

A Modular Family of High Data Rate SDR Transceivers

Mathias Reibe, Klaus Jäckel
 IQ wireless GmbH
 Carl-Scheele-Straße 14, 12489 Berlin, Germany; +49 30 6392-80611
 mathias.reibe@iq-wireless.com

Merlin F. Barschke, Clément Jonglez
 Technische Universität Berlin, Institute for Aeronautics and Astronautics
 Marchstr. 12, 10587 Berlin, Germany; +49 30 314-28743
 merlin.barschke@tu-berlin.de

ABSTRACT

IQ wireless GmbH developed a family of modular SDR transceivers to serve a wide range of different mission scenarios. Transceivers of this family are formed by two printed circuit boards accommodated in a compact housing. The SDR platform handles data interface and coding, while the analogue frontend implements frequency conversion and amplification. To increase the potential for customization, the architecture provides two independent channels for both up- and downlink. The first implementation of the new transceiver design is the X band transmitter XLink that was developed in cooperation with Technische Universität Berlin. Here, the two downlink channels are both configured for X band transmission. In a first development step, broadband data rates up to 25 Mbps are achieved and CCSDS compliance facilitates the use of existing ground infrastructure. Alternative configurations use both channels for redundancy and MIMO to implement highly reliable and efficient proprietary transmission modes. The implementation of increased data rates in the range of 150 Mbps is currently investigated. The two uplink channels of XLink are configured to support X and S band, respectively. This paper presents the transceiver family's architecture and details the XLink configuration including results from the ground qualification campaign and performance testing.

INTRODUCTION

During recent years, the performance capabilities of small satellites and especially CubeSats improved substantially. Here, the ever more sophisticated applications such as Earth observation with high-resolution optical payloads or radars call for ever-increasing data downlink capabilities while requiring keeping the utilized radio transceivers at a limited size and weight. In this context, peak data rates of more than 200 Mbit/s could already be demonstrated on a 3U CubeSat in X band [1].

Flexibility is also becoming a significant aspect in satellite communication, as applications such as IoT networks require transceivers that allow communication between multiple nodes and in some cases the ability to be reconfigured in flight. Another application with increasing commercial interest is constellations of large numbers of communication satellites, which drive the need for data throughput and flexible communication solutions such as inter-satellite links.

Here, software-defined-radio (SDR) based transceivers are particularly relevant, as they can be adapted to different use-cases and may even be reconfigured after launch by means of software updates [2,3]. Furthermore, SDR-based transceivers allow to implement capabilities that were traditionally performed by complex hardware modems such as CCSDS-compliant protocols or two-way ranging [4].

In this context IQ wireless GmbH developed a family of flexible SDR transceivers that can be adjusted to a wide range of application scenarios. The X band transceiver XLink is the first implementation within this family [5]. This paper gives an overview over the architecture of the transceiver family and details design and ground qualification of the XLink transceiver.

TRANSCEIVER FAMILY ARCHITECTURE

It is a common approach to use commercial-off-the-shelf (COTS) components stemming from industries such as consumer electronics and automotive to develop small satellite equipment offering high performance at low mass and volume. In the field of radio frequency (RF) advanced transmission schemes furthermore enable efficient transceiver designs offering high data-rates and reliable transmission. Here, especially the use of forward error correction (FEC) based on convolutional codes, TURBO codes, or low-density parity check codes (LDPC), as well as the implementation of higher order modulation schemes such as APSK are commonly used for small satellite transceivers. However, other techniques widely used in terrestrial communication systems may offer additional potential to increase the performance of such devices:

- Adaptive modulation and coding procedures (AMC)
- Multiple input multiple output (MIMO) schemes

The presented family of high data-rate SDR transceivers enables the application of such approaches

by implementing a modular architecture that forms a flexible platform adoptable for a wide range of application scenarios. The transceiver family is based on two printed circuit boards, namely the SDR platform and the analogue frontend.

The SDR platform features powerful field programmable gate arrays (FPGAs), digital signal processor (DSP) chips, memory and the necessary interfacing. Using this hardware, protocol layer and framing are realized and data encoding and decoding as well as modulation and demodulation procedures are performed by software algorithms in baseband. A highly integrated transceiver chip with DSP functionality and analogue RF/IF interfaces offers two transmit and two receive channels. It can be adjusted in RF bandwidth and data rate according to the needs of the application and offers functionality such as digital filtering, decimation and interpolation. High-speed A/D and D/A converters are forming the interface to the analogue parts of the chip. Here, up- and down-converters to realize input and output frequencies of up to 6 GHz are available using a central oscillator signal and mixers. Analogue filters and amplifiers enable individual IF channel management, the setting of the required low power IF level, gain control, as well as the suppression of unwanted and spurious signals.

The SDR platform supports symbol rates of up to 56 Msymbols/s. Based on this, data rates of 150 Mbps can be achieved by using higher order modulation schemes like 16-APSK. The recommended data interface to the spacecraft platform is based on transfer frames as defined by the CCSDS standard [6]. Channel coding and synchronization as well as all physical layer processing is performed within the transceiver, which enables a flexible implementation of various transmission protocols with low complexity.

The analogue frontend performs operations for the transmit signal, including the up conversion to higher frequencies, such as X band, the filtering of the RF signals, and the amplification to the maximum RF output power of 0.5W (27 dBm) per RF channel. Here, the two parallel Tx channels can be used simultaneously.

A simplified block diagram of the transceiver family's basic layout, indicating the SDR platform and the analogue frontend, is shown in Figure 1.

The two parallel Tx paths can be used simultaneously, which can for example be exploited to increase the transmitter reliability through redundancy. Another option is to use right-hand-circular-polarization (RHCP) and left-hand-circular-polarization (LHCP) in parallel

within the same radio channel. As only minor mutual interference of both planes is expected in this configuration, appropriate transmission schemes may allow to double the transmission data rate using this approach. Finally, the two transmit signals can be combined to a single one with higher RF output power.

The two receive channels can also be configured individually. The main application is redundancy, while the implementation of two distinct frequencies or even frequency bands for the receive channel might also be an advantage for certain applications.

The transmit and the receive bands of the analogue front-end module cover the whole RF bandwidth which is up to several hundred megahertz. However, the individual channel management and selection of the occupied bandwidth is performed within the SDR platform.

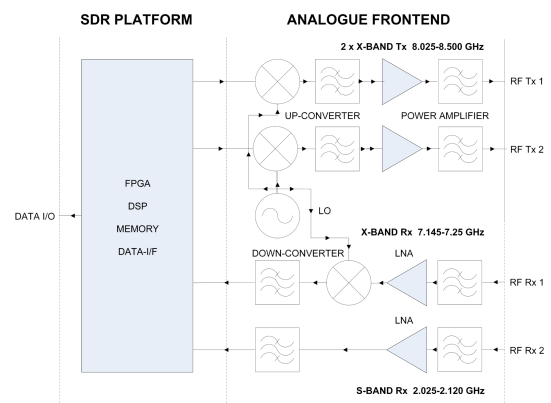


Figure 1: Simplified Block Scheme of the Transceiver Family's Architecture

Form factor and power consumption of transceivers based on the presented architecture have been designed to be applicable with CubeSats. The overall volume with housing is approximately 90 x 65 x 28 mm³ and the mass is below 200 g. As physical data interfaces, various options including Gigabit Ethernet are available.

XLINK IMPLEMENTATION

The first specific implementation of a transceiver based on the presented architecture is XLink, which was developed by IQ wireless GmbH in cooperation with Technische Universität Berlin.

On XLink both transmit paths are configured for operation in X band. For the receive path, two alternative frequency bands are available. The first Rx band covers the X band at 7.2 GHz and the receiver includes an LNA and a down-converter to S band with

some filters and amplifiers for signal conditioning. The second Rx band is configured to the standard S band at 2.1 GHz. It also contains all required equipment, such as LNA, amplifier and bandpass filters.

Figure 2 shows a photograph of the XLink engineering qualification model along with the dimensions of the device.



Figure 2: Photograph of the XLink engineering qualification model

As first option, CCSDS standard conform protocols with moderate data rate requirements were implemented. Modulation schemes based on QPSK and 8-PSK are quite common and have good performance with nonlinear distortions of the power amplifier.

QPSK combined with a convolutional code ($k = 7$ and $r = 0.5$) is useful for robust communication links and very limited link budget margins. The maximum achievable payload data rate with such FEC encoded QPSK would be 12 Mbit/s.

For the telecommand receiver, only wideband data performance is required. Typically, BPSK with BCH coding is used for a data rate of 64 kbps.

As a next development step, the implementation of a more flexible transmission protocol is planned. E.g. the procedures as defined in the CCSDS standard 131.2-B-1 for flexible advanced coding and modulation schemes used in high rate telemetry applications combine TURBO-like encoding principles with adaptive modulation schemes from QPSK to 64-APSK [7].

The main technical specifications for the XLink transceiver are gathered in Table 1.

Even if only a subset of the large number of available coding rate and modulation options is used, an improvement of the net payload rate by up to a factor of

five could be achieved when the carrier-to-noise (C/N) ratio is enhanced by 12 dB. This increased C/N ratio may be observed at higher elevations.

Table 1: Specifications of the XLink transceiver

Parameter	Value
Downlink frequency	8,025 – 8,500 MHz
X band uplink frequency	7,145 – 7,250 MHz
S band uplink frequency	2,025 – 2,110 MHz
Maximum RF output power	up to +30 dBm
Data rate satellite to ground	25 Mbps +
Modulation scheme	BPSK, QPSK, 8PSK
Data rate ground to satellite	64 kbps +
Data interface	Ethernet, SPI
Power consumption (send and receive)	< 15 W
Power consumption (receive)	< 4.5 W
Temperature range	-20 ... +50°C
Case	Passivated aluminum
Volume	90 x 65 x 28 mm ³
Mass	< 200 g

For this estimation, only QPSK, 8-PSK and 16-APSK modulation schemes at fixed symbol rate and occupied RF bandwidth but with varying FEC rates are required. Such an adaptive scheme could be very useful in exploiting the changing C/N ratio during the satellite’s pass over the ground station to transfer a much higher data volume when compared to the same pass using a fixed transmission scheme.

All these examples show that a wide range of applications can be realized with the provided configurations based on the flexible SDR transceiver architecture.

Figure 3 gives an overview over the different configuration options for the XLink transceiver enabled by the flexible SDR architecture.

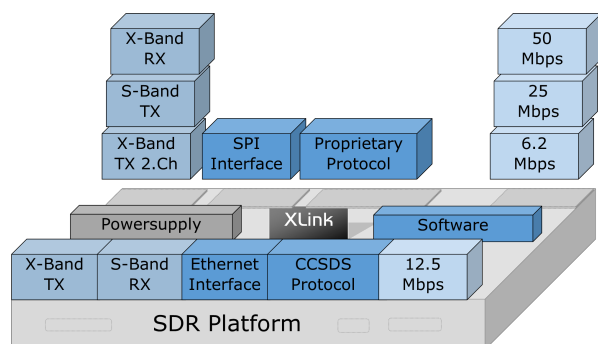


Figure 3: Illustration of Possible XLink Configurations Based on the Flexible Transceiver Architecture

Application Scenarios

As described above, XLink supports multiple transmission modes which are offering several data rates in order to comply with the needs of different application scenarios. Currently, CCSDS compliant modes offering data rates of 6.25, 12.5 and 25.0 Mbit/s are foreseen. Table 2 shows an estimation of the data rate achievable with typical ground stations as a function of the antenna dish's diameter to ensure a link margin of 3 dB. It assumes that the dish has an efficiency of 60 percent and that the system noise temperature is 180 Kelvin, which is typically for a low-cost ground station at low elevation angles.

Table 2: XLink Data Rate vs. Ground Station Dish Diameter and Elevation

Dish diameter	2.0 m	3.0 m	4.5 m
Antenna gain	42.5 dBi	46.0 dBi	49.5 dBi
G/T	19.9 dB/K	23.5 dB/K	27.0 dB/K
Elevation for 6.25 Mbit/s	> 13 deg	always	always
Elevation for 12.5 Mbit/s	> 24 deg	> 10 deg	always
Elevation for 25.0 Mbit/s	> 40 deg	> 22 deg	> 9 deg

A ground station with 7.3 meter dish and 31.2 dB/K factor of merit was also considered. It enables to achieve the maximum data rate of 25 Mbit/s regardless of the elevation angle.

Performance Testing

The capabilities of the XLink transceiver have been demonstrated in various performance tests. An overview of selected performance test results is given in Table 3, while Figure 4 shows how the transceiver is tested in the laboratory.



Figure 4: XLink RF Performance Testing

The parameters shown in Table 3 were tested with varying environment conditions such as temperature and pressure. Furthermore, the already implemented modulation schemes BPSK, QPSK, 8PSK, 16QAM and 64QAM (QAM as a test scheme only) were analyzed and demonstrated an appropriate EVM.

The measured frequency deviation over the full qualification temperature range was below 1ppm and the maximum transmit power deviation was measured with +1 / -1.5dB.

Table 3: Selected Performance Test Results

Parameter	Value
Transmit power per channel	+26.8 dBm
Error vector magnitude (EVM)	
QPSK, 12.5MSymb, 26.8dBm	11%
QPSK, 12.5MSymb, 25dBm	6%
Receiver sensitivity	
X Band, BPSK, BER <1E-03	-105 dBm
S Band, BPSK, BER <1E-03	-107 dBm
Power consumption	
2x TX, 2x RX	14 W
1x TX, 1x RX (S)	8.5 W
1x RX (S)	3.6 W

Figures 5 to 7 show laboratory tests results of the transmit parameters measured with a digital vector signal analyzer. For analyzing the sensitivity of the two receiver paths in X and S band a digital signal generator was used.

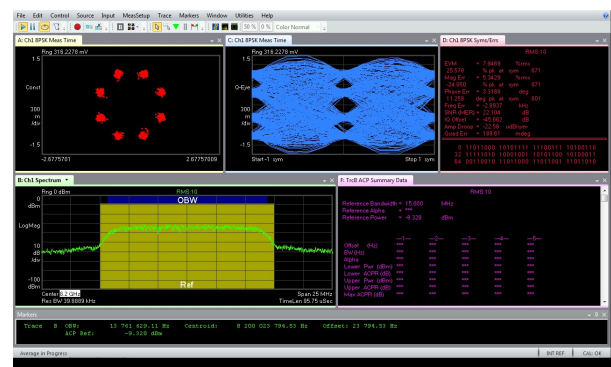


Figure 5: 8PSK Transmitter Constellation Diagram



Figure 6: Modulation Performance

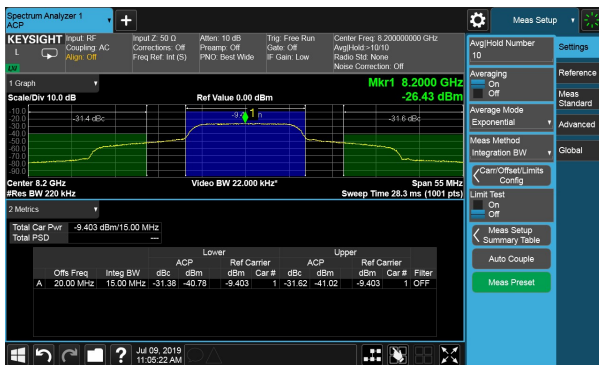


Figure 7: ACPR Measurement

A special waveform for this test adapted to the CCSDS frame and modulation scheme was implemented within the signal generator, which allows for fast adaption of test parameters for testing the performance of the automatic Doppler shift compensation algorithm.

Further, the implemented CCSDS protocol was tested successfully against a commercial ground station receiver.

Ground Qualification

The XLink transceiver was qualified on-ground through a comprehensive qualification campaign comprised of the following tests:

- Mechanical testing
 - Sinusoidal vibrations
 - Random vibrations
 - Shock
- Thermal-vacuum (TV)
- Electromagnetic compatibility (EMC)
- Total-ionizing dose (TID)

The test levels for the mechanical test campaign were derived by forming an envelope curve based on launchers' user's manuals such as PSLV, Soyuz, Vega and Falcon 9. The mechanical test campaign was

performed according to ECSS [8]. Figure 8 shows the XLink engineering qualification model mounted to the shock test table during the mechanical ground qualification campaign.

Thermal-vacuum testing was performed to qualify the transceiver for operation in a temperature range of minus 20 to plus 50 degrees Celsius measured at the transceivers thermal reference point. The test included eight test cycles. The test profile, margins and environmental conditions were defined following [8]. Figure 9 shows the XLink qualification model during preparation of the thermal-vacuum qualification test.

Electromagnetic compatibility (EMC) testing of XLink was conducted following MIL-STD-461G [9].

Within the total-ionizing-dose radiation test campaign, the XLink hardware was subjected to 12 krad (Si) with removed housing by means of a CO⁶⁰ radiation source. Figure 10 shows the XLink qualification model during preparation of the total-ionizing-dose radiation test.

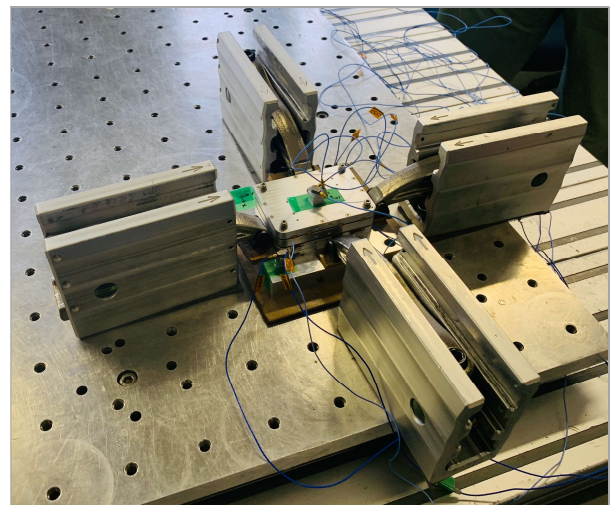


Figure 8: Qualification Model of the XLink Transceiver during Shock Testing

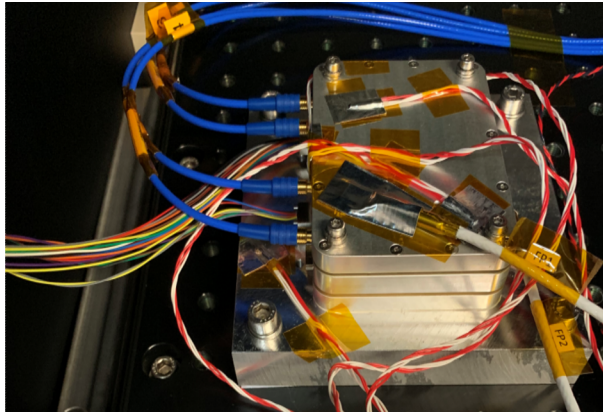


Figure 9: Thermal-Vacuum Qualification Test Setup

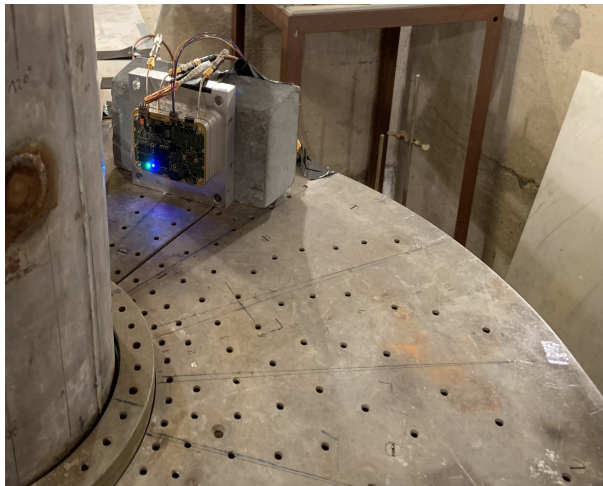


Figure 10: Preparation of the Total-Ionizing Test of XLink

CONCLUSIONS AND OUTLOOK

In this paper the systems design of a modular family of SDR transceivers that features each two up and downlink channels was introduced. Furthermore, XLink, the first transceiver implementation based on this family was presented.

For XLink both downlink channels are configured for transmission in X band while uplink is supported both in S and X band. The transceiver offers CCSDS compliant transmission modes of up to 25 Mbps, as well as proprietary modes either focusing on high data rates or increased reliability. Further options to offer data rates of up to 100 Mbps and more are currently investigated.

The paper furthermore presents results from performance testing and gives an overview over the ground qualification campaign that was conducted for XLink.

Acknowledgments

The development of XLink is funded by the Federal Ministry for Economic Affairs and Energy (BMWi) through the German Aerospace Center (DLR) on the basis of a decision of the German Bundestag (Grant No. 50 YB 1633 and 50 YB 1634).

References

1. Devaraj, K., R. Kingsbury, M. Ligon, J. Breu, V. Vittaldev, B. Klofas, P. Yeon, K. Colton "Dove high speed downlink system", Proceedings of the 31st AIAA/USU Conference on Small Satellites 2017.
2. Maheshwarappa, M. R., M. Bowyer, and C. P. Bridges. "Software Defined Radio (SDR) architecture to support multi-satellite communications", Proceedings of the IEEE Aerospace Conference. Big Sky, USA, 2015.
3. Perlaza, S. M., E. A. Hoyos, and P. V. Vera. "Reconfigurable satellite payload model based on software radio technologies", Proceedings of the 3rd IEEE International Congress of the Andean Region, Quito, Ecuador, 2006.
4. Lucresi, I., A. Di Carlofelice, and P. Tognolatti. "SDR-based system for satellite ranging measurements", IEEE Aerospace and Electronic Systems Magazine, vol. 31, iss. 1, 2016, pp. 8-13.
5. Noack, D., K. Jäckel, M. Reibe, F. Hartmann, S. Pirwitz and K. Brieß, "XLink – a 0.3 U sized X-band Transceiver for NanoSats", Proceedings of the 68th International Astronautical Congress, Adelaide, Australia, 2017.
6. Recommended Standard CCSDS 401.0-B-26 Radio Frequency and Modulation Systems, Part 1: Earth Stations and Spacecraft, Blue Book, October 2016.
7. Recommended Standard CCSDS 131.2-B-1 Flexible Advanced Coding and Modulation Scheme for High Rate Telemetry Applications, Blue Book, March 2012.
8. European Cooperation for Space Standardization, "Space engineering testing", ECSS-E-ST-10-03C, 2012.
9. Department of Defense, "Electromagnetic interference characterization requirements for equipment", MIL-STD-461, 1967.