) (b)

FIGURE 5 (a) Radio observatory or satellite link application as an example for RFoF with potential networking architectures; (b) tethered vehicle links as another example application for RFoF.

COMPONENTS FOR IMPLEMENTATION OF FIBER LINK

Optical transmitters and receivers for analog signal transmission over fiber that are offered by APIC Corporation are shown in Figure 6 For frequencies up to 5 GHz, the compact direct modulated laser transmitter, shown in Figure 6(a), can be used. Otherwise, the transmitter using a high-performance continuous wave (CW) laser with an external modulator for operation up to 20 GHz is used (Figure 6(b)). This module is a self-contained package with all necessary support electronics and control software. The optical receiver (shown in Figure 6(c)) recovers the RF from the modulated optical signal. It is comprised of a high linearity photodetector module that is mounted on a printed circuit board (PCB) for user convenience. It is available optimized for operation at various frequency bands including 10, 20, and 40 GHz.



(a) (b) (c)

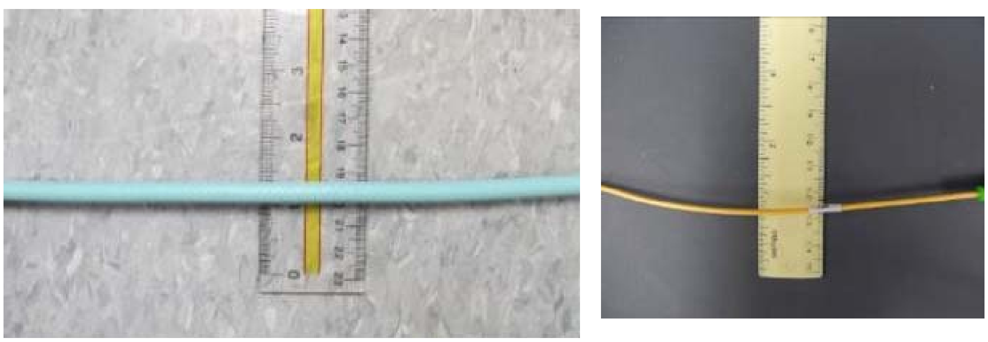
FIGURE 6 (a) Direct modulated RF over fiber optical transmitter and packaged receiver; (b) optical transmitter for up to 20 GHz in a compact module; and (c) optical receiver package mounted on a circuit board.

OPTICAL FIBER ADVANTAGES

Optical fiber provides high bandwidth, low loss, lightweight, electromagnetic interference-resistant connectivity for RF signals that have applications in a number of platforms and installations. The RF signal is used to modulate light from a semiconductor laser in a highly linear process, which is then carried over a compact single mode optical fiber, replacing bulky copper cable. Benefits of fiber over copper are:

- Flexibility and easier to route through tight spaces than the more inflexible and larger diameter copper cable;
- Low maintenance, lower susceptibility to corrosion and degradation due to age;
- No electromagnetic emission or susceptibility in the cable;
- Lighter weight overall, even when considering the additional optical transmitter and receiver required.

An example comparison is shown in Figure 7, with Figure 7(a) showing aircraft grade copper coaxial cable for up to 20 GHz and Figure 7(b) showing a section of single mode fiber, including its protective jacket.



(a) (b)

FIGURE 7 (a) High-performance copper coaxial cable (used in an aircraft avionics system); (b) single mode fiber optic cable shown to scale for comparison.

LINK CHARACTERISTICS AND PERFORMANCE

LINK SIGNAL ATTENUATION COMPARISON

Copper RF cable, even expensive high-performance versions, has significant signal attenuation at higher frequencies and over long link distances. An example of the signal loss over various transmission distances is shown in Table 1, which compares of Times Microwave QEAM-400 cable that is used for harsh environment antenna links to a fiber optic link using the APIC optical transmitter and receiver over single mode fiber. The loss is considerable as the frequency increases and over distances exceeding 100 ft., which would include most aircraft cable runs and ground station links. On the contrary, the signal loss in fiber remains relatively constant as a function of distance.

	Copper Cable				APIC Fiber Optic Link		
Link Hardware	Times Microwave QEAM-400 Cable				Micro ATX (unamplified link), SMF, and ARX		
Link Length	Loss/ Length	40 ft	100 ft	500 ft	40 ft	100 ft	500 ft
RF Attenuation, 6 GHz	0.156 dB/ft	6.2 dB	15.6 dB	78.0 dB	6.0 dB	6.0 dB	6.1 dB
RF Attenuation, 10 GHz	0.205 dB/ft	8.2 dB	20.5 dB	102.5 dB	8.0 dB	8.0 dB	8.1 dB
RF Attenuation, 18 GHz	0.281 dB/ft	11.2 dB	28.1 dB	140.5 dB	11.0 dB	11.0 dB	11.1 dB

TABLE 1 Link loss comparison between copper cable and fiber optics.

The copper cable loss (from the manufacturer's data sheet) ranges from 0.156 to 0.281 dB/ft from 6 to 18 GHz. The fiber optic link loss shown includes the RF loss from signal conversion as well as attenuation through the optical fiber, which at 0.2 dB/km at 1,550 nm is a negligible component of the total loss. At distances of 40 ft or greater, the copper cable link shows increasing signal loss, which may require significant in-line amplification. The fiber link can be made lossless by using a low noise amplifier (LNA) at the fiber optic transmitter to compensate for conversion loss.

The link budget for both the copper cable and fiber example cases are shown in Figure 8. The signal source is an antenna/preamplifier combination, with 100 ft distance separating it from the receiver. Copper cable has approximately 16 dB total RF signal loss, which results in -66 dBm signal strength at the receiver input. For the fiber optic case, the unamplified fiber optic link has 6 dB loss, which is almost all from the conversion loss. The additional optical signal loss from fiber attenuation is almost negligible, so the loss is unchanged regardless of link length. The received signal is -56 dBm, for a 10 dB loss advantage over the copper link. By using an internal low noise amplifier (LNA) in the optical transmitter module, an amplified link can be configured, where the LNA compensates for the conversion loss and improves the noise figure of the link.

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.

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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.

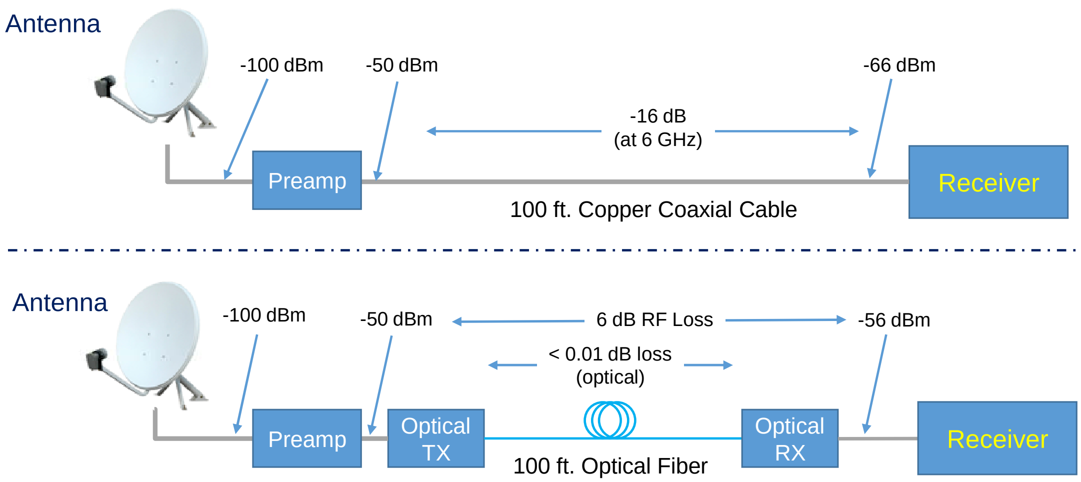

FIGURE 8 Copper cable link replacement using RF over optical fiber.

Cable Length	40 ft		100 ft		500 ft	
	Copper Cable	Fiber Optics	Copper Cable	Fiber Optics	Copper Cable	Fiber Optics
Cable Weight per Length	0.15 lbs/ft	0.04 lbs/ft	0.15 lbs/ft	0.04 lbs/ft	0.15 lbs/ft	0.04 lbs/ft
Cable Weight	6.0 lbs	1.6 lbs	15 lbs	4.0 lbs	75 lbs	20.0 lbs
RF to Fiber Interface Hardware Weight	---	0.7 lbs	---	0.7 lbs	---	0.7 lbs
Total Weight (All Link Hardware)	6.0 lbs	2.3 lbs	15 lbs	4.7 lbs	75 lbs	20.7 lbs
Difference (Fiber vs. Copper)		-3.7 lbs		-10.3 lbs		-54.3 lbs

TABLE 2 Weight difference between fiber and copper for different link lengths.

EMI BENEFITS

The fiber optic link also has the advantage of reduced electromagnetic emission and susceptibility. An example of the measured emission from the APIC Micro ATX transmitter (used for conversion of RF to fiber optics at frequencies up to 20 GHz) is shown in Figure 9. There is no difference between the background and measurement scans between 1 and 18 GHz. Similar results were obtained at other frequency bands from 2 MHz to 1 GHz.

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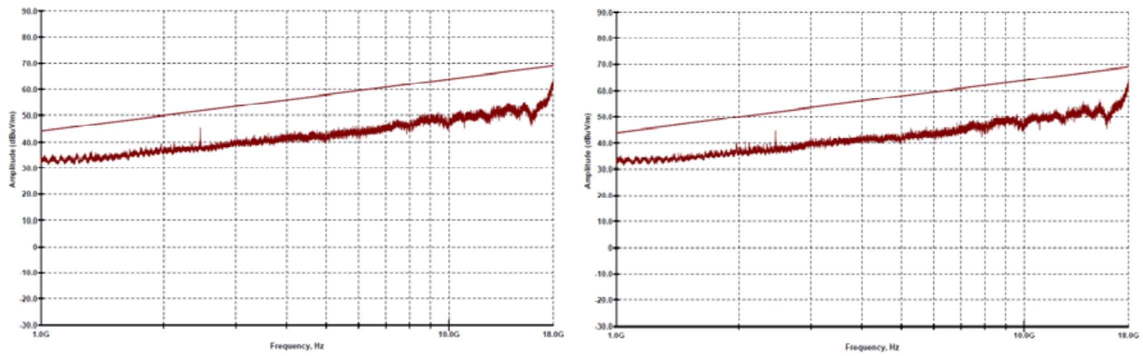

(a) (b)

FIGURE 9 (a) Emission spectrum from the Micro ATX in the 1 to 18 GHz range, vertical polarization; (b) reference ambient scan for vertical polarization.

The reasons for reduced EMI and susceptibility of the fiber optic link include:

- ♦ The fiber cable is non-conductive, so it is unaffected by high electromagnetic fields—copper cables in similar environments require considerable shielding;
- ♦ Lower loss of the fiber link eliminates the need for most RF amplifiers, reducing RF-emitting hardware;
- ♦ Link components have shown low emission and susceptibility to electromagnetic interference in accordance with MIL-STD-461F/G, RE101 and 102 and RS101 and 103.

The RF link noise figure (NF) and gain were measured using the APIC Micro ATX as the optical transmitter and high linearity photodetector as the receiver, with the link configuration as shown in the lower section of Figure 8. Two cases were characterized—one using the direct input of the RF source into the transmitter (unamplified link case) and the other using a low noise amplifier (LNA) at the signal input to the transmitter (amplified link case). Use of the LNA improves the noise figure but reduces dynamic range. Figure 10(a) shows the measured noise figure results for these two cases, while Figure 10(b) shows the corresponding link gain.

The second and third order input intercept point (IIP2 and 3, respectively) and spur-free dynamic ranges (SFDR2 and 3) are shown in Figures 11 and 12. These plots also show the comparison of amplified (with the optional LNA in the optical transmitter module at the RF signal source) and unamplified link cases.

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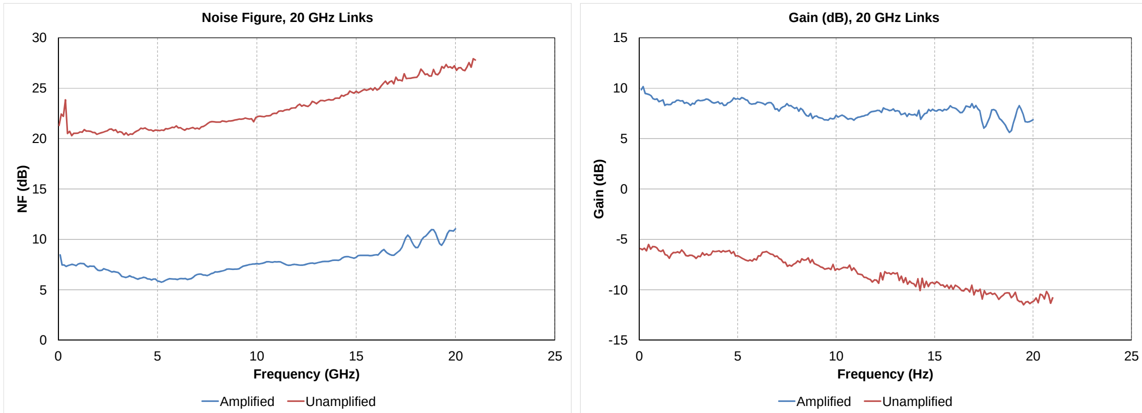
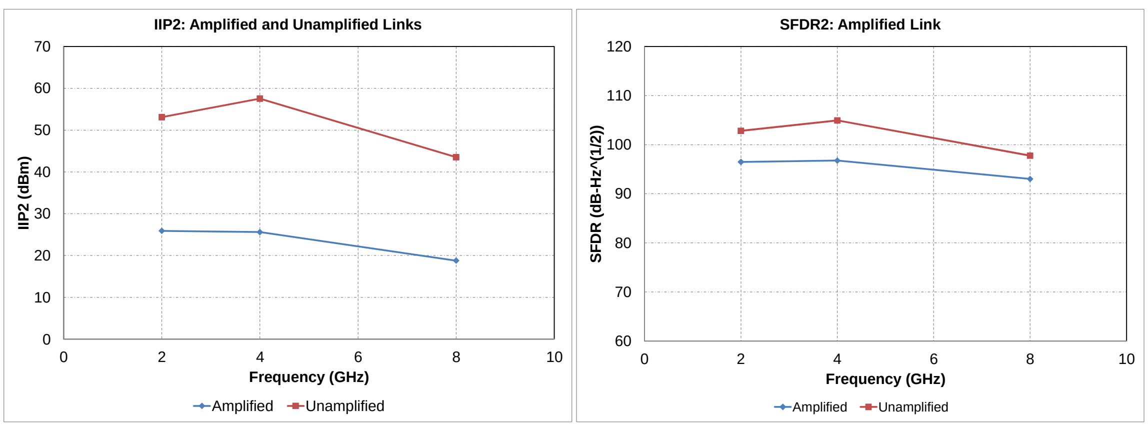


(a) (b)

FIGURE 10 (a) Link noise figure (NF) for both amplified and unamplified cases; (b) gain for both the amplified and unamplified cases.



(a) (b)

FIGURE 11 (a) IIP2 for the amplified and unamplified links; (b) SFDR2 for the amplified and unamplified links.

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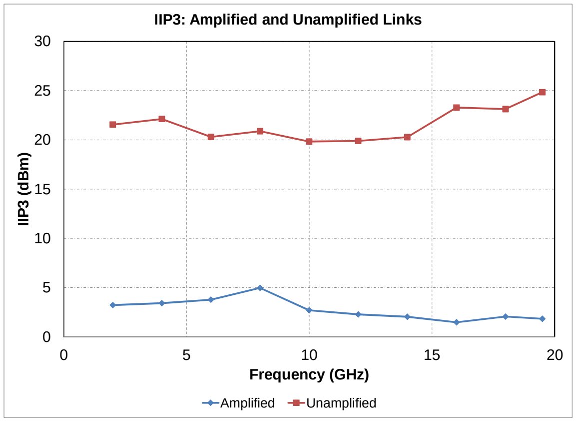
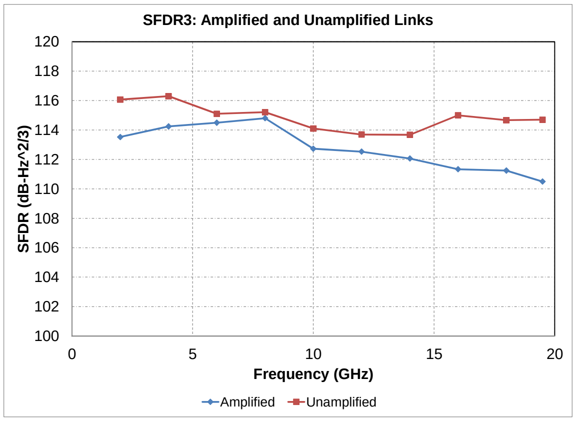


(a)



(b)

FIGURE 12 (a) IIP3 for the amplified and unamplified links; (b) SFDR3 for the amplified and unamplified links.

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 20 GHz in a variety of harsh environments. Using APIC's self-contained optical transmitter and receiver as conversion hardware, a seamless interface between the RF and optical signals is provided. The links are especially advantageous for high frequencies and long distances of several hundred feet and longer, such as for radio astronomy, wireless communication base stations, and local area networks. The extra weight of the interface hardware is more than compensated by cable weight savings even for short (few tens of feet) cable runs. As the interconnect distances become longer, the greater the weight reduction benefits. The benefits accrue for even shorter distances as the operating frequency increases. The links are available as both unamplified links for maximum linearity or with LNA's at the input to the optical transmitter to improve noise figure.

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