

Comparing architectures for bi-directional telemetry ground stations

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Abstract:

Over the past decades, data recorded onboard test aircrafts has expanded much faster than downlink capacity. Given the bandwidth and power limitations, a bi-directional link appears as the best way to ensure delivery of the largest amount of relevant data per test by leveraging in-flight reconfiguration capabilities. Moreover, an uplink improves communication reliability when offering on-demand data retransmission during the flight.

Transmission capability comes with a set of constraints for the ground station that depend on communication protocols and other characteristics of the test case. In this paper, we address these challenges and compare the trade-offs and performance of several ground stations architectures using state-of-the-art components and technologies in order to achieve bi-directional communication.

Key words: RF Design, Receivers, Antennas, Ground Stations, Bi-directional

Introduction

Bidirectional telemetry systems are a developing trend in flight test telemetry as they come as a solution for many new functionalities:

- Retransmit important data: makes tests more reliable
- Reconfigure in flight: makes testing more flexible depending on test results and environmental conditions. Also allows transmitting the most important data for each step of the test and to combine more tests in a single flight
- Send data from the ground to recalibrate the on-board inertial measurement unit in the case of a launcher stage recovery
- Command the transmission of on-board recorded data. One example is for a launch vehicle to record massive videos during the launch. Beyond a certain distance, it is not possible to recover the data in real time as the link budget does not provide enough bandwidth, however the video can be stored on-board, and transmitted during the first stage descent.
- Provide another voice channel, in addition to VHF link for redundancy

Bi-directional links between the test article and the ground is a vast topic that encompasses a whole stack of functions and protocols. In this paper, we focus on the physical layer of communication [1].

At the Radio Frequency (RF) level, the biggest challenge brought by bi-directional telemetry is the Receive (RX) – Transmit (TX) isolation: preventing the High Power Amplifier (HPA) output to damage the low Noise Amplifier (LNA), especially if using the same frequency band. Fortunately, the throughput need in telemetry is non-symmetrical: we want to downlink as much data as possible but only need to send seldom commands to the aircraft.

In order to propose and study bi-directional architectures, we first analyze the Inter-Range instrumentation Group (IRIG) 106 standard, before proposing ground station architectures that answer to various potential use cases.

IRIG 106 Telemetry Network Standard (TmNS)

IRIG 106 [2] is the comprehensive telemetry standard developed in the United States of America by the Range Commanders Council and sponsored by the International Foundation for Telemetry.

IRIG106 describes a bi-directional functionality as the Telemetry Network Standard in chapters 21,22, 25, 26, 27 and 28.

The prescribed modulation are Feher Quadrature Phase Shift Keying (FQPSK) or Shaped-Offset QPSK (SOQPSK) for high data rate and Pulse Code Modulation/Frequency Modulation for low data rates. Communication is in C-band, within 0-20MHz carriers at frequencies between 4900 and 4922MHz. Access sharing of the communication medium is Time Division Multiple Access (TDMA). Effective Isotropic Radiated Power (EIRP) of all transmitters is limited to 25W.

IRIG's standard provides a very powerful structure in order to build a reliable network between aircrafts and the ground, allowing air-to-air communications and many advanced functions [3]. Unfortunately, this ambitious architecture also comes with challenges:

- Identical 25W EIRP limitation for on-board and ground imply a symmetric RF communication that does not benefit of having the capacity to use large antennas on the ground while having small ones onboard. For a 1Mbps bidirectional link, the maximum distance for communication with 3dB link margin is about only 6km.

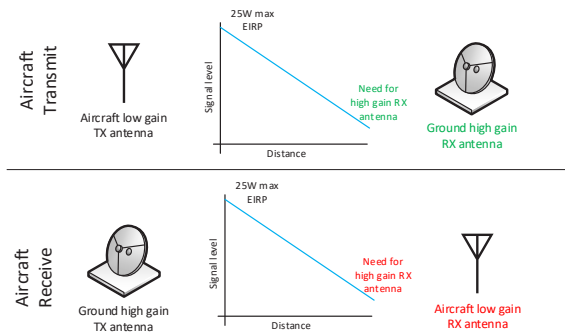


Fig. 1 challenge of EIRP limitation

- TDMA infrastructure represents a very costly investment for the network scheduler both to initially develop and then to equip every range
- TDMA signals are not compatible with current auto-track technologies
- Transmitting and receiving at identical frequencies is a significant challenge on the antenna side for RX-TX isolation
- Only the C band is considered

Fast RX-TX switching system

Including a fast RX-TX switch in the ground station is a classic TDMA way to ensure for good isolation between RX and TX signals.

With today's technology and IRIG's switching speed requirement, the switch should be pin-diode based.

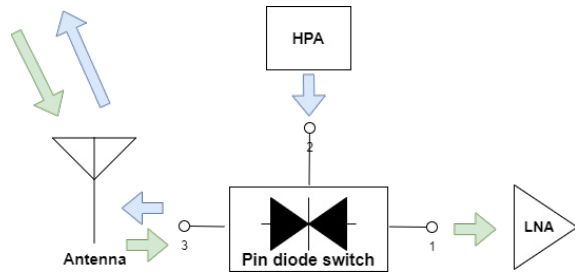


Fig. 2 Fast RX-TX switching

This architecture is compatible with IRIG, and could handle high TX power.

However the switch causes a high loss on the RX channel before LNA which has a strong negative impact (almost 2dB) on the figure of merit (G/T). Moreover, the switching times needs to be precisely controlled by the modem. Finally power dissipation is a significant integration challenge as they require huge heat sinks to sustain the transmit signal.

Circulator based architectures

Another idea to isolate TX power from LNA is to use circulators that route TX signal towards the antenna and RX signals coming from the antenna towards the LNA.

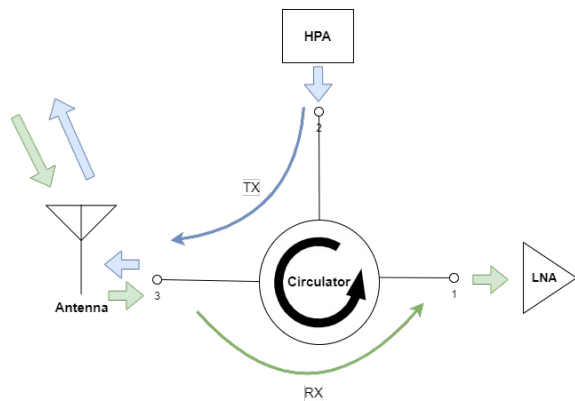


Fig. 3 Ideal circulator architecture

A single circulator architecture allows for a low power transmit only because the TX signal reflected by the feed's Voltage Standing Wave Ratio (VSWR) and the circulator's isolation leaks are quickly saturating the LNA.

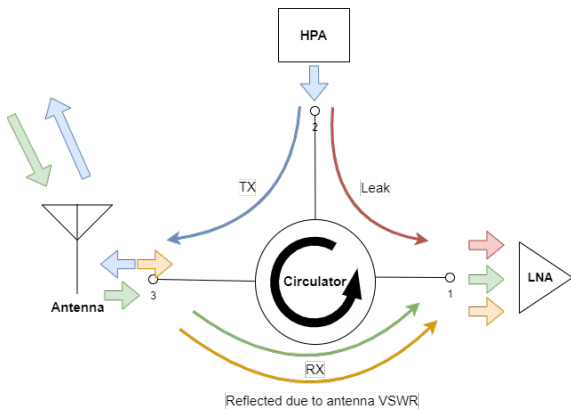


Fig. 4 Real circulator behavior

A partial mitigation is to optimize VSWR of the feed for the TX frequency and to use two circulators in series in an architecture that cancels most of the leak [4].

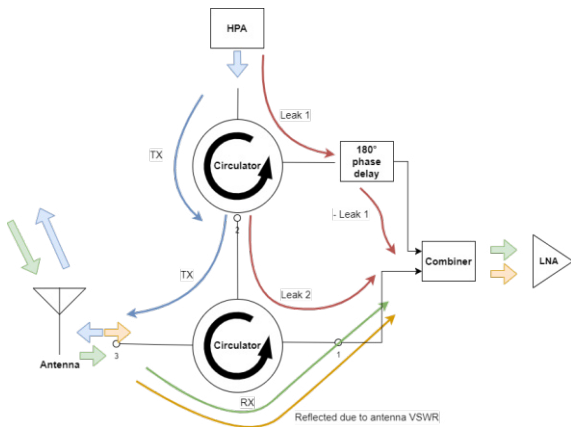


Fig. 5: Dual circulators architecture

This architecture is a compromise between maximum feed input transmit power, flexibility on the transmission frequency and has a G/T degradation of about 0.7dB in L/S-bands and 1.1dB in C-band. This solution is entirely passive which makes it more robust. Integration complexity is higher with more equipment to fit into the feed and requires per-system tuning.

Multiple antenna systems

RX-TX isolation can be achieved by using different antennas, to be installed on the same pedestal or on two distinct pedestals whose pointing direction is slaved. A tradeoff needs to be made between TX antenna gain and HPA power.

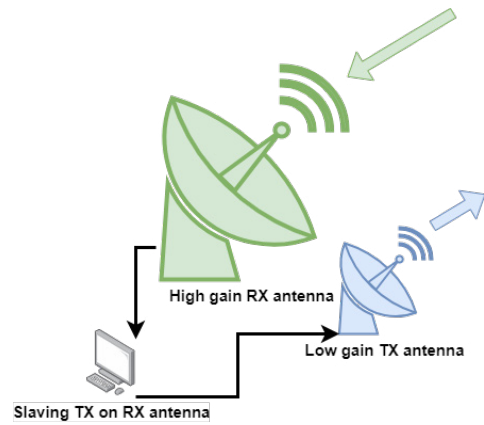


Fig. 6: slaved pedestals

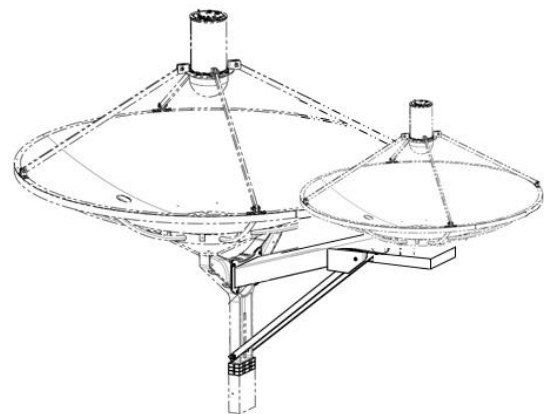


Fig. 7: dual reflectors

This architecture is compatible with IRIG, handles high TX power, is flexible but usually costly. Coupling between RX and TX feeds needs to be analyzed in order to determine spatial separation constraints.

In order to assess how relevant this solution is, we computed multiple uplink budgets in SOQPSK for various antenna sizes and computed the maximum communication distance assuming the target is visible at 5° over the horizon. We supposed that the transmitter power is 20W regardless of the gain of the transmit antenna and the gain of the board antenna is 1dBi.

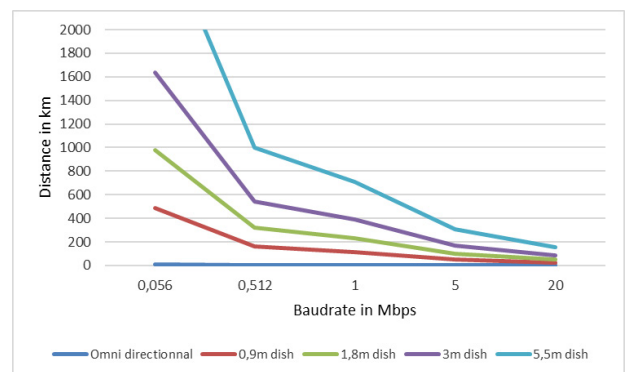


Fig. 8: Maximum communication distance depending on the baud rate

When considering the multiple antennas architecture, ground based omnidirectional antenna can only close the link over distances of a few kilometers or less. However, we notice that even the smaller dishes can provide uplink data rates sufficient for most use cases over long distance as long as the link can be non-symmetric.

Separated RX-TX frequency systems

The easiest way to prevent LNA saturation by TX signal is to use dedicated frequency bands. It is even possible to add switches to the design in order to remotely configure which of the L, S and C band is used to transmit and the two others are receiving.

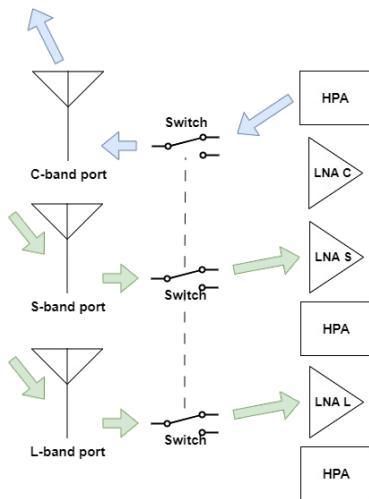


Fig. 9: Band-switching

This architecture has a low G/T degradation (0.4 to 0.5 dB), lowest cost and complexity impact but is not compatible with IRIG's TDMA used both for receive and transmit.

The other way to use frequency separation is to use a diplexer splitting RX and TX signals based on frequency within the same band.

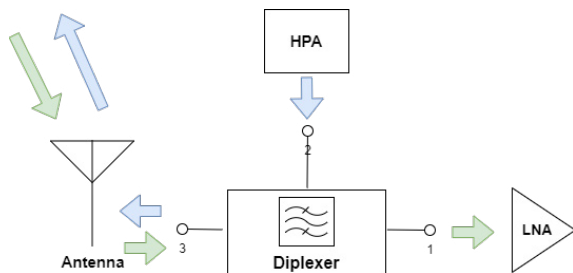


Fig. 10: Diplexer architecture

Separating RX & TX frequencies has G/T and integration difficulty impacts that mainly depend on the maximum power to transmit and the frequency separation between RX and TX signals. For Telemetry, this solution is always custom based on TX & RX frequencies whereas the Consultative Committee for Space

Data Systems has standardized frequencies for space communication [5]. Safran has years of experience implementing diplexers on bidirectional feeds, with a typical 1.1dB loss on S-band G/T when integrating a 200W diplexer allowing transmit between 2.025-2.120GHz and receive between 2.2-2.3GHz.

Comparison of architectures

There is no one size fits all solution to bidirectional telemetry. We proposed four families of architectures in an attempt to cover most of the needs. Here is a comparison of the strength and weaknesses of each solution.

Tab. 1: Architecture's features comparison

	Fast switch	Circulator based	Multiple antennas	Separated frequencies
Max TX power	✓✓✓	-	✓	✓
G/T impact	- -	-	=	-
Flexibility	=	-	✓	- -
Cost effectiveness	-	✓	- -	✓
Suitable for TDMA	=	=	=	only for links in the same direction
Suitable when TX baudrate is lower than RX	-	✓	✓	✓
Single Channel Monopulse compatibility	✗	✓	✓	✓

We assumed in this table that when the downlink baud rate requirement is lower than the uplink one, fast switching will be unaffected (and still poor) while circulator based architectures can be optimized for performance rather than isolation, side antennas can be made smaller and diplexer based architectures can prioritize low insertion loss over isolation.

Focus on a band-switching solution

Safran developed a band-switching feed that allows transmitting up to 20W CW in any of the L, S or C bands while receiving and Single Channel Monopulse (SCM) auto-tracking in the other two. Switching is remotely controlled, and transmission only occurs in one polarization at a time. Reception is simultaneous in both polarizations.

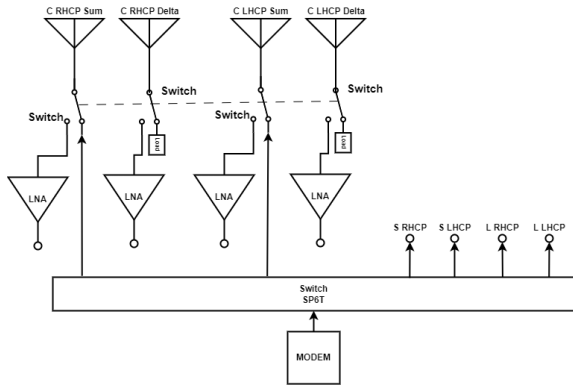


Fig. 11 Triband switching

The same architecture is employed for all 3 bands but for clarity, only the C-band has been fully represented on the diagram.

Tab. 2: Performance measured

	Lower L-band	S-band	C-band
TX losses (dB)	2	2.5	2.8
TX return loss (dB)	< -9.6	< -14.2	< -16
RX return loss (dB)	< -10.6	< -13	< -9.7

The table summarizes key performance of the feed.

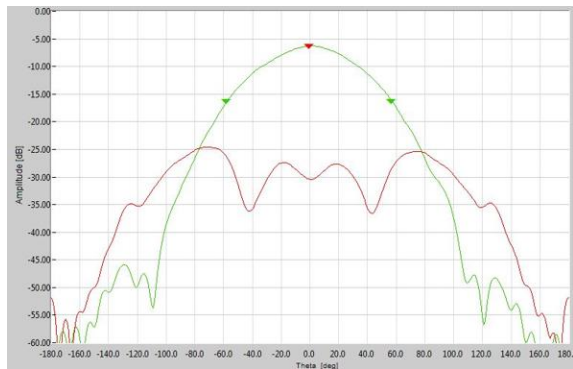


Fig. 12: TX pattern in S-band

In green is the co-polarization and in red the cross-polarization of an anechoic chamber measurement of a triband TX feed. One can see that the pattern is clean and that there is about 23dB between the transmission in the selected polarization and the other one.

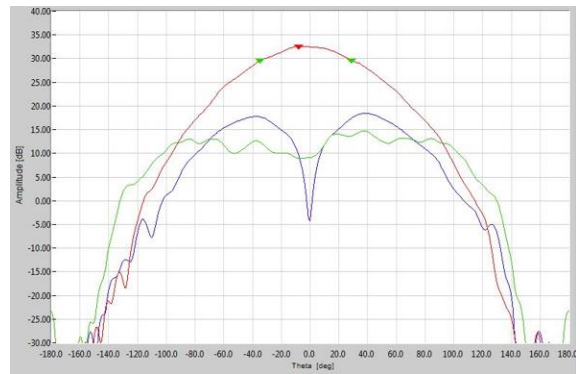


Fig. 13: RX patterns in C-band

In red is the co-polarization sum channel, in blue the delta one and in green the cross-polarization sum of an anechoic chamber measurement of a triband TX feed. This diagram features a clean sum pattern and a deep, well centered null on the delta diagram.

System level performance measured on a 1,8m pedestal delivered to an experimented customer are: G/T of 2dB/K in L-band, 3.3dB/K in S-band and 10.1dB/K in C-band with a 20W transmit capability. These are compliant with the customer's needs to enable bi-directional communication with test articles.

Modem and HPA integration considerations

Flight test pedestals are usually of type Elevation (EL) over Azimuth (AZ) as shown on the following diagram.

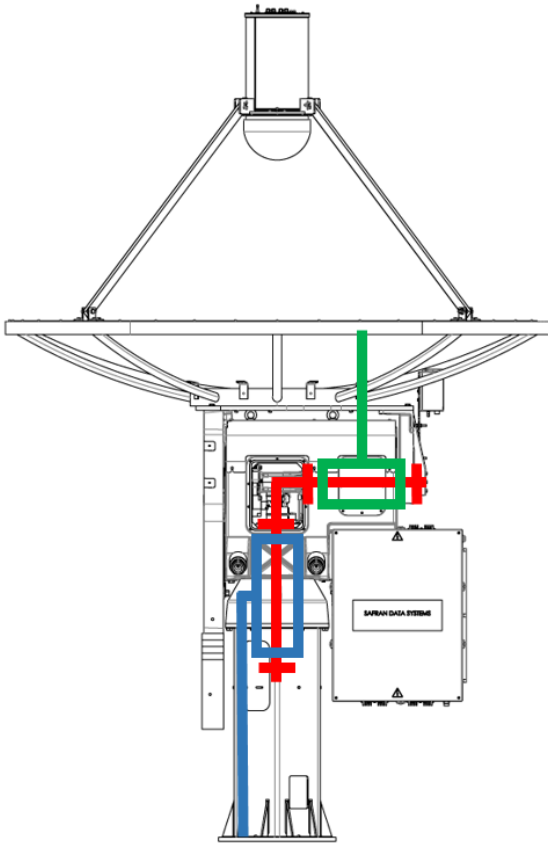


Fig. 14: EL over AZ pedestal joints

Test cases require unlimited AZ motion and therefore a RF rotary joint is installed on the AZ pivot. Rotary joints are much more expensive with increasing number of channels. As a consequence, integrating the HPA and the modem over the AZ axis (blue-red joint on the figure) is a good way to reduce cost. As long as power remains below 50W, signal is transmitted to the feed using cables whose flexibility is suitable to handle the elevation axis range (red-green joint on the figure) of the pedestal. This drives the need for outdoor HPAs as well as small modulators suitable for pedestal integration and adapted for use during antenna motion.

Conclusion

In this paper, we presented the challenges that bi-directional telemetry represent for ground stations and introduced multiple technical solutions. We compared the solutions and presented the performance of a field tested product that offers bi-directional telemetry capabilities.

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