Adapting RF/IF over IP for Range Applications

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Introduction

The significant improvement in IP network capabilities in recent years, driven by the Internet revolution, enables the next step forward for ground data processing: RF/IF over IP technology (also called “packetized IF”) shown in Figure 1. This technology extends the transport of analog RF or intermediate frequency (IF) data to IP-based networks, e.g., the Internet. Using specialized techniques packetized IF can move digitized spectrum deterministically anywhere over an IP network, and reconstruct it at the destination so it can be processed by either digital or analog equipment. The specialized techniques achieve this with minimal added latency and no lost data all while being agnostic to the spectral content being transported. Since IP network protocols provide neither deterministic data transport nor minimal latency, the implementation of packetized IF requires several innovations to achieve these objectives.

Figure 1. Packetized IF decouples transport and processing from receive/transmit

Packetized IF is not a new technology. VITA-49 and SDDS are two standards that have been around for several years and have provided guidance to industry for how RF spectrum samples can be digitized and placed in IP packets for network transport. But leveraging these standards to build real-world range ground systems has been difficult until now for several reasons: processing power, IP network bandwidth, and the faithful recreation of the RF spectrum (frequency, phase and timing) from diverse RF sources. Each of these limitations must be addressed in conjunction with using IP packets that suffer the problems often associated with network transport impairments – dropped packets, jitter and variable packet latency.
Advances in both hardware and software technology have now brought IF-over-IP to the point where the signal processing equipment (typically receivers, recorders) can be located anywhere in your IP network – independent of the physical location of antennae on your range, and without degrading signal quality. This paradigm shift enables several changes to the range system ground architecture.

Technical Overview

TCP/IP is reliable but unsuited to IF data transport. Methods are needed to provide both data reliability and latency determinism over IP.

IP networks use the Internet protocol stack to isolate the users of the network from the physical details of data transport. Data is grouped into packets (typically 1500 bytes long). Because of network congestion, traffic load balancing, or other unpredictable network behavior, IP packets can be lost, duplicated, or delivered out of order. The TCP Internet protocol achieves reliable transport in the face of these errors by requiring that the receiver acknowledge correct or failed packet receipts. This additional reliability, however, comes at a heavy price in network efficiency. When network transport is unreliable, such as over long-haul shared WAN links, TCP/IP can perform excessive retransmissions and acknowledgements, making latencies high and unpredictable. If error density and latency gets too high, a phenomenon called “NACK implosion” can occur, where effective throughput crashes due to excessive retransmissions. These factors make TCP/IP unsuitable for the deterministic, low-latency transport requirements of packetized IF. In contrast, the User Datagram Protocol (UDP), which provides low-overhead and latency but unreliable packet transport, is a more effective foundation for IF transport, so long as occasional packet losses and out-of-order delivery can be overcome.

Components of RF over IP Systems

A typical RF over IP system contains components located on each side of a wide area network which bridges connectivity between an antenna subsystem and an operations data processing center. The RF over IP system consists of a digitizer front end, select digital filtering, conversion of the filtered data to IP packets, a network pre-processing scheme such as data buffering and FEC coding to address packet drops, latency, and jitter, and a re-conversion of the IP packets back to analog RF Spectrum at the distant end using highly accurate clocking schemes on the recovered samples. The front end A/D is used to capture analog RF bandwidths selected and tuned for transport. Pre-detect filtering ahead of the A/D
is used primarily for two reasons: to eliminate out-of-band noise and to eliminate out-of-band signals that can cause aliasing. Markets for high-speed A/D converters are significant in size and many are growing rapidly. New markets emerge regularly based on A/D technology advances, lower costs, and the general trend of replacing older mechanical and analog systems with DSP (digital signal processing)-based RF over IP systems. DSP offers significant advantages for handling signal complexity, communications security, improved accuracy and reliability, reduced size, weight and power (SWAP).

Figure 2 shows traditional front end interfaces for range antenna communication systems. A mixer combination within the ground antenna is used in up and down conversion process to provide the A/D with a compatible RF/IF frequency range for sampling.

**Figure 2. Traditional A/D Translation Models**

But many of today’s A/D’s can handle higher RF inputs directly as part of a direct sampling process, and also couple in mixing within the chip to allow for sub-band tuning as shown in Figure 3. As discussed in “Components of RF over IP Systems,” direct sampling and tuning schemes when combined with digital signal processing in RF over IP systems allow for options to consolidate range antenna functions and thereby reduce SWAP.
Overcoming Limitations of TCP/IP

To enable accurate regeneration of the analog spectrum at the transport destination location, packetized IF schemes must overcome the packet loss problem. Traditional Forward Error Correction (FEC) codes, such as Reed-Solomon codes, provide no protection against IP data loss. If a bit error occurs within a packet, the IP checksum fails and the entire packet is lost, providing no opportunity for the user’s FEC algorithm to repair it. As a result, error correction must be performed at the packet level. To overcome this, there are IP-based Packet Forward Error Correction (P-FEC) schemes that treat successive packets in a packetized IF data stream as data elements subject to loss/repair. If a packet is lost, the error-correcting code information available in nearby packets allows the reconstruction of the lost data, just as a traditional error-correction code can reconstruct lost bits from nearby encoded received bits. This allows the P-FEC method to improve effective data rate greatly over straight UDP, without incurring the two-way traffic impacts and high latency associated with TCP/IP protocol. P-FEC algorithms demonstrated within the range environment have proven that lossless, low-latency transport of packetized IF data is feasible even in the presence of severe burst packet losses.

Most P-FEC algorithms have several parameters that are user adjustable including overhead that can be adapted. (Some networks will exhibit random packet losses, but some will have correlated packet losses where two, three, four, or more packets may be lost with narrow separation. Figure 4 shows user parameters which allow its effects to be adjusted to the

- Antenna Signals are usually in the microvolt range
- RF amplifier boosts signal to full scale input voltage of the A/D – usually 0 to +10 dBm
- RF amplifier often includes a tuned bandpass filter centered on the signal of interest
- No analog frequency translation before the A/D
- Appropriate for HF signal frequencies (3-30 MHz)
situation.) PFEC rides on top of UDP and latency depends on packet data rates but increase is modest (order of msec) relative to regular UDP.

<table>
<thead>
<tr>
<th>Increasing</th>
<th>Latency</th>
<th>Overhead</th>
<th>Error Tolerance</th>
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<td>Groups Per Interleave</td>
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<td>Reordering Window</td>
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**Figure 4. P-FEC Adjustable Parameters and Effects**

**IP Network Throughput Implications**

Even in modern networks, data throughput is a precious resource. Due to Nyquist Theorem, any A/D sampling process used to capture and digitize an input RF source requires minimal network throughput to achieve sufficient data transport and spectrum regeneration. The amount of required network throughput is directly related to the A/D sampling rate used (dictated by the instantaneous RF capture bandwidth), and the amount of sampling resolution in the number of sample bits set per A/D sample. This relationship is shown in Figure 5. As seen in the figure, a 10 to 20x factor is applied to the capture bandwidth in MHz when determining the resulting network throughput requirements in Mbps.
To help minimize the impact of network loading, it is useful for packetized IF schemes to include technology that allows the desired signal center frequency and instantaneous capture bandwidth to be sub-band tuned from the input RF spectrum source so that no unneeded data (i.e., unoccupied noise floor region) is sent over the network. This spectral channel capability also allows multiple signals of interest to be selectively tuned and distributed to different destinations for either digital or analog processing. The bit resolution setting of the A/D sampler is also adjustable from 4-12 bits to optimize the network loading while preserving signal integrity for modem processing.

**Retaining RF Performance at S- and C-Bands**

RF over IP architectures are now more economically feasible given the commoditization of IP network components and throughput. This combined with advancements in today’s A/D capabilities and more affordable hardware processor price points enables new cost effective RF over IP architectures within the range’s ground segment. There are a few key capabilities of an RF over IP architecture that are desired in these architectures to become cost effective:

- RF and IF analog switching: Allow 1 to N front-end RF digitizer front ends to transport and switch analog signals with 1 to M distant end analog regeneration channels.
  - Multiple RF channels to be processed at the antenna front end could also support beamforming applications when combined with synchronous (coherent) processing across multiple packetized IF channels. Synchronization
for these applications must be highly accurate based on the sample rate, with a delay compensated sample clock distributed to each converter element.

- Incorporate digital tuning in the front end to provide digital-based frequency conversion for each channel.

- Provide for independent configuration of each transport channel within the RF front end to help preserve network throughput. Configuration parameters may include digital channel filtering on an RF/IF input signal, digital sample rate, or full channelization processing whereby subchannels within the capture bandwidth are extracted, optionally re-routed, frequency translated, and/or multicast to multiple destination locations across the network for spectrum regeneration.
  
  - This allows the desired signal center frequency and bandwidth to be sub-band tuned from the input spectrum source so that no unneeded data (i.e.; noise floor region) is sent over the network. This spectral channel capability also allows multiple signals of interest to be selectively tuned and distributed to different destinations for either digital or analog processing. The bit resolution of the A/D sampler is also adjustable to optimize the network loading while preserving signal integrity for modem processing.

- Deterministic latency is a key requirement needed for the accurate regeneration of the analog spectrum at the destination end. Provide a delay calibration mechanism on RF-to-processing and processing-to-RF paths to define a fixed latency for each communications path. Data handling algorithms are needed to ensure accurate time-release of data to output D/A converters. This allows retention of RF signal modulation characteristics and ensuing coding schemes that rely on precise timing, such as TDMA and frequency-hopping waveforms, to be correctly processed after WAN transport.
  
  - A highly accurate timing reference can be used for synchronization such as a 1 pulse/s (1PPS), 10 MHz frequency reference, and/or IRIG signals from a Global Positioning System (GPS) receiver.

- Support synchronous control channels between the RF front-end and the back-end digital processing that are tightly integrated with data channels to provide for hard real-time control in frequency-agile applications. VITA-49 packets contain customizable meta data fields that can be used for this capability.
Applications of Packetized IF

RF over IP introduces a paradigm shift in the operations, maintenance, security, and logistics associated with managing ground segment missions.

The use of IP network transport and reconstruction of any waveform brings fundamental changes to overall architectures for antenna facilities, operations centers, and the communications network ground segment enterprise as a whole. As shown in Figure 6, and highlighted in the following paragraphs, these changes permit major paradigm shifts in the operations, maintenance, security, and logistics associated with managing ground segment missions. The application of packetized IF can enable many high-value use cases that can minimize costs, maximize operational efficiency and flexible, and generate additional revenues.

Figure 6. Packetized IF opens many new applications in the ground segment

Centralization to Simplify Operations and Lower Costs

Packetized IF technology enables RF spectrum from an antenna at any location to be digitized, transported to, and faithfully reconstructed at a centralized operations facility. This enables teleport and satellite operators to centralize processing and operations (Communications and/or TT&C).

One example is how the technology enables significant reduction in required equipment at a ground antenna site. This can greatly reduce facility, personnel, and sparing costs, especially for ground sites at austere or remote locations, as shown in Figure 7.
In addition to lifecycle cost-savings achieved through equipment and personnel reduction, this architecture also enables centralization of expensive commercial, EAR-restricted or sensitive cryptographic equipment and software, thus improving overall risk posture and allowing lower protection-level security approaches to be used at teleport sites.

Moving ground modems and other processing equipment away from the antennas allows this equipment to be shared among multiple antennas and allows multiple ground sites to work with the same data. This data architecture improves resilience of the enterprise in the event of a site failure, adversary action, rain fades, or test activities. Since the site footprint is smaller and non-sensitive, it becomes much simpler to provision new teleport locations to support regional surges or changing mission needs.
Equipment centralization also provides antenna operators new options to manage maintenance operations. When an antenna is down for maintenance, its reception responsibilities can be shifted to a backup antenna at any location. The received RF can be digitized and transported using packetized IF to original antenna processing equipment. This greatly simplifies the scheduling and execution of maintenance operations.

**Use of Digital Data for Diagnostics**

The ability for packetized IF systems to record and playback raw I/Q data has several uses in both test and operations. During system test, recorded IF data can be used to provide repeatable test cases for integration, test, and verification of the communications paths between range antenna components and the ground processing equipment. Coupled with IP data transport, this allows the antenna shelter and data processing equipment to be physically separate from each other while still permitting end-to-end testing. After launch, the recorded IF data can be used to assist follow on test and to provide trusted regression test cases for modifications to ground components and architecture.

An IF recorder can also be used as an online ‘black-box’ recorder. Like an airliner’s black-box recorder, such a system continuously records link IF data during normal operations, retaining a rolling window (such as the last few hours) of data on disk. In the event of an anomaly or in-flight event, the data is then retrieved to allow detailed analysis and troubleshooting. For cases where problems occur rarely or under unusual conditions, such a black-box recorder greatly improves the ability of system engineering experts to diagnose and fix issues as shown in Figure 8. For range systems, the black-box recorder allows recovery from downstream processing errors such as those due to incorrectly configured ground equipment or operator error. After the missed contact, the IF data is played back into the ground string to recover data that would have previously been lost due to the tracking failure.
Antenna Placement Flexibility for Tactical Environments

With packetized IF, antennas are now freed from the constraints of being located near processing equipment. Range antennas can now be placed at more optimal locations based on tactical need, costs, range availability, and signal reception. Dynamic geographical needs for range tracking found in tactical applications are more easily met using packetized IF provided adequate IP connectivity is available between the tracking locations and the data processing center as shown in Figure 9.
Combining Legacy Range Functions to Lower Costs and Increase Operational Flexibility

Packetized IF is a key enabler to consolidate and reduce ground hardware footprints resulting in simplified operations and maintenance.

One key benefit is packetized IF’s ability to support both legacy operations and set the path for eventual transformation to all digital implementation within the range architecture. The front end can regenerate the RF spectrum (and translate to IF, see next paragraph) in order to allow low risk support to legacy range receivers requiring IF inputs. In addition, the digitizer still creates simultaneously the IP VITA-49 packets that can be used for transport to other networked sites once they are retrofitted for packetized IF. Both RH/LHCP polarizations are separately configured and digitized to support combining across the analog and digital domains. This transitional architecture using packetized IF provides a very low risk approach to its adoption within the legacy operation, as shown in Figure 10.
Another key benefit is the combining of traditional range functions within the digital domain (digital frequency conversion, pre-detect diversity combining, antenna tracking, and digital recording) to reduce equipment costs and hardware footprint at the range antenna as shown in Figure 11.

The front end A/D digitizer when configured with sufficient number of bits per sample resolution can be used as an agile digital based frequency conversion subsystem. This can help reduce the number of discrete analog up/down converters used in the antenna today. Very high resolutions for agile tuning and nearly infinite combinations of input/output frequency translation can also be achieved depending on the accuracy of the GPS timing source to the digitizer subsystem.

The digitizer is a viable front end to supplement an inherent diversity combiner function within its platform. This allows for further reduction in needed combining receiver hardware at the antenna site. Instead of separate RH/LHCP channels being transported across the network, the combiner provides a pre-detect combined output to the network which further reduces network throughput loading. A distant end receiver can accept the combined signal for further demodulation post detect, either from accepting the VITA-49 packets as an all digital receiver, or using legacy analog when combined with a remote end D/A digitizer.

Finally, an AM tracking receiver/envelope detection function is also a feasible addition to the A/D platform. This is used to replace traditional analog AM tracking receivers found at the
antenna further reducing the antenna footprint. The output of the AM tracking function is used to feed the legacy interface to the Antenna Control Unit (ACU).

Figure 11. Combining of remote antenna functions using RF over IP

Digital recording can also be added to record IP traffic on each side of the transport interface. All previously discussed digital recorder benefits still apply when implemented with the digitizer front end. All of these digital based functions (digital frequency conversion, pre-detect diversity combining, antenna tracking, and digital recording) can aide in the reduction in hardware footprint at antenna sites which provides increased remote operations capability and lower maintenance costs. The transition to this architecture is a natural extension using the already present digital domain provided and inherent within the packetized IF architecture.

Summary

The ability to perform digital conversion, IP network transport, and reconstruction of any waveform brings significant benefits to the range ground installations in support of current and new tracking applications. These benefits include lower costs, more flexible software-based processing, improved resilience, improved test and troubleshooting, and reduced hardware at remote ground tracking sites. Sustained IP transport at up to several hundred MHz instantaneous bandwidth has been operationally proven and is currently available commercially. This capability can provide zero packet-loss, deterministic latency, and spectral reconstruction even over severely impaired wide-area networks.
Many cost saving benefits and increased capability result for range operations when the technology is properly considered and applied within the range ground architecture. This can also be achieved with minimal risk to legacy operations and investments when considered as part of a longer term transition plan moving to all digital technology.

### Acronyms & Abbreviations

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<tr>
<th>Acronym</th>
<th>Meaning</th>
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<tbody>
<tr>
<td>A/D</td>
<td>Analog to Digital</td>
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<tr>
<td>D/A</td>
<td>Digital to Analog</td>
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<tr>
<td>EAR</td>
<td>Export Administration Regulations</td>
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<td>FEC</td>
<td>Forward Error Correction</td>
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<td>IF</td>
<td>Intermediate Frequency</td>
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<td>IP</td>
<td>Internet Protocol</td>
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<td>LEO</td>
<td>Low Earth Orbit</td>
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<tr>
<td>P-FEC</td>
<td>Packet Forward Error Correction</td>
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<td>RF</td>
<td>Radio Frequency</td>
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<tr>
<td>SLA</td>
<td>Service Level Agreement</td>
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<td>TCP</td>
<td>Transmission Control Protocol</td>
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<td>TDMA</td>
<td>Time Division Multiple Access</td>
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<tr>
<td>TRL</td>
<td>Technology Readiness Level</td>
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<tr>
<td>TT&amp;C</td>
<td>Telemetry Tracking and Command</td>
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<tr>
<td>UDP</td>
<td>User Datagram Protocol</td>
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<tr>
<td>WAN</td>
<td>Wide Area Network</td>
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### References