MAIN APPLICATIONS OF RF OVER FIBER TECHNOLOGY IN THE DEFENSE AND CIVILIAN MARKETS

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RFOptic
Optical RF Solutions

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Glossary

3GPP	3rd Generation Partnership Project
ACLR	Adjacent Channel Leakage Ratio
CWDM	Coarse Wave Division Multiplexing
DAS	Distributed Antenna Systems
DF	Direction Finder
DUT	Device Under Test
EM	Electromagnetic
EMI	Electromagnetic Interference
EVM	Error Vector Magnitude
EW	Electronic Warfare
Ft.	Feet
GHz	Gigahertz
GNSS	Global Navigation Satellite System
NOC	Network Operations Center
ODL	Optical Delay Line
OPEX	Operational Expenditure
QAM	Quadrature Amplitude Modulation
RCS	Radar Cross Section
RF	Radio Frequency
RFoF	RF over Fiber
UAV	Unmanned Aerial Vehicle
VLB	Very Long Baseline
VNA	Vector Network Analyzer
W	Watt

1. INTRODUCTION

RF-over-Fiber (RFoF) technology is transforming the landscape of signal transmission systems by offering a wideband transport of RF signals between antennas and control locations. In this eBook, we explore the key advantages of RFoF technology, including exceptional signal integrity, immunity to electromagnetic interference (EMI), high bandwidth capacity, reduced size and weight, environmental resistance, and enhanced security.

We will explore what makes RFoF the preferred solution across diverse applications in both defense and civilian markets. We will also take a look at a few examples and case studies that are representative for RFoF technology in defense and civilian applications.

2. WHY RFOF TECHNOLOGY?

RF over Fiber (RFoF) technology is a revolutionary approach in signal transmission systems, transmitting RF signals between antennas and control locations. It is a small signal wideband transmission technology handling signal levels that are typically under +20dBm.

Key advantages include:

- **Exceptional Signal Integrity:** RFoF systems deliver high-quality signal transmission over extended distances far greater than coax cables can sustain. That is crucial for applications such as radar, communication and surveillance where signal fidelity is vital.

- **Immunity to Electromagnetic Interference (EMI):** Fiber optics are not affected by EMI, making them ideal for environments rich in electronic noise, such as military installations and urban areas. Single-mode optical fibers are essentially glass conduits that carry the signal in a cross-section that is 9um in diameter. It is practically impossible to disrupt this optical transmission by induced EM radiation. Running fiber into sheltered areas is far safer than using coaxial cables since EM radiation could be induced onto and conducted by the coax into the sheltered compound.

- **Wide Bandwidth Capacity:** RFoF can accommodate large volumes of data at high frequencies, enabling wideband or multiple frequency division channels to operate simultaneously with minimal degradation. Each RFoF link can deliver signals of bandwidths exceeding 40GHz with reasonable flatness to distances ranging from a few meters to many miles. For comparison, a 50m long RF cable develops an insertion loss slope of about 5dB over a bandwidth of just 1MHz to 1GHz.

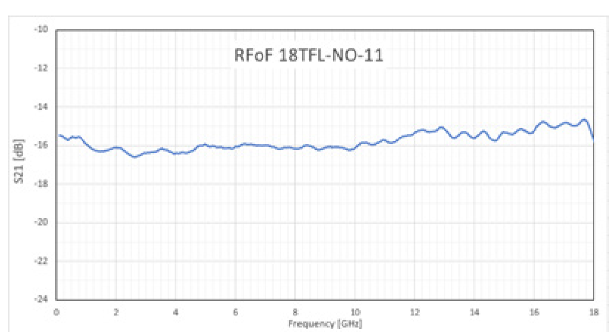

Figure 1 Typical flatness and insertion loss of an 18GHz RFoF link without amplifiers

- Small Size and Weight: Fiber optic cables are lighter and far less bulky than traditional coaxial cables. Single and multiple fiber strands can transport nearly unlimited amounts of RF signals and data at a minimal cost. This enhances deployment flexibility in defense scenarios, particularly for surveillance sensors, EW transponders and drones using expendable interconnect fibers.

- Low Power consumption: RFoF links consume a couple of watts per pair and compare very favorably with coaxial transmission, which necessitates booster power amplifiers in between short cable intervals. In a 60m. application transporting an RF signal of 18GHz bandwidth, the RFoF link required about 5W while a comparable coax transmission requires about 25W to power the amplifiers that recondition the signal at 15-meter intervals.

- Environmental Resistance: Optical fibers are resistant to moisture, chemicals, and extreme temperatures, reducing the need for excessive shielding compared to RF coaxial cables.

- Enhanced Security: Fiber optics offer a higher level of security against eavesdropping and signal interception due to their highly confined transmission properties. Splicing into existing fiber networks can be easily detected.

These advantages position RF over Fiber technology as a preferred solution across various defense and civilian applications.

2.1 EXAMPLE

A 1000m long section of a single mode fiber (SMF) transmits a 20GHz RF signal with an insertion loss that is 7,500 times lower than the loss of a 0.15" equally long coax cable.

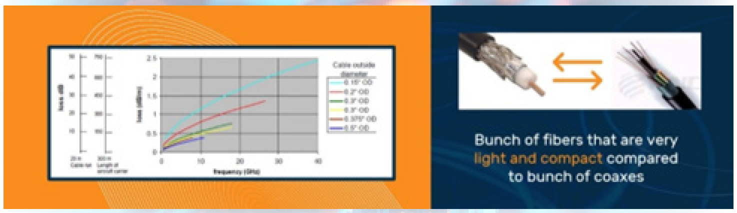

Figure 2 Example: Single Mode Fiber loss versus Coaxial cable

3. RFOF TECHNOLOGY IN DEFENSE APPLICATIONS

In defense applications, RFoF technology plays a critical role in comprehensive remote sensing, secure communication, and surveillance systems. Such systems can be hardened against external interference, preventing damage to sensitive sheltered equipment from electromagnetic pulse scenarios.

Main defense applications using RFoF technology

Optical Delay Line (ODL): ODLs combine RFoF technology with optical delay fiber segment(s). Progressive ODL's can produce a range of delays by incorporating optically switched fiber segments, usually arranged in increasing delays. These instruments play an integral role in the test and calibration of radar systems by introducing precise time delays to the RF signal that simulate target distances for surveillance and fire control radars. ODL's with fast delay switching can simulate range closing for proximity fuses or homing radars. To watch the video, click here.

Figure 3 Progressive Optical Delay Line

Altimeter radars are calibrated and or verified using ODLs that simulate heights above ground. ODL solutions are customized based on application requirements, supporting delays ranging from a nanosecond to millisecond or from 0.5ft to more than 100,00ft at virtually any desired step resolution. Additional features such as high-speed delay state switching, number of delays, precision and accuracy, Doppler modulation, RF gain, bidirectional RF transmission, and many more RF and optical may be added to meet application requirements. Both local and remote ODL control options are available.

Figure 4 Overview Optical Delay Line

Phase-Matched RFoF multi-channel for Military Applications: This technology is essential remoting Direction Finding (DF) antenna arrays. Such arrays are used in radar and electronic warfare systems, which use interferometry to determine target direction.

Stable phase-matched RFoF multi-links over time and temperature simplify DF algorithms and reduce the phase calibration overhead. Such systems can employ a 4-antenna array for azimuthal location or an 8-antenna array which adds elevation discrimination. A wider bandwidth of DF RF transmission correlates with higher spatial resolution of the target location.

Furthermore, wide DF RF bandwidth allows the use of frequency-dependent target reflections to identify said target. An innovative militarized high-frequency phased-matched RFoF system is shown below. It supports DF link bandwidth of 1MHz to 6 GHz and uses CWDM optical multiplexing technology. It is designed for a 4-antenna DF array system and includes additional an omnidirectional and a calibration RFoF links bringing the total of phase-matched channels to 6.

This RFoF DF solution has built-in step attenuators, which are used to match the RFoF link gains among the 4 channels to improve the performance of the system. The RFoF links feature good gain stability over a wide range of operating temperatures.

Phase-matched RFoF technology achieves bandwidths up to 18 GHz with phase-matching accuracy of ±10° for a 1km optical fiber cable length, and even a 40 GHz phase-matched link with similar performance was demonstrated. These microwave and mm-wave DF solutions use more advanced WDM technologies to guarantee phase-matched performance. Both remote and local management capabilities are provided through an ethernet-enabled Management & Control system or local USB connections.

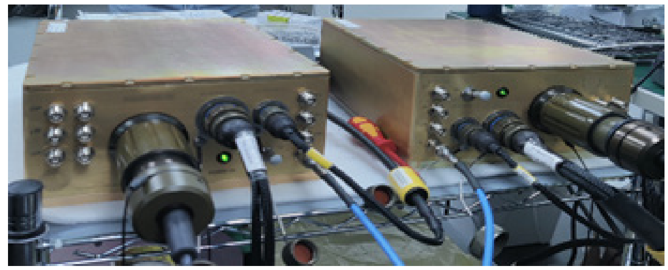

Figure 5 6 channels RFoF militarized phase-matched system

Remote Antenna Ground Stations for Drones: Using RFoF technology, it is possible to distance radiating, potentially targeted drone control and telemetry antennas from the drone control trailers. Distancing that antenna significantly increases the survival rate of the control trailer and personnel while it enhances the communication reliability during drone operations. For the video, click here.

The system effectively transmits flight control signals and receives real-time video and reconnaissance data across all compatible frequency bands. Optical switching can be applied to allow handover between antenna locations and allow for better resiliency and redundant operations.

Figure 6 Overview of RF over Fiber for Ground Station Drone

Target Simulators: RFoF technology is used to create realistic product calibration, training and test conditions for evaluation of radar systems. Such simulators use multiple emitters either fixed or moving along with sophisticated RFoF signal distribution and ODL segments to form a set of simulated maneuvering targets. The radar signal can be distorted or modulated to replicate real signals and RCS variations along with EW jamming and spoofing techniques.

Remote Sensing and Surveillance: RF over Fiber technology enables physical separation between expendable sensors or antennas and the sophisticated signal processing and aggregation equipment typically placed in a safe and shielded central location. RFoF technology can be utilized to offer coherent detection by optical distribution of a common LO to a group of sensor locations. Such a surveillance system tends to be light enough for mounting into UAVs and larger dedicated platforms to address airborne reconnaissance applications.

3.1 DEFENSE USE CASE: PHASE-MATCHING FOR RADAR SYSTEMS

Phase-Matching for Radar Systems

RFOptic provided a phase-matched system comprised of ten channels in an outdoor enclosure, which included channels for communications. The system underwent approximately six months of rigorous testing, during which parameters such as stability, signal quality, and repeatability were meticulously measured. The RFoF system was qualified and deployed to transport signals in a direction-finding application for border protection. It has demonstrated an innovative phase-matching technology with exceptionally stable performance.

Figure 7 Example of Phase-Matching for Radar Systems

3.2 DEFENSE USE CASE: RFOF MULTI-SIMULATOR RADIO INTERCONNECT SYSTEM

RFoF Multi-Simulator Radio Interconnect System

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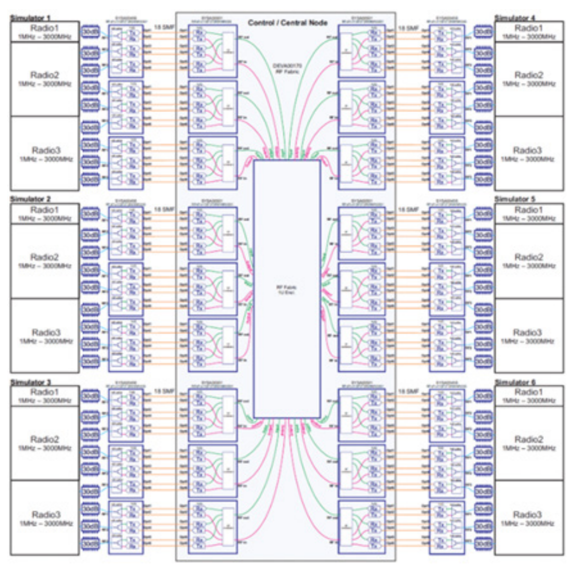

Figure 8 Diagram of the RFoF Multi-Simulator Radio Interconnect System

The system supports numerous radio channels of flight simulators and similar trainers and enables group training with cross-communication between all the radios. This system has been tested and is being deployed by the military.

4. RFOF TECHNOLOGY IN CIVILIAN APPLICATIONS

In the civilian market, RFoF technology is crucial for 5G/6G cellular network performance and interoperability tests. It also extends Global Navigation Satellite System (GNSS) applications, enables range extension of Distributed Antenna Systems (DAS), and supports astronomical research in radio telescope observatories.

5G Testing and Interoperability

RFoF technology gradually replaces traditional RF switches and coaxial cables with optical switches and RF over Fiber links. This transition in technology is driven by the demands of 5G and emerging 6G cellular and data communication technologies.

The increasingly higher frequency communication bands, such as 5.8GHz cannot be effectively transmitted using coax cables with pure RF infrastructure. One area that has seen a fast adoption of 5G RFoF technology is the test environment, which focuses on validating interoperability of base stations and mobile devices produced by different vendors.

An array of base stations is connected using RFoF bidirectional terminals connected to a massive optical switch from which fibers lead to RFoF bidirectional terminals, which service mobile devices and test equipment.

The optical network is configured as needed for the proper test scenarios in a programmed sequence. The operational expenditure (OPEX) reduction of this reconfigurable test environment is phenomenal, as not only is test equipment shared and sees high use rates, but the manpower required to reconfigure the test setup between different tests drops to near zero. To watch the video, click here

The whole test environment becomes programmatically reconfigurable using the RFoF subsystem HTML/REST webserver-based remote management system to monitor, verify, and control individual channel performance.

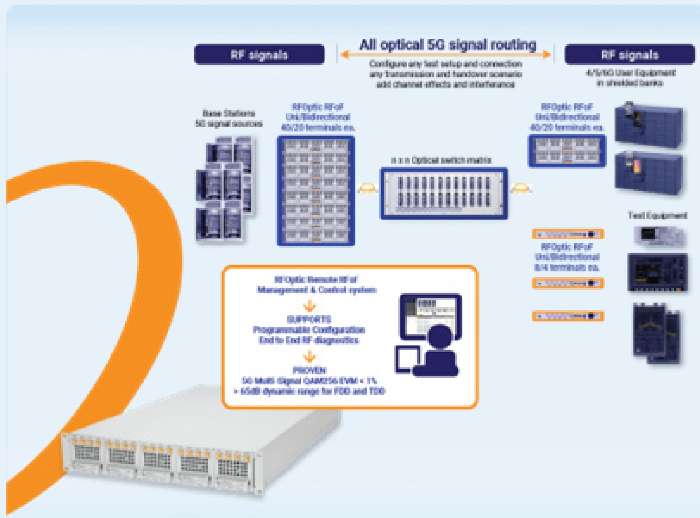

Figure 9 Overview of RF over Fiber for 5G testing

GPS over Fiber

RFoF solutions provide reliable coverage extension of Global Navigation Satellite System (GNSS) and Global Positioning System (GPS) signals to shielded locations where direct satellite reception is blocked. Such locations include parking garages, office buildings and tunnels, datacenters, and more. The RFoF GPS solution allows signal distribution and extension over large distances with minimal degradation, which is crucial for navigation and timing.

Distributed Access Systems (DAS) for Mines and buildings

RFoF technology allows broadband communication range extension into sheltered or shielded areas. Typically, an area without reception is covered by antennas carrying a signal that is transported (downstream) by RFoF from a nearby area or rooftop, which has good reception, referred to as the Donor.

In most cases the DAS communication is bi-directional, requiring the aggregation of the upstream signals from all the antennas and their transport back to the Donor. DAS solutions improve communication reliability and safety of mining operations by extending the communication coverage throughout the mine or in any similar sheltered areas, including parking garages, office buildings, tunnels, and the like.

Radio Telescope Observatories

RF over Fiber technology plays a vital role in astronomical research, especially for radio telescope operations. RFoF systems facilitate efficient transmission of wideband high-frequency RF signals over long distances, a critical requirement for applications like Very Long Baseline Interferometry (VLBI).

Typical solutions provided to radio telescope centers include outdoor units with multiple RFoF transmitters that cover different frequency bands and are installed near the observatory dish antenna(s). These RFoF transmitters convey the signals on bundles of optical fibers that range 100ft to several thousand feet to a corresponding set of receivers, which are placed at the observatory

The RFoF links are designed for extreme phase stability to allow the processing of the received signals into a high-resolution radio astronomical image of the observed target. RFoF enables seamless transport of wideband high-frequency signals, which is essential for high-precision astronomical research.

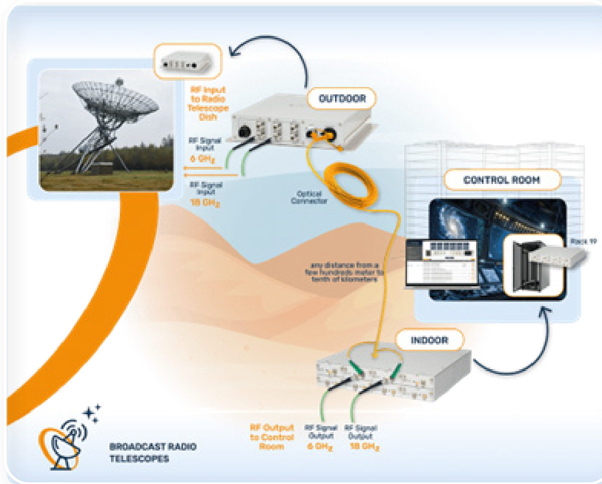

Figure 10 Overview of RF over Fiber for Radio Telescope

4.1 CIVIL USE CASE: 5G NETWORK ROLLOUT

RFOptic partnered with leading base station manufacturers to transition from coaxial infrastructure to an efficient optical fiber-based test system. The program had ambitious goals aiming to reduce the amount of test equipment, increase its use rate, and reduce the setup reconfiguration overhead. The implementation was successful, enabling the telecom company to enhance its capabilities for 5G interoperability testing, switch test plans from one test to the next in minutes instead of days, and dramatically increase the test equipment use rate.

The telecom company specifically required a solution that could address the limitations of existing RF switches and coax infrastructure and exceed the requirements of EVM and ACLR of the 3GPP specifications for 5G cellular communication. The pilot deployment took place in their European laboratories targeting base station equipment testing and interoperability validation. A bidirectional demonstrator RF over Fiber system was provided for several weeks of extensive testing, and after successful validation of the required performance, the telecom company selected RFOptic's HD 4GHz system.

This system, which accommodates up to 20 bidirectional links in five modular drawers, was chosen for its outstanding performance, compact design, and innovative management and monitoring system, which is programmatically configurable to support the visionary integration and achieve reduced OPEX and integration time.

4.2 CIVIL USE CASE: HYBRID SOLUTIONS FOR 5G/6G TESTING

RFOptic's 6GHz and 8GHz Ultra Prog. modules covering frequencies up to 8GHz, suitable for 5G/6G applications. These modules utilize an advanced laser technology to achieve an extended usable RF signal input power range approaching 10dB. At the same time, better than 47dB ACLR and EVM below 1% for QAM256 and even 1024 modulations are achieved. These new modules have been tested successfully for a channel bandwidth up to 200MHz. In the 5G deployment of a global telco, Ultra Prog. showed an excellent dynamic range EVM and ACLR, which makes it ideal for meeting the 5G/6G requirements of customers for testing applications.

4.3 CIVIL USE CASE: RFOF FOR LOW EARTH ORBIT (LEO) APPLICATIONS

RFOptic's RF over Fiber links are widely utilized in the satellite industry to transmit satellite signals between antennas and Network Operations Centers (NOCs). These links operate efficiently in both uplink and downlink paths, particularly in L and C bands. Additionally, S-Band is employed for satellite telemetry, while 10 MHz Satcom timing and reference links ensure seamless connectivity to Low Noise Amplifiers (LNAs), Low Noise Block converters (LNBs), and Block Up Converters (BUCs). Most of our solutions come with redundancy to ensure reliability.

As Low Earth Orbit (LEO) satellites gain popularity, there is a growing demand for comprehensive solutions that integrate indoor and outdoor enclosures with multi-link capabilities. Features such as remote management, monitoring, and other ancillary services are increasingly essential.

4.4 CIVIL/DEFENSE USE CASE: ANECHOIC CHAMBERS

In its simplest application, an RFoF system consists of two sets of one transmitter and one receiver each, connected via single-mode fiber passing through the wall of the chamber. The RF signal source and measurement equipment can be positioned outside the chamber. One RFoF link delivers the signal from the source into the chamber, while the second RFoF link conducts the DUT output signal back to the test equipment. More advanced setups may include additional RFoF links to provide and an extended full 2-port remote VNA interface, including phase correction channels, where the DUT or the test source are set in motion within the chamber. Those applications of RFoF links in anechoic chambers and antenna ranges maintain the integrity of the RF signals and enhance the chamber's functionality and usability.

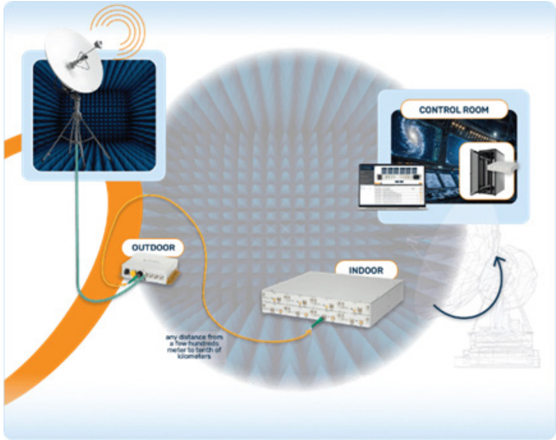

Figure 11 Example of an RFoF System in an Anechoic Chamber

5. CONCLUSION

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6. RFOPTIC

RFOptic is a leading provider of RF over Fiber (RFoF) and Optical Delay Line (ODL) solutions in 5G industries and by aerospace & satellite companies and research labs. RFOptic offers various RFoF off-the-shelf products and custom solutions that are optimized for a wide range of applications at affordable prices and quick delivery. RFOptic's mission is to help its customers turn innovation into real business by providing the highest quality, off-the-shelf, cutting-edge, RFoF-based, innovative customized solutions.

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