OPTIMIZING TELEMETRY LINKS IN MIL-AERO ENVIRONMENTS

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ABSTRACT

Military and commercial aerospace businesses involved with the testing of multiple and simultaneously present powered flying objects, such as manned aircraft, drones or missiles, need to be able to receive and send telemetry data during the entire course of the test flights. By its remote nature, this can be accomplished wirelessly using radio communications systems to provide high quality communication links with no signal dropouts or data corruptions. This paper describes the optimization of these links through an RF over Fiber backhaul system ensuring high fidelity and wide dynamic range.

KEY WORDS

Radio frequency over fiber, telemetry link optimization, long distance antenna remoting, optical distribution

INTRODUCTION

A seemingly insatiable thirst for data connectivity continually drives commercial exploitation of wireless resources. Ever expanding technology bandwidths are leading spectrum regulators to re-evaluate historical norms of use [1], putting pressure on the pristine frequency bands hitherto reserved for government and military use, resulting in a compression of available spectrum. This trend drives a need for optimizing the ground-based segments of telemetering systems to ensure the Electromagnetic (EM) spectrum is most efficiently allocated and interference between commercial and military technologies is minimized. With the optimal positioning of antenna apertures also constrained by the quantity and classification of radio assets, tradeoffs are often required that result in sub-optimal ground systems architectures.

This paper initially provides a brief introduction to basic analog RF over Fiber (RFoF) principles, then goes on to summarize how it is currently used in boresight communication and testing. Next a description is given of how the benefits of RFoF are realized in common commercial applications, and a brief is provided of how these benefits have been developed for Electronic Warfare (EW) and Signals Intelligence (SIGINT) applications. Lastly a depiction of how this might combine to further extend utility to the telemetering community, supporting resolutions to some of the issues involved in operating in a congested EM spectrum.

BODY

The underlying principles behind the transport of analog radio frequency signals over fiber optic cables have been applied in commercially available products for many decades, with the mass adoption of optical technologies to the world's digital telecommunications networks facilitating the availability of components for the more niche analog optics domain. As the increasing digital data demands pushes demand for higher order modulation schemes, so the latest advancements in optical component technologies present ongoing opportunities to evolve the performance and application of the analog approach; from what has historically manifested as point-to-point cable replacements, to more fully featured analog networks.

Developments in the speed and fidelity of digitizing technologies has long promised a world where all signals can be converted at source and distributed in the digital domain using Internet Protocol (IP), but users of this technology have yet to realize the promised benefits. With the high cost and operating power of high performance digital convertors, the challenges of managing the floods of data they produce, and the increasingly complex information assurance environment; the stalwart analog RFoF approach continues to be the practical go-to choice for both commercial and government solutions.

RF OVER FIBER PRINCIPLES

RF over Fiber (RFoF) is an entirely analog technology, which means at no point in the process is the signal digitized by the electro-optic (EO) convertor when it is transformed into the optical domain; with the opto-electric (OE) conversion equally being an analog process of restoration back to the electrical domain. The EO conversion process involves intensity modulating the laser diode (LD), either by directly perturbing the laser's bias current, or by modifying a CW laser source with an external device. As the process is not typically a coherent modulation scheme, the OE conversion process is most often achieved with a simple photo detector (PD) that strips the optical carrier from the signal, leaving the wanted RF remaining.

Image source: Pulse Power & Measurement

Figure 1: RFoF link products: 3U chassis card, compact OEM, and IP rated OEM

The process of modulating the laser with the RF signal is inherently noisy and limited in signal amplitude, so to make this technology useful as a radio transport mechanism appropriate signal conditioning is required ahead of the LD and after the PD to ensure the conversion metrics fits within the overall system RF cascade. The ability to tune these signal conditioning aspects of any EO and OE products (fig. 1) is a key part of making RFoF systems function effectively.

KEY ADVANTAGES OF RF OVER FIBER

Perhaps the best understood advantage of going optical is the extreme low loss that signals experience as they propagate along the optical waveguide; RFoF signals at 1550 nm will experience a loss factor of just 0.2 dB per km in standard G.652.D fiber. This feature lends RFoF to applications where the analog front-end and digital back-end of the radio signal chain are separated by a significant distance. Practically, a typical 10 m run of coaxial cable will add approximately 3 dB of loss at 2 GHz, with this increasing to 7 dB at 10GHz and getting significantly worse as frequency increases. De-coupling the loss function from the RF system layout by utilizing RFoF frees the designer to place antennas in their optimum positions without concern for their proximity to valuable radio assets.

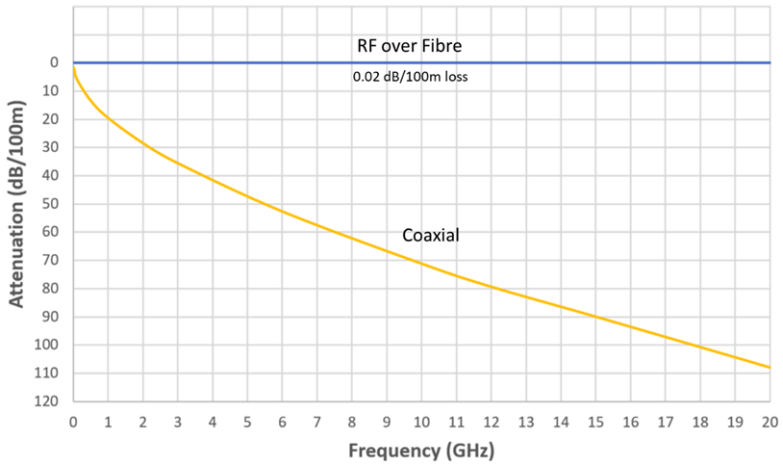

Image source: Pulse Power & Measurement

Figure 2: RF losses on coaxial cabling (FSJ1-50A 7.4mm) vs RF over Fiber

An important metric used to define the quality of an RFoF link is Spurious Free Dynamic Range (SFDR). This metric can be applied to any RF circuit, from an individual amplifier to a complete RF system cascade, as it is a useful figure of merit that encompasses both noise and linearity, which are the two end-stops of a usable dynamic range.

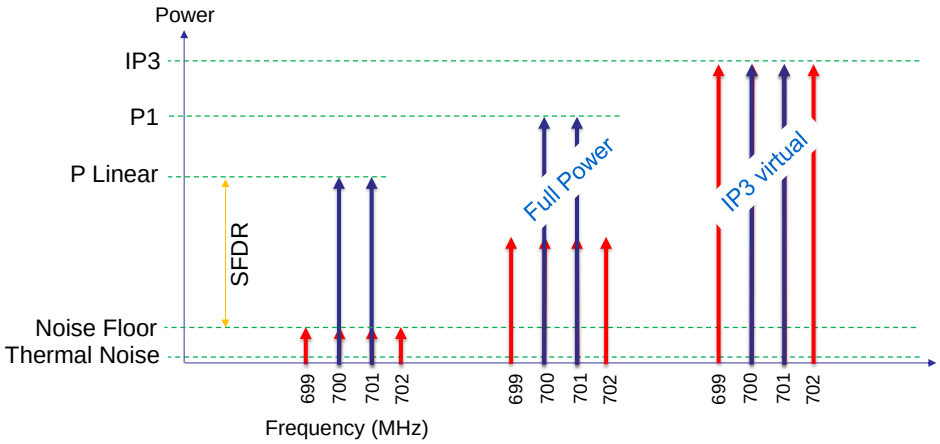

Image source: Pulse Power & Measurement

Figure 3: Depiction of SFDR in $dB/Hz^{2/3}$

There are of course other impairments such as phase noise, group delay, and temperature effects, but these can be managed by design; and so SFDR is important as a defining metric of the technology. RFoF is often considered as a cable replacement, but SFDR is not a suitable metric to assign to a cable so a direct comparison is not easily made in that respect; however, a cable would form part of an RF line-up, containing components that would limit SFDR, and thus comparisons can be made between the two at the system level to optimize performance.

Example SFDR values are shown in fig. 4, from single components to integrated sub-systems. As previously described RF over Fiber's use in communication systems is warranted by way of its long distance transport capability, and its SFDR clearly exceeds that of the components it is connecting to. It is fair to assume that in most wireless use cases the air interface or component electronics will be the limiting factor for dynamic range, and that the fiber transport impact will be minimal over even moderate distances.

Circuit configuration	SFDR (dB/Hz$^{2/3}$)
Single stage of amplification	122
2 stage amplifier with gain control	116
High dynamic range RFoF Link	113
Standard RFoF link	109
Complete Heterodyne receiver	108
Block Up-Converter, NF=15dB OIP3=22dBm G=23dB	105
Ka LNB, NF=0.9dB OIP3=23dBm G=63dB	89

Data source: Pulse Power & Measurement

Figure 4. Typical SFDR metrics

Interfacing RF over Fiber (RFoF) sub-systems between wireless radio-sets and remote radio-heads requires the signal's frequency range and power to be well defined in both transmit and receive directions. Unlike with cables, for optimal dynamic range it is crucial to match the maximum source RF signal power to the RFoF convertor's maximum input acceptance power. If the output power of the radio-set/head is too low, the noise figure of the optical link will impact the overall system noise floor and reduce ultimate dynamic range. If the power of the radio-set/head output is too high, the third order intercept point (IP3) of the optical link will affect its linearity and reduce the overall system dynamic range.

The final key advantage of RFoF is realized through the previously discussed analog nature of the conversion process. The lack of any digitizing elements in the system results in a process that is completely agnostic to the signals that are being transported. Provided the signals fit within the previously described frequency and dynamic range constraints, any signal, of any modulation format, with any correction and encryption measures implemented, will pass unimpeded through the system. This lends the technology well to applications where having encrypted radio assets at remote locations is either problematic from a physical / information security standpoint, or connecting them to an IP network interface presents Information Assurance (IA) concerns. Further to this, a unidirectional flow of data is inherent through the fiber by virtue of the hardware's optical diode set, allowing fixed physical data path isolation by design. The glass fiber transmission medium also results in an absence of emissions, and maximum immunity from the local EM environment. All of these features make the technology ideal for penetrating tightly managed Sensitive Compartmentalized Information Facility (SCIF) boundaries.

TELEMETRY APPLICATIONS OF RF OVER FIBER

In the case of military aerospace applications, Air Force, Navy, and Army facility radio systems often work simultaneously across frequencies in the P, L, S and C-bands, so in aggregate have wideband frequency coverage up to 6 GHz. The telemetry antennas utilized can be of various types including parabolic dishes and directional horn feed antennas; this type of setup is often known as boresight communications and testing.

When the physical nature of the deployment prohibits the use of coaxial cables to transport the RF signals due to high cable losses and RF immunity concerns, the signals received are sent to the mission control room through an RFoF backhaul network to be analyzed and recorded [3]. Linking telemetry antennas to mission control sites can involve making connections over a number of kilometers; with frequencies up to 6 GHz these long distances mean traditional RF coaxial cables are not appropriate to the task. RFoF benefits from a very small conversion delay, with very low signal dispersion; both of which are important when tracking fast moving objects. When radio signals are affected by Doppler shift, multipath propagation, and shadowing, it is critical to ensure that the backhaul connection does not add detrimentally to this.

As described, the inexpensive and lightweight fiber optic medium is stable across varying environmental conditions and offers a high degree of RF immunity. The routing and connectivity freedom that RFoF brings to planners of telemetry ground systems could be advantageous when addressing some of the issues and challenges currently presenting themselves to the telemetering community.

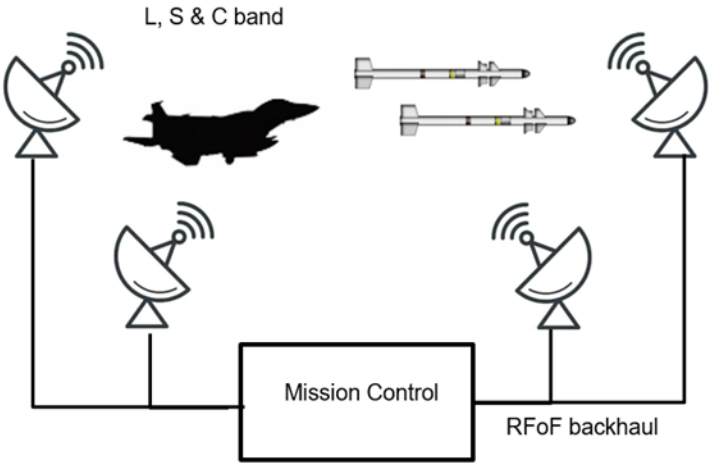

Image source: Pulse Power & Measurement

Figure 5: typical telemetry system using RFoF backhaul

The demand for Electromagnetic (EM) spectrum has grown persistently over a number of decades, and only promises to get more frenetic as the availability of wireless technology continues the proliferation of data connections to more devices types. L-Band, S-Band, and C-Band (from 300 MHz to 4940 MHz), that are all critical to Aeronautical Mobile Telemetry (AMT) activities, including Command and Control (C2) and Time Space Position Information (TSPI) systems, are also well suited to commercial mobile communications as they are ideal for their RF propagation characteristics. As EM spectrum that has traditionally been allocated for commercial activities reaches capacity, pressure builds for spectrum that has historically been allocated for defense applications be used more efficiently; this at the same time as missions requiring more RF bandwidth to complete [1]. The Department of Defense (DoD) is also experiencing the need to change how it addresses spectrum use due to increasing bandwidth requirements for higher resolution radar; driving the need to be agile, adaptable, and flexible in order to defeat threats [2]. This has driven programs such as the Department of the Navy's Spectrum Efficient National Surveillance Radar (SENSR) to consolidate its use of spectrum in support of upcoming auctions.

RFoF systems have the ability to aid the deployment of ground systems, enabling them to build the flexible and extensible architectures required to address this immediate need, at the same time as being malleable to evolve with the changing regulatory landscape.

LONG DISTANCE RAIN-FADE DIVERSITY SYSTEMS

With disruptive technologies being developed to address the multi-constellations, multi-orbits, and multi-technologies being deployed in the satellite domain, proprietary systems from companies such as 'Starlink' and 'Apple' are contending with efforts from standards bodies such as the 3GPP REL-17 for Non-Terrestrial Networks (NTN). This is creating a demand on the EM spectrum that has been traditionally the reserve of a conservative satellite broadcast domain, driving a heavier use of Ka-band spectrum, and requiring an increasingly flexible ground segment.

Further to this new space race disrupting the commercial broadcast market, 'SES Space & Defense' are testing a link between its Low Earth Orbit (LEO) constellation and a flight-representative terminal for relaying telemetry, tracking and command services using C-band [4]. Part of NASA's Communications Service Project (CSP), this aims to provide a commercial alternative to the retiring Geostationary Earth Orbit (GEO) Tracking and Data Relay Satellites (TDRS).

RF over Fiber (RFoF) has been used in the satellite ground segment market for many decades [5]; typically enabling antenna farms with static links to satellites in geo-stationary orbits. The technology has become a mature part of the standard L-band intermediate frequency (IF) connection between the modem in the equipment rooms and the LNB/BUC at the dish; however, an issue does exists in the radio link between the ground station and the satellite.

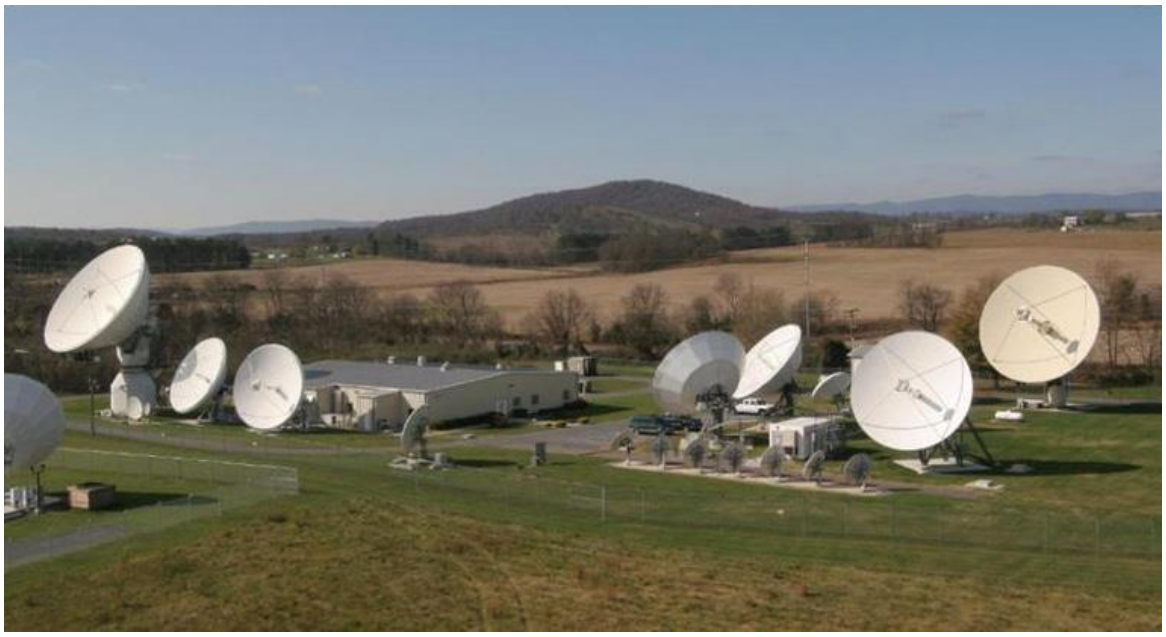

Image source: Telesat

Figure 6: Telesat, Mount Jackson Teleport, USA

During adverse weather events, water droplets in the rain clouds cause variations in the path loss of the feeder link; at best driving a reduction in supportable modulation codecs, and at worse dropping the signal entirely. In recent years RF over Fiber (RFoF) has been used to mitigate this problem by taking advantage of its low loss and subsequently the extreme distances it can cover without significant signal degradation; with many such systems being designed and delivered into active service over for many operators, such as Telesat's Mount Jackson Teleport [6].

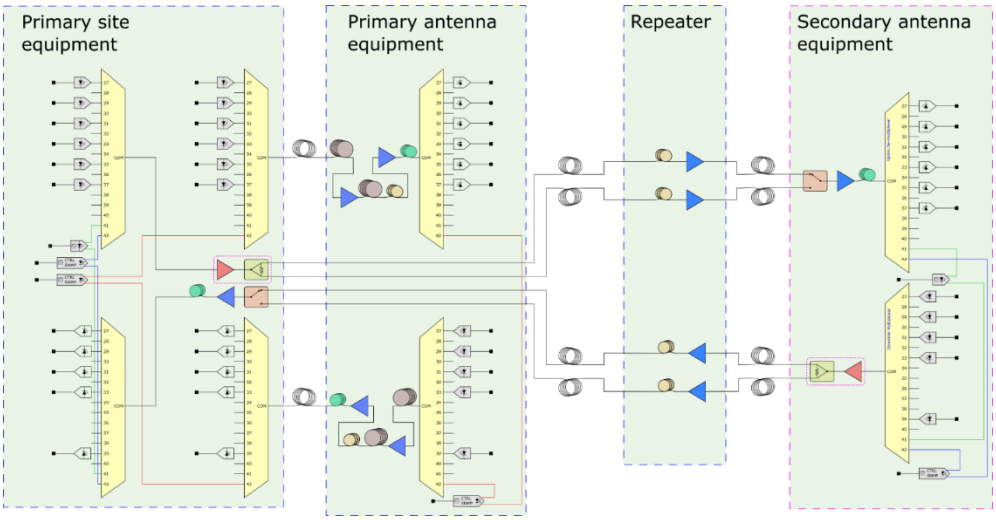

Image source: Pulse Power & Measurement

Figure 7: six uplink and four downlink OFCS, with secondary site at 77km

These 'long-distance rain-fade diversity' systems provide a secondary path for the modems to connect to an antenna farm that can be located typically 75-150 km away from the primary site. When a weather system draws in, the ground station can rapidly switch the entire antenna farm over to the remote diversity site: high and low bands, left and right

hand polarizations, and up and downlinks. This switchover effectively circumvents the weather system; connecting to the same satellite resource from another location on the ground. The huge available bandwidth of optical fibers allows this to be done over a single core, which can be split and replicated on separate strands to provide route redundancy in case of fiber path disruptions. With no need to digitize the signal, the switch over between primary and secondary sites is limited only by the EO / OE convertors (12 ns per conversion) and the speed of light in glass; so switches seamlessly at the nanosecond scale within data protocol boundaries, without any loss of payload information.

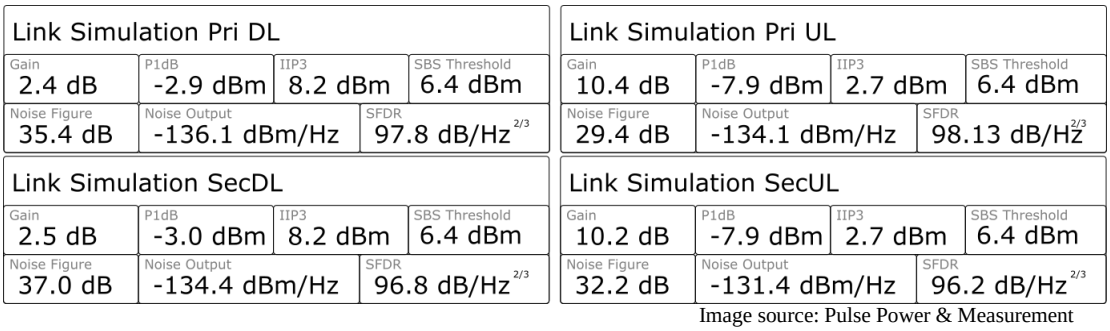

Image source: Pulse Power & Measurement

Figure 8: typical simulation model outputs

With requirements for each Optical Fiber Communication System (OFCS) being unique, understanding how signals propagate through the optical domain is key, so requires the use of well characterized simulation models to build confidence that the finished solution will deliver the intended performance. Use of an optical system design tool [7] ensures that all elements used within the OFCS are fully modelled, allowing any path through the system to be understood prior to a physical build taking place. Future operators of the system can also interact with simulation models and run what-if analysis to ensure the optimum solution is arrived at for each deployment. Common RF metrics such as gain, linearity, noise figure are all modelled, including key optical domain thresholds such as Stimulated Brillouin Scattering (SBS).

RF SIGNAL ROUTING AND OPTICAL DISTRIBUTION NETWORKS

Utilizing the low-loss nature of optical signal routing opens many options for the distribution of RF signals; in its most basic form, this is most commonly used for distribution of GPS signals. Many applications need GPS for time, such as underground rail systems [8] and in-building telecommunications equipment. By far the most ubiquitous use is distributing GPS signals from the roofs of datacenters around the myriad of timeservers that are installed amongst the server racks and data-drives that are crucial for financial institution's high frequency trading systems [9].

Whilst traditional distribution systems are typically static in nature, optical technology exists that facilitates a more dynamic distribution arrangement. For applications that require more than just point-to-point connections, where fan-in (combining) and fan-out (splitting) distribution is desired, optical solutions can support these requirements with all its benefits included.

Reconfigurable transceiver arrays are of use when numerous transceivers are present in a system that require reconfigurable access to a multiplicity of antennas. Each active antenna can be either transmitting or receiving and each Software Defined Radio (SDR) can be either a transmitter or receiver. Furthermore, single or many connections to a radio or antenna may be necessary for: one SDR Tx to many antenna, many SDR Tx to one antenna, one antenna to many SDR Rx, and many antenna to one SDR Rx; the diagram in fig. 8 shows the optimal solution for the 4x6 example. With this arrangement all requirements can be met without restriction on fan-in/out and if a particular deployment is constrained, then it may be possible to alter or drop some of the splitter/combiner options and reduce the size of the matrix switch. For larger scale systems, supporting all possible connections isn't usually necessary; as

a typical deployment will not require such flexibility as not all antennas will be the same, and there will be a known sub-set that only require support for fan in/out.

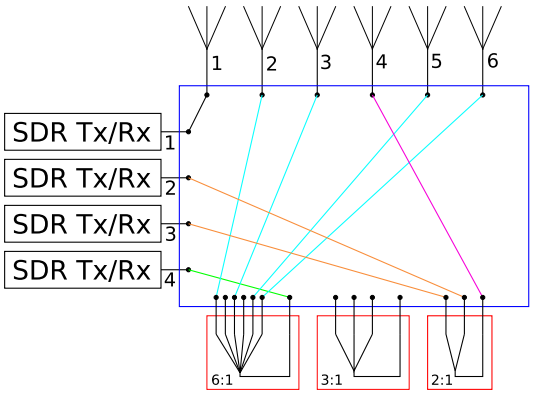

Image source: Pulse Power & Measurement

Figure 8: reconfigurable optical array for antenna and radio stacking

A more niche application domain is the utilization of these reconfigurable optical arrays [10] to combine multiple banded antenna feeds for various EW and SIGINT applications, where the use of RFoF delivers a number of key advantages: cable losses between Electronic Counter Measure (ECM) equipment are minimized so power can be delivered where it is needed for barrage attacks, frequency stacking allows many SDR to be dynamically deployed to different antennas to focus the processing power in the bands or the directions required, and the ease of fiber routing minimizes Through Armor Connections (TAC) in military vehicles to limit collateral 'splash' from kinetic events.

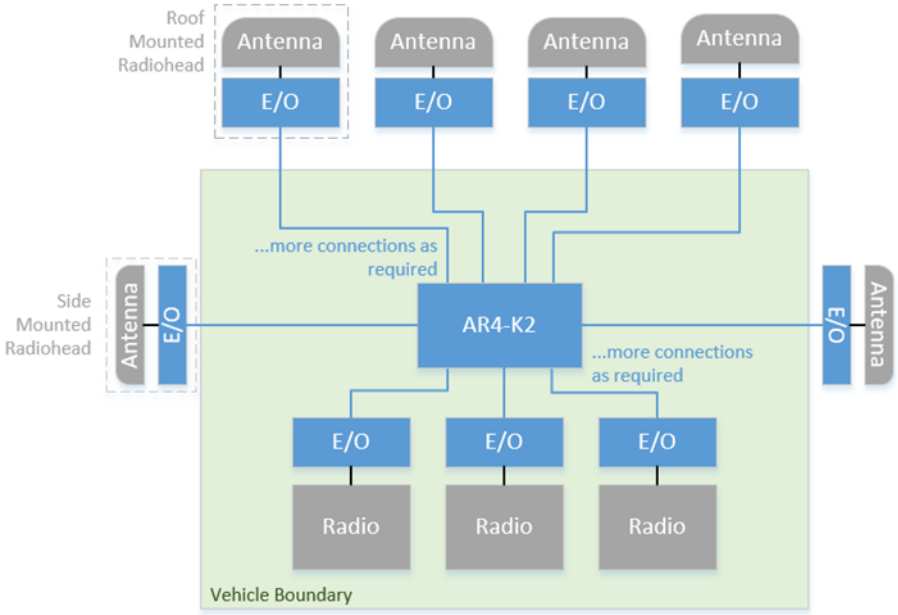

Image source: Pulse Power & Measurement

Figure 9: land platform optical distribution topology

Optical distribution provides a dynamically configurable networking functionality to enable any signal to be routed to any location. For example, routing a waveform produced by an SDR to several side and roof mounted antennas, and routing a received signal to multiple SDRs. This hub network topology (fig. 9) enables finite processing power and

available techniques to be optimized to each platform, and with software base re-configurability, enables the dynamic optimization of each platform for the changing threats in an operational environment.

The most recent developments in the optical distribution technology detailed in this section has combined it with the previously described rain-fade diversity long distance capabilities systems, to provide an RF as a Service (RFaaS) solution for large maritime platforms. This pairs the range that the low-loss characteristics of optics provides and the spectral reconstruction that the distribution system provides, to create a stacking system that aggregates many apertures from a wide array of antenna types, from a few kilohertz to tens of gigahertz, and makes them all appear as a contiguous spectrum to a range of different users running missions on Software Defined Radios (SDR). This concept may well also provide a route to optimizing the use of the RF spectrum for telemetry ground systems architectures.

CONCLUSION

This paper describes some of the current uses for RF over Fiber (RFoF) in both commercial and defense oriented ground systems architectures. It describes how these historical applications are now being merged together to gain further benefit from the optical domain through analog optical networks, and describes how combining RFoF principles has been shown to provide benefit for multi-aperture systems in land and maritime contexts.

Further to this, the paper proposes using the long reach of RFoF to optimize the location and positioning of telemetry antennas over large test ranges; centralizing radios assets within operations centers to facilitate a more dynamic allocation of them across sites. RFoF distribution supports this active routing of analog RF signals, allowing network planners the flexibility to adapt to changing frequency allocations; de-coupling radio sets from the apertures that feed them.

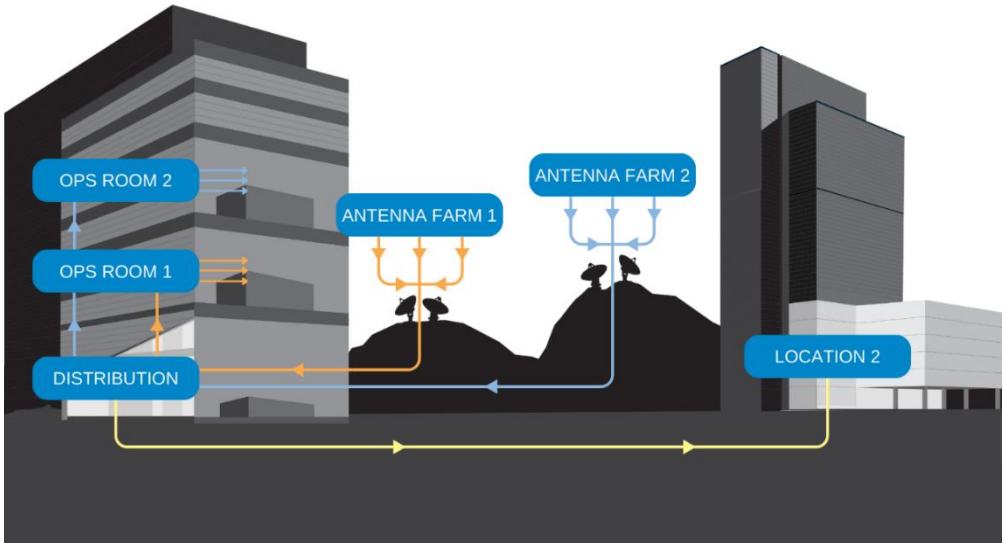

Image source: Pulse Power & Measurement

Figure 10: visualization of a multi-SCIF, multi-farm, analog optical network

The optimization of ground systems architectures through the application of RFoF enables the centralization of radio assets, the virtualization of the EM spectrum, and supports dynamic frequency allocation and re-use; bringing the spectrum to the radio, rather than taking the radio to the spectrum.

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