Full-duplex High-Speed S-band Transceiver

Introduction

The Satlab SRS-4 is a full-duplex S-band transceiver designed for high-speed data transfer on micro- and nano-satellites. The transceiver operates on the ITU space operations S-band frequencies with BPSK, QPSK and 8PSK modulation and CCSDS recommended channel coding, enabling integration with both independent and commercial ground station networks.

Features

- Variable transmit symbol rate up to 5 MBd
- BPSK, QPSK and 8PSK transmit modulation
- BPSK and QPSK receive modulation up to 5 MBd
- Run-time configurable convolutional and/or Reed-Solomon forward error correction
- Adjustable output power up to 33 dBm with power monitoring and regulation
- CAN-bus and RS-422 interfaces using CubeSat Space Protocol (CSP)
- Ethernet interface using IP
- AES-256-GCM link-layer encryption and authentication
- PC/104 form factor aluminum enclosure
- Delivered with support library for easy integration
- Fully on-orbit software upgradable

Key Parameters

Parameter	Specification
Transmit frequency range	2200 MHz to 2290 MHz
Transmit modulation	BPSK/QPSK/8PSK, 100 kBd to 5000 kBd
Transmit power	20 dBm to 33 dBm
Receive frequency range	2025 MHz to 2110 MHz
Receive modulation	BPSK/QPSK, 100 kBd to 5000 kBd
Receive sensitivity	−122 dBm (<1 % PER, 100 kBd BPSK)
Input voltage	5.1 V to 28.8 V
Typical power consumption (6 V input, 20 ℃)	RX: 1.5 W (5 MBd) TX: 10.8 W (5 MBd, 33 dBm output)
Operating temperature RX	−40 ℃ to 85 ℃
Operating temperature TX	−40 ℃ to 70 ℃
CAN-bus bitrate	Up to 1 Mbit/s
RS-422 bitrate	Up to 12.5 Mbit/s, full-duplex
Ethernet bitrate	100 Mbit/s, full-duplex
Dimensions	93.0 mm × 87.2 mm × 18.0 mm
Mass	253 g

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1 Description

The Satlab SRS-4 is a full-duplex S-band transceiver designed for high-speed data transfer on micro- and nano-satellites. The transceiver operates on the ITU space operations S-band frequencies with BPSK, QPSK and 8PSK modulation and CCSDS recommended channel coding, enabling integration with both independent and commercial ground station networks.

Figure 1 shows a simplified block diagram of the external connections to the transceiver.

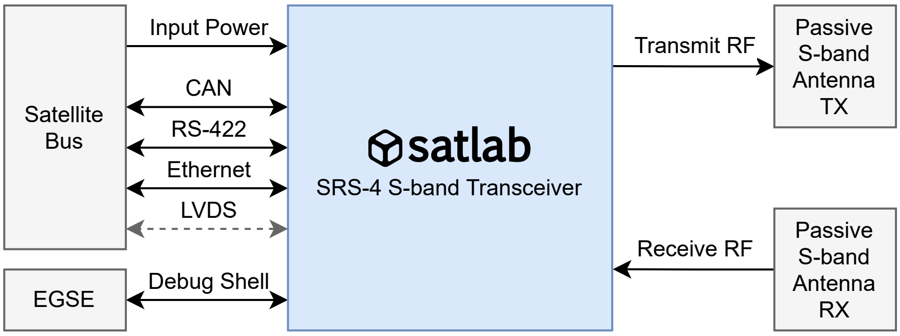

Figure 1: Simplified overview of the SRS-4 transceiver with external interfaces.

The SRS-4 is powered from a single 5.1 V to 28.8 V input. All onboard regulated voltages are protected against over-current.

The board is operated via CAN-bus and/or RS-422 using CubeSat Space Protocol (CSP) commands, and routes CSP packets between the space link interface and the satellite bus. CSP is a small network-layer delivery protocol designed for CubeSats, which allows subsystems to provide services and exchange messages using a common protocol on different physical layer interfaces (e.g. CAN-bus and RS-422). An open source reference implementation is available on `http://www.libcsp.org`. Both communication interfaces can be enabled simultaneously and serve as backup. Satlab supplies source-level client libraries in C and Python to wrap the CSP protocol, along with example code to simplify integration even further. Documentation for the support libraries is distributed separately along with the source code.

The Ethernet connection can be used to forward IP traffic between the space link and an internal satellite IP network. CSP and IP routing can be enabled simultaneously and coexist on the same space link interface.

The SRS-4 is prepared for future LVDS support as a high-speed serial data interface with two RX pairs and two TX pairs.

Separate full detent coaxial SMP connectors are used for the transmit and receive antennas, with on-board high-order ceramic monoblock filters allowing for flexibility in selection of the antenna configuration. The system monitors the output power during transmit and uses an Automatic Level Control (ALC) loop to adjust the transmit gain to achieve and maintain the target output power.

The transceiver uses a polyimide PCB for high thermal performance and reliability, and is delivered in a milled aluminium enclosure which provides a strong mechanical interface as well as EMI shielding and thermal contact to the thermal interface. The connectors P1 to P3 are latching, high-reliability Harwin Gecko connectors with gold-plated contacts.

A serial command line shell is available through the EGSE connector, which can be used for on-ground configuration, testing and performance verification.

The SRS-4 has successfully demonstrated interoperability with commercial ground station networks. Satlab also provides a GNU Radio (`https://www.gnuradio.org`) example flowgraph that can be used with compatible software-defined radios for ground testing and validation of the radio interface.

2 Hardware Overview

Figure 2 shows a simplified block diagram of the transceiver with the external interfaces in orange: Two RF connectors, one for RX and one for TX, the main connector P1, the EGSE connector P2 and the LVDS connector P3. The EGSE connector is used for software updates on ground and can also be used for configuration and performance testing. The microcontroller ties together the functions and interfaces of the board and handles configuration of the FPGA-based modem. The FPGA also handles configuration of the RF and baseband components.

The system includes on-board transceivers for CAN-bus, RS-422, Ethernet and LVDS to simplify integration with different satellite buses. Via configuration, the Ethernet PHY is powered up/down as needed to save power when not in use. Configuration of the MCU allows for the use of one or more interfaces at a time while the MCU will buffer and route frames to the desired interface and subsystem address. Configuration and calibration values are stored persistently in an F-RAM device. Telemetry (TM) sensors include temperature, voltage, current and power measurements (see section 2.3).

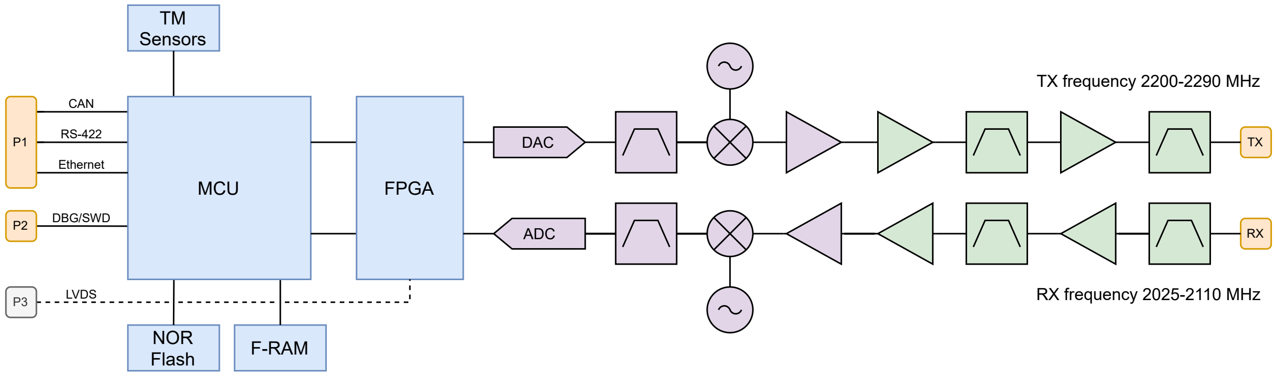

Figure 2: Overview of the SRS-4 hardware design. Some blocks have been left out for clarity.

2.1 RF Design

The RF section is shown in green and purple on figure 2. The RF path is constructed as independent receiver and transmitter chains that share a common factory-calibrated frequency reference (VCTCXO). The RX and TX local oscillators can be programmed independently to allow individual selection of RX and TX frequencies. The SRS-4 includes on-board low noise amplifier and power amplifier for simple integration with passive antennas. High-order ceramic monoblock filters are used on both RX and TX to lower the TX noise in the RX frequency band and to isolate the receiver from the TX frequency band.

RF forward and reflected power is monitored via a directional coupler and power sensors to allow the Automatic Level Control (ALC) to keep output power stable over frequency and temperature. The reflected RF power measurement is used for transmitter protection.

2.2 Power Domains

Figure 3 shows the local power domains of the SRS-4. Each power domain of the transceiver features over-current protection for latch-up isolation. The input buck converter generates a local 3.3 V regulated voltage from the input voltage. A 3.3 V LDO from the input voltage is used to drive the dedicated watchdog timer (WDT) circuit. The WDT circuit is also used as a power on reset timer that actively discharges the internal power nets of the transceiver before starting the power-on sequence, and as a latching self-resetting over-current protection. During an over-current event, or if the MCU does not reset the WDT, the power on reset sequence, with active discharge, will be re-initiated. The transmit PA is supplied from a 27.7 V switch-mode converter (SMPS). The PA driver is supplied from the 3.3 V via a protected (limiting) switch. A set of buck converters from 3.3 V are used for 1.0 V and 1.8 V for the FPGA and parts of the RF circuit for efficiency.

Key RF components in the receiver and transmitter chain are supplied through LDOs to keep the impact of power supply noise to a minimum. These are omitted in figure 3.

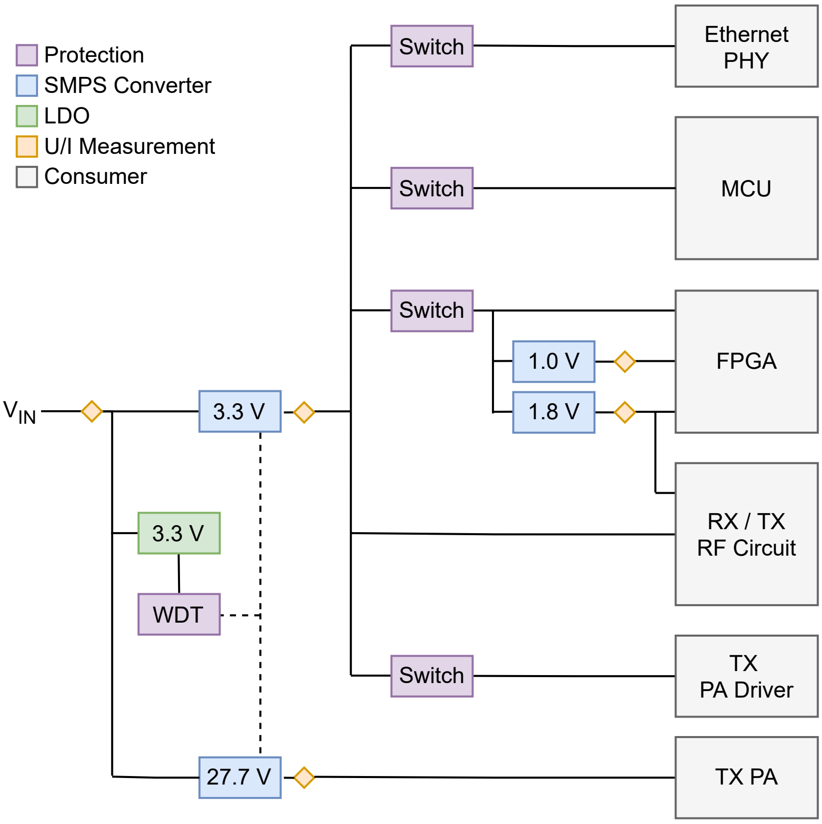

Figure 3: SRS-4 power domains and voltage/current measurement points.

2.3 Telemetry Sensors

Voltage, current and power can be measured on the V_{IN}, 3.3 V, 1.8 V, 1.0 V and V_{PA} rails and can be downloaded using telemetry properties (see figure 3). The SRS-4 has six temperature measurement points, located on-die or near key components on the PCB. The temperature and power sensors are listed in table 1 along with their telemetry property name. For additional telemetry available from the MCU, refer to section 3.2.

Table 1: Onboard telemetry sensors

Property	Description
`tm.{volt,cur,power}.vin`	V_{IN} voltage, current and power
`tm.{volt,cur,power}.3v3`	$V_{3.3V}$ voltage, current and power
`tm.{volt,cur,power}.1v8`	$V_{1.8V}$ voltage, current and power
`tm.{volt,cur,power}.1v0`	$V_{1.0V}$ voltage, current and power
`tm.{volt,cur,power}.pa`	Power amplifier voltage, current and power
`tm.temp.psu`	Power supply temperature
`tm.temp.mcu`	MCU temperature
`tm.temp.fpga`	FPGA on-die temperature
`tm.temp.xcvr`	RF baseband temperature
`tm.temp.lna`	LNA temperature
`tm.temp.pa`	Power amplifier temperature

3 Software Overview

Figure 4 shows the main software components and packet flow in the SRS-4 transceiver. The transceiver essentially functions as a router of CSP (CubeSat Space Protocol) and IP packets between the radio interface and satellite bus.

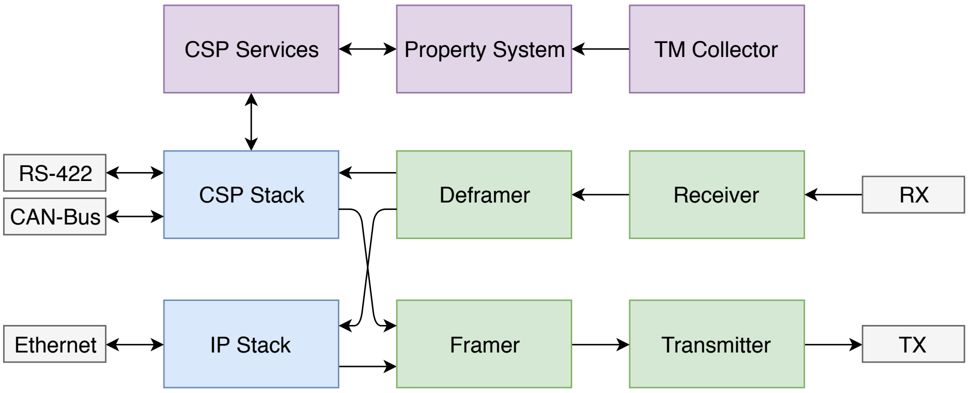

Figure 4: Overview of the transceiver software components and data flow. The property system indirectly interfaces with all other components, but the connections have been left out for clarity.

The receiver module is responsible for configuration and interfacing with the FPGA. Received frames are passed onto the deframer module, which verifies the frames using the configured framing format and FEC, and forwards valid frames to either the CSP or IP protocol stack depending on the frame type. Equivalently, the framer module accepts frames from the protocol stacks, applies error correction data and enqueues them with the transmitter module which pass them on to the FPGA.

The CSP protocol stack receives frames from the system interfaces, and forwards them according to the current routing table. Both the CAN-bus and RS-422 interfaces can be enabled simultaneously and used for CSP communication. The SRS-4 can also be configured to route CSP packets between these interfaces, so nodes on the CAN-bus can communicate directly with nodes on RS-422 and vice versa. Alternatively, both interfaces can be connected to the same systems and serve as backup routes using the CSP routing table.

Configuration and telemetry readout is handled through a local CSP service that interfaces with the onboard property system. See section 3.2 for more information on the property system. The TM Collector module is responsible for periodically collecting telemetry values from on-board sensors, and updating system properties accordingly. See section 3.2.2 for more details.

The Ethernet interface is used for IP packet forwarding and the SRS-4 does not currently provide any local IP services except replying to ICMP echo (“ping”) requests. A CSP connection on CAN-bus or RS-422 is required to operate the system.

3.1 Modem

Figures 5 and 6 show an overview of the components that are implemented in the FPGA, comprising the SRS-4 modem. While not shown on the figure, the FPGA is also responsible for low-level control such as modem and RF configuration, including the ALC loop that continuously monitors and adjusts the transmit gain to achieve the configured output power.

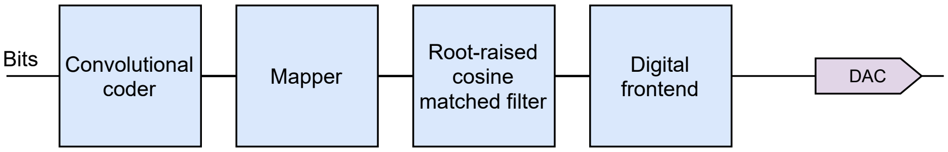

Figure 5: Overview of TX-related components implemented in the FPGA

The FPGA is loaded on boot by the MCU. Being an FPGA-based modem, it can be fully upgraded with the MCU firmware both through the EGSE connector during integration or on-orbit through the spacelink. Safeguards are in place to ensure a fallback firmware is loaded if an upgrade fails. More details in section 3.4.

On the transmit side, submitted frames are considered a continuous stream of bits to the modem. The modulator processes this stream of bits:

- If convolutional FEC is enabled, bits are convolutionally coded as described in chapter 4.
- Bits are mapped to either BPSK, QPSK or 8PSK symbols following [1].
- Symbols are interpolated and shaped with a root-raised cosine filter.
- The digital frontend scales and resamples symbols to match the symbol rate.

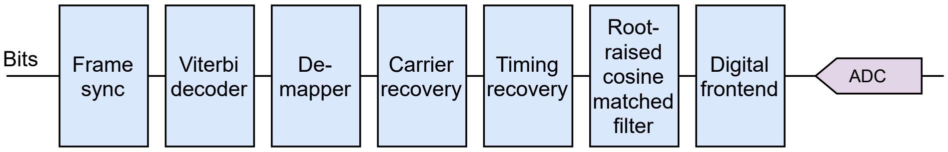

Figure 6: Overview of RX-related components implemented in the FPGA

On the receive side, samples from the ADC are processed as follows:

- The digital frontend conditions and resamples the input. The digital frontend also holds the automatic frequency control (AFC), which does coarse frequency offset compensation if enabled.
- A root-raised cosine filter matched to that of the transmitter filters the input.
- Symbol timing offset is recovered by a timing recovery loop.
- Fine carrier frequency and phase offset is recovered by the carrier recovery loop. The frequency pull-in range is approximately 1 % of the symbol rate, but depends on the SNR. The output symbols are used to estimate the received E_b/N_0.
- Symbols are mapped to soft bits depending on the chosen modulation type, following [1].
- The soft bits are decoded by a Viterbi decoder or sliced to hard bits if convolutional FEC is disabled.
- A frame synchronizer aligns the output bit stream with the beginning of a frame using the syncword.

The carrier recovery frequency pull-in range is limited to approximately 1 % of the symbol rate. This may be insufficient at low rates and can be extended by the AFC up to 15 kHz. For applications with high Doppler shift relative to the symbol rate (such as satellites in low Earth orbit using low symbol rates), Doppler shift compensation on the ground station may be required.

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[1] CCSDS, *401.0-B-30 Radio Frequency and Modulation Systems — Part 1: Earth Stations and Spacecraft*, 2020.

3.2 System Properties

Configuration, status and telemetry download from the SRS-4 is handled using a number of system property variables. Each variable has a type (signed/unsigned integers of various sizes, floating point numbers, strings, etc.) and a default value. Some properties are used for configuration and can be modified and stored in (optionally write-protected) non-volatile memory using the debugging shell or remotely via CSP commands. Others are read-only and used for telemetry purposes. These properties are periodically updated by the system during operation, and can also be viewed using either the debug shell or downloaded via CSP.

Most property changes take effect immediately, while others require a store and a system reset after update.

The system properties are divided into a number of property groups, each covering a specific part of the firmware. Property values can be read and updated remotely using CSP. The `prop-client` support library contains wrapper functions around the CSP protocol to read and update properties. The `satctl` Linux application can be used as a reference for the use of the library.

A full list of system properties and a description of their values is included in the SRS-4 software documentation.

3.2.1 Configuration

On boot, the system loads stored properties from F-RAM. Most property groups can be stored in both a *boot* and a *fallback* location, where the latter is write protected. The boot location has priority over the fallback values, and is used if it is valid. A set of default settings are hardcoded into the system firmware and used if no valid stored properties are found. The SRS-4 is equipped with a ground watchdog timer (GWDT) that must be reset periodically using a telecommand (by default every 24 hours). If the GWDT expires, it clears the receiver and transmitter boot configuration and reboots the system to return to the fallback settings.

It is possible to change properties runtime without saving them to F-RAM. It is strongly recommended not to alter write-protected properties on-orbit (e.g. CSP address), since setting them to a invalid value could render the device unresponsive.

Listing 3.1 shows the use of the `prop list` command to show properties and their values from the `rx` group.

Listing 3.1: List properties and values from the receiver property group.

```
[srs-4] prop list rx
Property        Type  Stat  Flag  Value
freq            u32   D     -     2029500000 hz
type            u8    D     -     1
rate            u32   D     -     1000000 baud
rolloff         u8    D     -     0
afc.enable      bool  D     -     true
afc.range       u32   D     -     15000 Hz
rs              bool  D     -     true
cc              bool  D     -     true
rand            bool  D     -     true
crc             bool  D     -     true
size            u16   D     -     217 bytes
id              u16   D     -     0
crypto.key      bin   D     S     <hidden>
crypto.decrypt  bool  D     -     false
crypto.auth     bool  D     -     false
frames          u32   M     NR    7316 frames
detected        u32   M     NR    7899 frames
rssi            flt   M     NR    -84.25 dBm
freqerr         flt   M     NR    -8123.85 Hz
symerr          flt   M     NR    -3.27 ppm
ebn0            flt   M     NR    14.34 dB
carrier.lock    bool  M     NR    true
frame.lock      bool  M     NR    true
```

3.2.2 Telemetry

The property system is also used to read the telemetry variables from the SRS-4. Telemetry values are collected periodically and are available through the `tm` property group. The example below shows the use of the `srs4 tm` shell command which uses the property system to read and output formatted telemetry values. In the example, the board is connected to a 6 V bench supply and waiting for incoming frames. Note that the voltage and current measurements are instantaneous, while the power measurements are averaged which is why the multiple of the voltage and current values are not exactly equal to the power measurements.

The ambient temperature in the example was approximately 25 ℃ and the average board temperature about 33 ℃ with the FPGA core temperature at 36.62 ℃ being the warmest. The transmit section and power amplifier is powered down when the system is not transmitting, so the PA sensor is the coldest at 32.56 ℃.

Telemetry data from the transmitter and receiver is also listed. This includes the number of received and transmitted frames, the measured output power and status of the receiver including instantaneous estimates of the input signal power (RSSI), signal quality (E_b/N_0) and offsets.

Listing 3.2: List telemetry properties and values.

```
[satctl] srs4 tm
System Info:
Bootcount            10 boots
GWDT counter   19:58:30 (71910 seconds)

Power Rails:
VIN             5957.00 mV    253.00 mA   1508.00 mW
3V3             3348.00 mV    423.00 mA   1419.00 mW
1V8             1805.00 mV    282.00 mA    510.00 mW
1V0              963.00 mV    372.00 mA    359.00 mW
PA                 0.00 mV      0.00 mA      0.00 mW

Temperature Sensors:
PSU               32.62 C
MCU               33.43 C
FPGA              36.62 C
XCVR              33.81 C
LNA               33.25 C
PA                32.56 C

Transmitter:
Frames             1131 frames
Forward power      0.00 dBm

Receiver:
Frames             1711 frames
RSSI             -98.75 dBm
Eb/N0             -3.63 dB
Freq error     11996.93 Hz
Rate error        74.97 ppm
Carrier sync   unlocked
Frame sync     unlocked
```

3.3 Debug Shell

The system provides a serial command line shell on the RX/TX pins in the EGSE connector (see section 7.2). The serial configuration is 8N1 at 115200 baud, and the console requires an “Enter” key press to be activated.

Listing 3.3 shows the nominal output on the serial shell during boot. A number of timestamped log messages are printed during boot from various logging groups. Additional logging can be enabled at runtime using the `trace` commands. The `help` command can be used to list available commands and their usage.

The installed software version and build information is also printed in the debugging shell during boot.

Listing 3.3: Example output from debugging shell.

```
[     0.010020] system: Copyright (c) 2020 Satlab A/S <satlab@satlab.com>
[     0.010128] system: boot: 10 reset cause: power-on reset
[     0.010240] system: board serial #31123456
[     0.011574] prop: using stored sys properties
[     0.017767] prop: using stored cal properties
[     0.024524] prop: using stored tx properties
[     0.031207] prop: using stored rx properties

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[srs-4] help
Available commands:
boot                Bootloader commands
csp                 CSP commands
help                Show available commands
history             Show previous commands
prop                System configuration properties
reboot              Reboot system
time                Time command execution
tm                  Telemetry commands
trace               Trace subcommands
uptime              Show system uptime
watch               Run command periodically
```

3.4 Software Upgrade

The SRS-4 uses two firmware images: a *primary* image containing factory firmware that can only be updated on ground, and an *alternate* image that can also be updated on-orbit using CSP. Each firmware image includes the FPGA bitstream.

By default, the system will always boot the primary image. Booting the alternate image for a number of boots can be configured through telecommand. After the set number of boot cycles, the system will return to the factory firmware unless the alternate image boot count is set again. The integrity of the alternate image is verified using an embedded checksum before it is booted, and the primary image is booted if the check fails.

4 Framing Format

The SRS-4 transmits and receives fixed size frames on the radio interface. Payload data size and FEC options are individually configurable through system properties for the transmitter and receiver. The actual length of transmissions is a function of the configured payload data size and FEC options as described below. The maximum payload data size is currently fixed at 1024 bytes.

Figure 7 shows the frame structures with the default payload data size of 217 bytes. Although the radio interface uses fixed size frames, the data contents can be variable length (up to the configured maximum). A two byte header is always prepended to every frame, to specify the content type and actual length of the data. The system supports encapsulation of two different frame types in the payload field: CSP frames and IP frames. Protocol overhead must also fit in the payload data field, so in the default configuration the maximum CSP MTU is 213 bytes because the CSP header occupies 4 byte of the payload field.

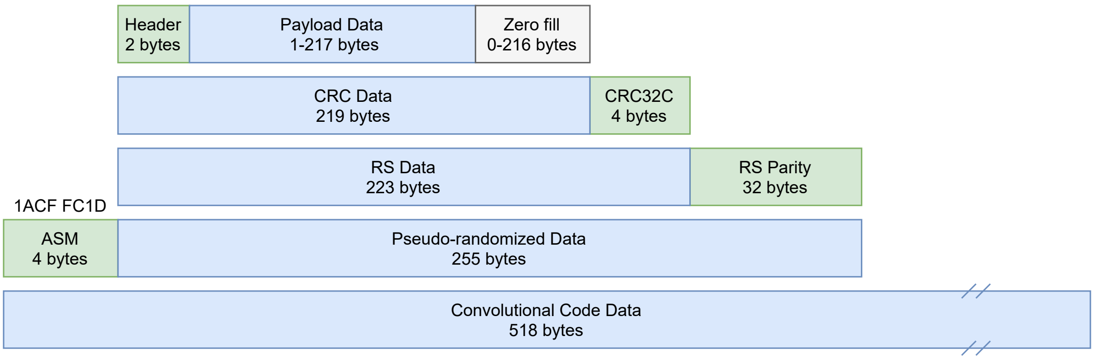

Figure 7: Default configuration frame with payload data length set to fit in 1 Reed-Solomon block.

The contents of the two byte header is shown in figure 8. The reserved bit is transmitted first and is always set to 0. The type field is set to 0 for CSP frames and 1 for IP frames. Frames with other type values are invalid and will be dropped. The length field denotes the number of payload data bytes following the header. With the default payload data size configuration in figure 7, it will have a value of 1-217. All fields are transmitted most significant bit first.

Figure 8: Two byte frame header

After the header is prepended, the frame is zero-padded to the configured frame size plus the header size (219 bytes in the example). A CRC32C checksum can optionally be appended to the frame for increased error detection. Using the `tx.id` property, a 16-bit satellite ID field can also be added immediately after the header, and used for filtering on the receiver.

If the `tx.rs` property is set to `true`, a (255,223) Reed-Solomon code is used to append 32 parity bytes to the frame as specified by [1] for each block of up to 223 data bytes. If the configured frame size results in fewer than 223 bytes input to the Reed-Solomon encoder, the code block length is shortened using virtual fill. If the frame size is larger than the Reed-Solomon data block size, the RS data is divided into (approximately) even blocks, and interleaved according to [1]. This ensures that each payload data byte has approximately the same error correction probability. The interleaving depth is determined from the frame size and can not be changed from $I = \lceil size / 223 \rceil$. Note that compliance with [1] requires the frame size to be a multiple of the interleaving depth. If the configured frame size is not a multiple of the interleaving depth, the last blocks will have an additional virtual fill byte. The default 217 byte frame size is chosen such that a maximum length payload frame results in a single RS data block of 223 bytes.

Pseudo-randomization, as described in [1], is applied to ensure a sufficient number of bit transitions in the frame if the `tx.rand` property is set to `true`. A 4 byte Attached Sync Marker (ASM) is then prepended to the frame. Convolutional coding using the r=1/2, constraint length 7 code from [1] can be enabled using the `tx.cc` property. Punctured code rates are not used.

When starting transmission, an idleframe (a frame containing all zeroes as payload, but with CRC and FEC applied) is transmitted first to allow the receiving end to synchronize. If no more frames are queued after the last data frame has been transmitted, idleframes are again transmitted. After transmitting only idleframes for `tx.idletime` seconds (rounded up to whole frames), the transmitter is powered down. This procedure allows the receiver to stay in lock between data frames.

4.1 Encryption

The SRS-4 can optionally encrypt and/or authenticate frames using AES-256-GCM encryption. Encryption is applied after frame padding but before the frame is passed to the CRC and FEC stages.

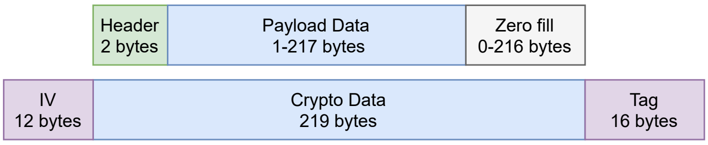

Figure 9: Encrypted and authenticated frame.

The 256 bit encryption keys are configured using the `tx.crypto.key` and `rx.crypto.key` properties, and can be changed on-orbit. If encryption or authentication is enabled using the boolean `tx.crypto.encrypt` or `tx.crypto.auth` properties, a 96 bit random nonce/IV is prepended to the frame, thus increasing the frame size by 12 bytes. If `tx.crypto.auth` is enabled, a 128 bit tag is appended and the frame size is increased by an additional 16 bytes. Similarly, `rx.crypto.decrypt` and `rx.crypto.auth` enable decryption and authentication on the receive interface.

Encryption and authentication can be enabled independently on both the RX and TX interfaces. Authentication can be enabled without encryption (GMAC mode) but it is recommended to always enable authentication when encryption is enabled, since the encryption itself does not protect against malicious messages.

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[1] CCSDS, *131.0-B-3 TM Synchronization and Channel Coding*, 2017.

5 Throughput

The channel symbol rates are configurable through the `tx.rate` and `rx.rate` properties, but the achievable information rate depends on configured frame size, FEC options, the choice of data interface and upper-layer protocols. The relevant layers in the network stack are illustrated on figure 10.

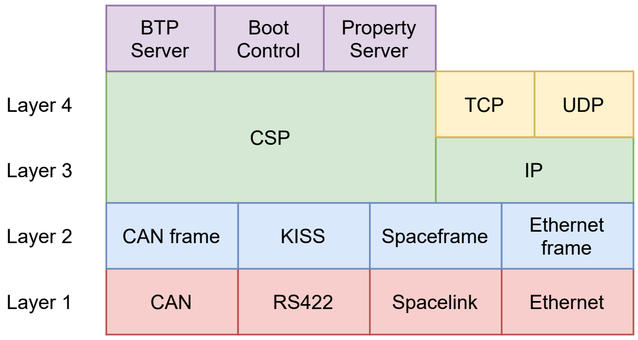


Figure 10: SRS-4 network stack

Each layer introduces an overhead in the form of headers, and some introduce a FCS or FEC for reliability. The exact overhead can depend on frame lengths and configuration, so care must be taken when estimating the effective information rate available to the application (sometimes referred to as “goodput” or “layer-4 throughput”). Further limitations are introduced by physical layer protocols where several nodes share the same bus such as CAN. Examples of achievable throughputs with different choices of data interface are shown on table 2.

Table 2: Example application-layer throughput versus data interfaces

Transport	Max layer-1 bitrate	Max goodput [Mbit/s]	
		217-byte frames	1024-byte frames
CSP over CAN	1.00	0.45	0.45
CSP over RS-422	12.50	9.47	9.74
UDP+IP over Ethernet	100.00	53.04†	84.30†

† Limited by CPU, not protocol overheads

The `tx.rate` and `rx.rate` properties dictate the spacelink symbol rate R_{sym}. The spacelink output bitrate (“layer-1 bitrate” or “channel bitrate”) is $R_{sym}M$, where M is the number of bits per symbol (1, 2 or 3 for BPSK, QPSK and 8PSK, respectively). Several overheads are added to data transmitted over the spacelink, as described in chapter 4 and summarized on table 3.

Table 3: Per-frame spacelink overheads with default 217-byte frame size

Overhead	Optional	Size [bytes]
Zero fill	No	0–216
Encryption/authentication nonce/IV	Yes	12
Authentication tag	Yes	16
ASM + spacelink frame header	No	6
CRC	Yes	4
Reed-Solomon FEC	Yes	32
Convolutional FEC	Yes	259

The throughput discussed in the remainder of this section refers to the maximum layer-2 input rate. Figure 11 shows this throughput as a percentage of the channel bit rate, as a function of the packet size and FEC configuration.

In the CRC-only case, the throughput approaches 100 % of the channel rate as the frame size is increased, because the overhead is fixed (ASM, header and CRC field). The CRC+CC case is similar, approaching the rate of the convolutional code (50 %). The jumps in throughput in the RS cases occur every time the frame size requires a new Reed-Solomon block to hold the data bytes. The throughput approaches the rate of the Reed-Solomon code, R_{RS} = 223/255 = 87.5 % of the channel rate. Similarly, when both Reed-Solomon and convolutional coding is enabled, the throughput approaches the rate of the concatenated code $R_{RS}R_{CC}$ = 223/255/2 = 43.7 %.

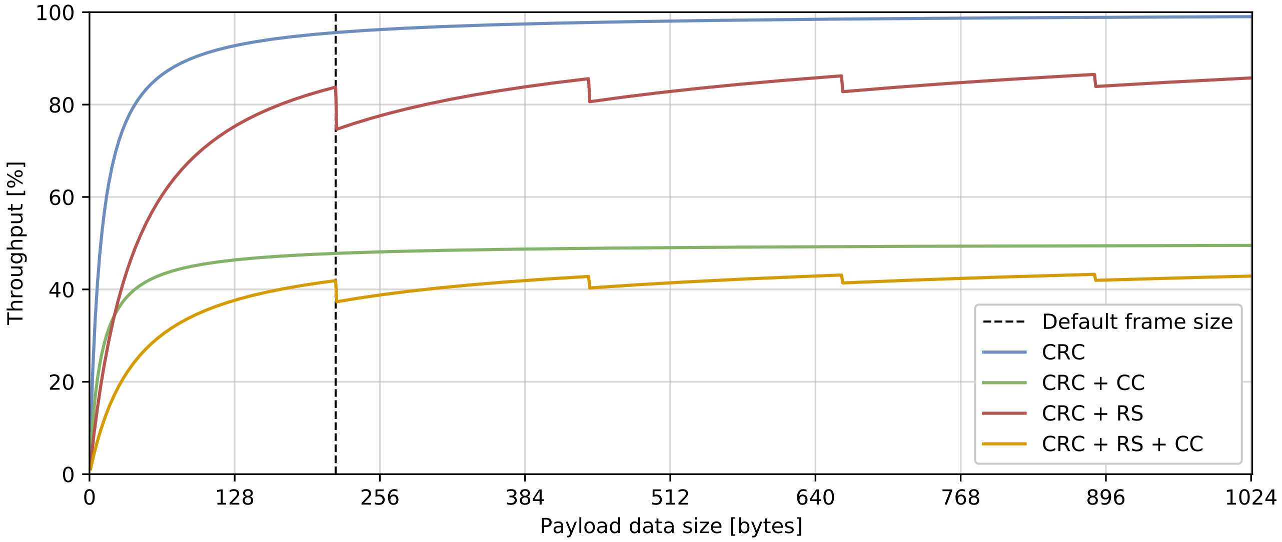


Figure 11: Theoretical throughput as function of payload data size

As described in the previous section, the default frame size is chosen to exactly fit in a single Reed-Solomon block. For this size, table 4 lists the throughputs at the default and maximum symbol rates of 1 MBd and 5 MBd, across modulation types.

Table 4: Theoretical throughput in Mbit/s with default 217 bytes payload size for selected symbol rates.

FEC configuration	Throughput	1 MBd (default)			5 MBd (max)		
		BPSK	QPSK	8PSK†	BPSK	QPSK	8PSK†
CRC	95.6%	0.96	1.91	2.87	4.78	9.56	14.34
CRC + RS	83.8%	0.84	1.68	2.51	4.19‡	8.38‡	12.57‡
CRC + CC	47.8%	0.48	0.96	1.43	2.39	4.78	7.17
CRC + RS + CC	41.9%	0.42	0.84	1.26	2.09	4.19‡	6.28‡

† Transmitter only

‡ Receiver is limited by RS decoder maximum throughput of approximately 4 Mbit/s

These throughputs do not include layer-3 and layer-4 overhead from CSP or IP.

6 Electrical Specifications

All electrical parameters in all tables are specified under the following conditions, unless stated otherwise:

- Typical values are based on T_{AMB}=20 ℃ and V_{IN}=6 V, by production test and/or design characterization.
- Minimum and maximum values represent the worst conditions across supply voltage, process variation, and operating temperature.
- All values refer to levels specified on the connectors, i.e. not including cable loss.

6.1 Absolute Maximum Ratings

The table below lists the minimum and maximum allowable levels on the connector pins. Exceeding these may damage the product permanently.

Table 5: Absolute Maximum Ratings

Parameter	Min	Max	Unit
Storage Temperature	–40	85	℃
Input Voltage	—	40	V
RF input power (TX Connector)	—	20	dBm
RF input power (RX Connector, TX frequency range)	—	30	dBm
RF input power (RX Connector, remaining frequency range)	—	10	dBm
CAN-L/H	–7	12	V
RS-422	–7	12	V
Ethernet	–50	50	V
LVDS	–0.5	4	V
Debug-UART (TTL)	–0.5	5	V

6.2 Operating Conditions

Operating conditions refer to four modes defined as:

- Idle Mode: Ready to transmit and receive, awaiting packets
- RX Mode: Actively receiving packets
- TX Mode: Actively transmitting packets
- RX+TX Mode: Full-duplex receiving and transmitting packets

The nominal power consumption is specified with the CAN-bus interface enabled and RS-422 and Ethernet disabled.

Table 6: General Operating Condition

Parameter	Min	Typ	Max	Unit
Operational Temperature (Idle, RX)	–40	—	85	℃
Operational Temperature (TX, RX+TX)	–40	—	70	℃
Supply Voltage	5.1	—	28.8	V
Input power (Idle)	—	1.5	—	W
Input power (RX)	—	1.5	—	W
Input power (TX, 33 dBm output power)	—	10.8	—	W
Input power (RX+TX, 33 dBm output power)	—	10.8	—	W
Additional input power for Ethernet enabled	—	160	—	mW
Additional input power for RS-422 enabled	—	60	—	mW
V_{IN} voltage rail	5.1	–	28.8	V
$V_{3.3V}$ voltage rail	3.28	3.35	3.42	V
$V_{1.8V}$ voltage rail	1.77	1.81	1.84	V
$V_{1.0V}$ voltage rail	0.944	0.963	0.983	V
V_{PA} voltage rail (During TX)	27.1	27.7	28.3	V
V_{IN} input equivalent capacitance at power-on	—	60	70	µF
Required antenna isolation (TX connector to RX connector)	13	—	—	dB

6.3 Receiver

The typical receiver packet error rate (PER) versus input signal power is illustrated on figure 12. The test is performed with RS+CC FEC and with the default packet size (217 payload data bytes — cf. chapter 4). This is repeated at 3 frequencies (bottom, middle and top of the band), at selected symbol rates, with BPSK and QPSK modulation and at ambient temperatures of –40 ℃, 20 ℃ and 85 ℃. The illustrated PER is averaged over frequency, with which performance varies by less than 0.5 dB.

QPSK at 5 MBd is not illustrated, since this case is limited by the RS decoder max throughput of 4 Mbit/s (refer to chapter 5).

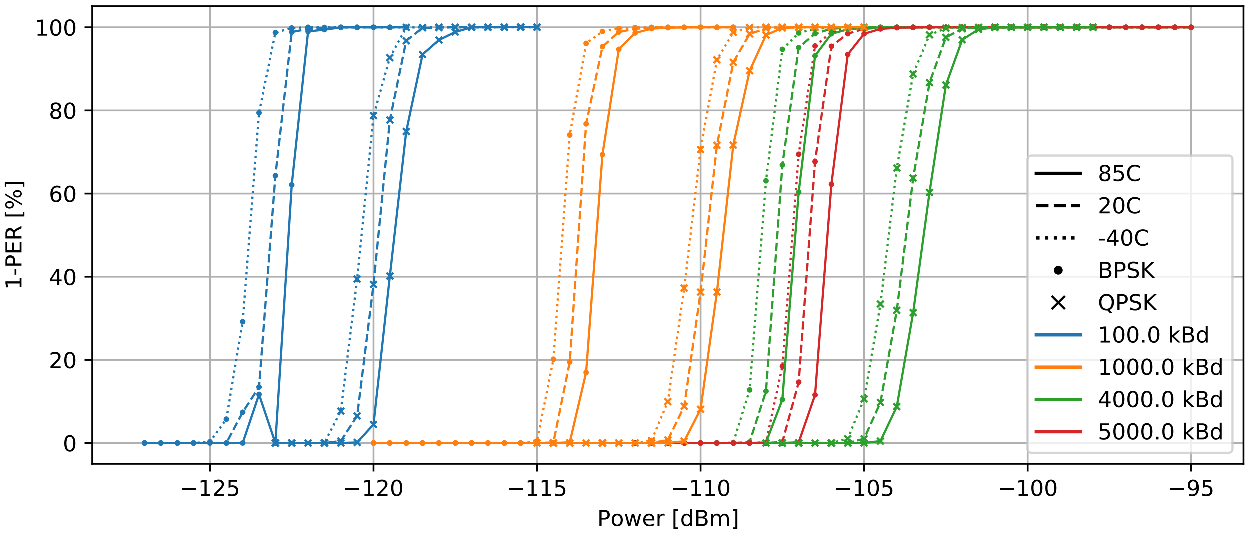


Figure 12: Typical receiver packet error rate, averaged over frequency

A summary of the required input power in dBm for a packet error rate of less than 1 % with the default packet size and various choices of modulation, symbol rate and FEC is shown on table 7.

Table 7: Required input power in dBm for PER <1 % at 2067.5 MHz (20 ℃)

Modulation	**Symbol rate [kBd]**	**Required input power [dBm]**			
		CC+RS	**CC**	**RS**	**No FEC**
BPSK	100	–122.0	–121.0	–114.0	–112.0
QPSK	100	–119.0	–118.0	–111.0	–109.0
BPSK	1000	–112.5	–111.0	–104.0	–102.0
QPSK	1000	–108.5	–108.0	–101.0	–99.0
BPSK	4000	–106.0	–105.0	–98.0	–96.0
QPSK	4000	–102.0	–101.5	N/A†	–93.0
BPSK	5000	–105.5	–104.0	N/A†	–95.0
QPSK	5000	N/A†	–100.5	N/A†	–92.0

† Limited by RS decoder max throughput

The bit error rate (BER) performance of the SRS-4 modem is illustrated on figure 13. These are on-hardware measurements with an input signal level high enough that the impact of the frontend noise figure can be ignored. The result is a measurement of the demodulator implementation loss. The loss is less than 0.3 dB for E_b/N_0 between 1 dB and 10 dB. Key receiver characteristics are summarized on table 8.

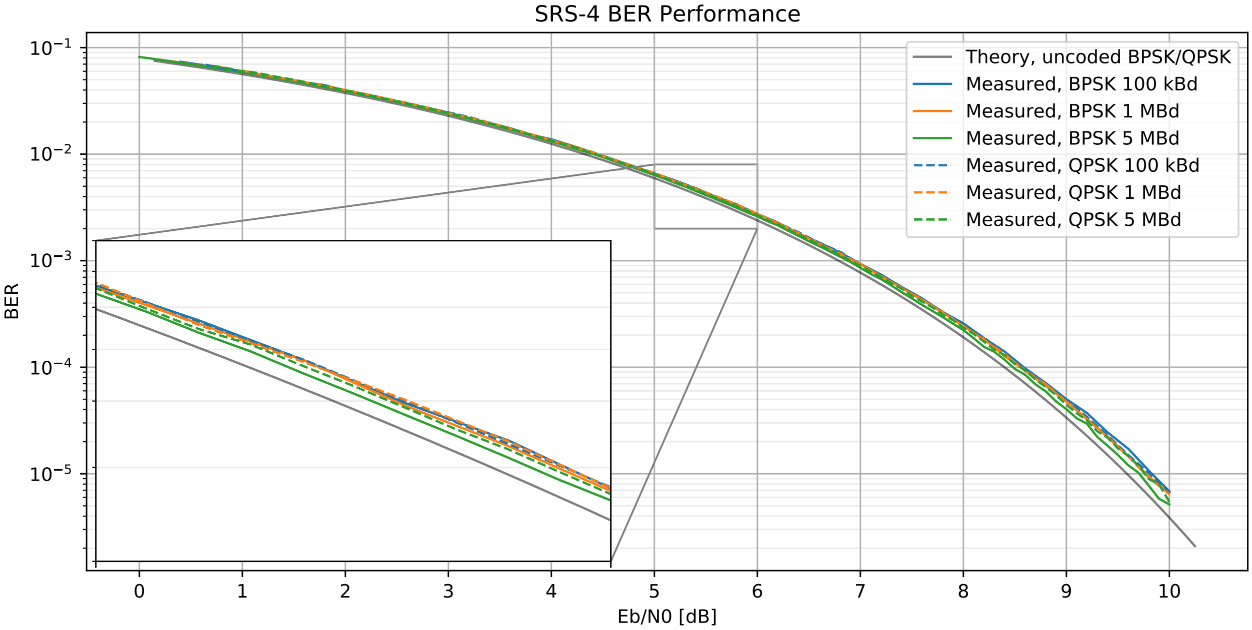


Figure 13: Receiver bit error rate for selected symbol rates

Table 8: Receiver characteristics

Parameter	Min	Typ	Max	Unit
Center frequency	2025	—	2110	MHz
Symbol rate R_{sym}	100	—	5000	kBd
Demodulator implementation loss[1]	—	<0.20	0.30	dB
Viterbi decoder implementation loss	—	0.3	—	dB
AFC frequency pull-in range[2]	—	—	15	kHz
Demodulator frequency pull-in range[2]	—	0.01 R_{sym}	—	
Receive sensitivity	See table 7			
Max receive power (<1 % PER)	–40	—	—	dBm
Noise figure (20 ℃)	—	2.05	2.50	dB
RSSI resolution	—	0.25	—	dB
Lock time (>3 dB E_b/N_0)	—	<1	—	s
Pulse shaping	Root-raised cosine, roll-off 0.2, 0.25 or 0.35			
Modulation	BPSK, QPSK			
Frequency error	See section 6.4			

[1] For E_b/N_0 between 1 dB and 10 dB

[2] Residual frequency tracking, refer to section 3.1

6.4 Transmitter

In figure 14 the typical output power spectrum is shown with α=0.2 RRC filter and 3 different output power levels. Measured using a PRBS sequence transmitted at 2245 MHz using 5 MBd QPSK.

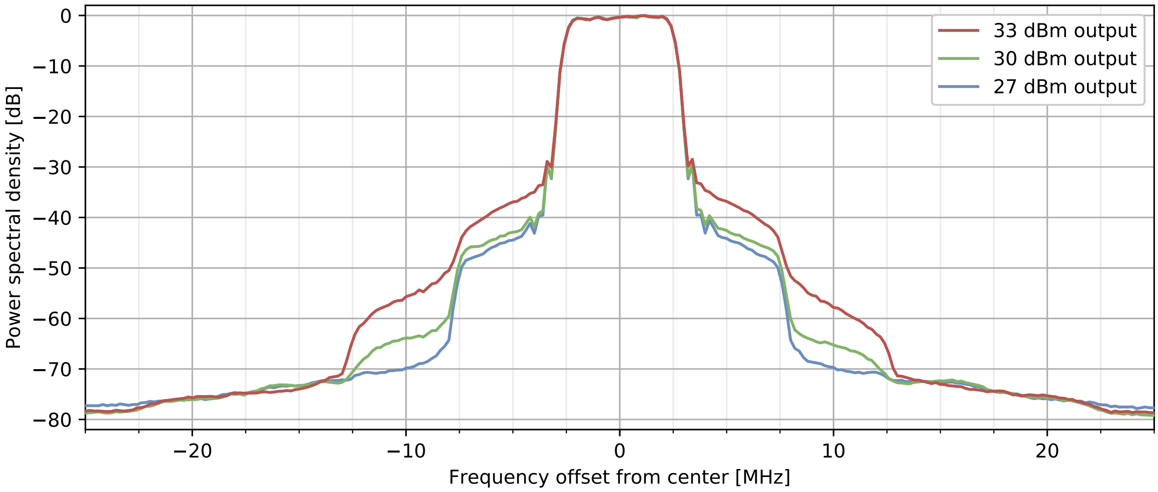


Figure 14: Typical transmitter power spectrum, 5 MBd QPSK, RRC α=0.2

Figure 15 shows the typical DC power consumption 3 different power settings over the transmit frequency range at 5 MBd QPSK. (TX at 20 ℃ and 6 V supply).

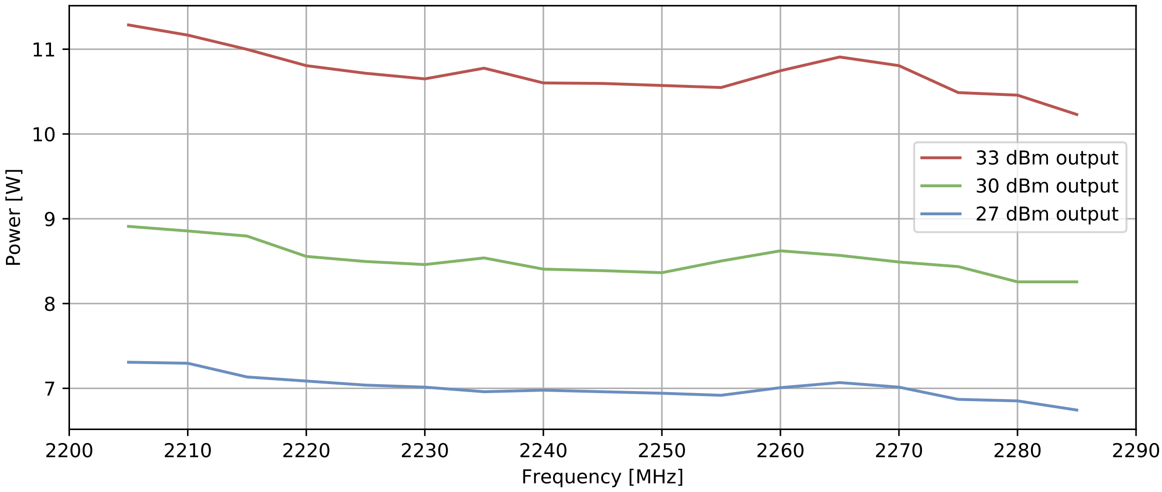


Figure 15: Typical DC power consumption (TX) as a function of configured TX frequency and output power.

Table 9 shows the transmitter key specification.

Table 9: Transmitter characteristics

Parameter	Min	Typ	Max	Unit
Center frequency	2200	—	2290	MHz
Symbol rate R_{sym}	100	—	5000	kBd
Output power	20	—	33	dBm
ALC loop step size	—	0.25	—	dB
Occupied bandwidth 99.0%[1]	—	1.07 R_{sym}	—	Hz
Occupied bandwidth 99.9%[1]	—	1.18 R_{sym}	—	Hz
SFDR	60	—	—	dBc
Initial frequency error (20 ℃)	—	—	0.5	µHz/Hz
Frequency error (over temperature)	—	1.0	2.5	µHz/Hz
Frequency error (aging per year)	—	—	1.0	µHz/Hz
Frequency error (20 kRad(Si) board level)	—	1.0	—	µHz/Hz
PA protection threshold (reflected power)	—	25	—	dBm
Pulse shaping	Root-raised cosine, roll-off 0.2, 0.25 or 0.35			
Modulation	BPSK, QPSK, 8PSK			
EVM (RMS, BPSK, 33 dBm)[1]	—	3.11	—	%
EVM (RMS, QPSK, 33 dBm)[1]	—	2.13	—	%
EVM (RMS, 8PSK, 33 dBm)[1]	—	2.06	—	%

[1] Measured with pulse shaping roll-off 0.20

6.5 Communication Interfaces

Table 10: Communication Interface Specification

Parameter	Min	Typ	Max	Unit
CAN-bus				
Bit rate	125	1000	1000	kbit/s
Termination resistor	—	120	—	Ω
CAN-L/H	–2	—	7	V
CAN-L/H recessive level	—	2.3	—	V
CAN-L output dominant level	0.5	—	1.3	V
CAN-H output dominant level	2.4	—	3.35	V
CAN dominant L/H difference	1.1	2.0	3.0	V
RS-422				
Bit rate[1]	9.6	1000	12 500	kbit/s
Receive termination resistor	—	100	—	Ω
RX differential level $\lvert RX+ - RX- \rvert$	0.15	—	6.0	V
TX differential output	2.0	3.0	3.5	V
Ethernet				
Bit rate	100	—	100	Mbit/s
ETH-TX Out diff. across 100 Ω termination	0.8	1.0	1.2	V
LVDS				
Receive termination resistor	—	100	—	Ω
RX input levels	0.0	—	2.4	V
RX input common mode	0.05	—	2.35	V
RX differential level $\lvert RX_n+ - RX_n- \rvert$	0.1	—	0.6	V
TX output levels	0.0	—	2.4	V
TX output common mode	1.125	1.200	1.375	V
TX differential level $\lvert TX_n+ - TX_n- \rvert$	247	340	454	mV
Debug-UART (TTL)				
TX output high	2.3	3.3	3.4	V
TX output low	0.0	—	0.5	V
RX input low	0.0	—	1.2	V
RX input High	1.9	—	4.0	V

[1] Supported values respect 100 MHz/N where N is an integer in [8;10417]

6.6 ESD Rating for Interfaces

Table 11: Communication Interface ESD Specification

Interface	ESD level [kV]	Standard
CAN-bus	12	IEC61000-4-2
RS-422	16	IEC61000-4-2
Ethernet	8	IEC61000-4-2
LVDS	12	MIL-STD-883C
EGSE	1	MIL-STD-883C

7 Qualification

The SRS-4 has been through a number of test campaigns to verify its performance over temperature, vibration and radiation. An overview of the testing performed on the SRS-4 is shown in table 12. As this list is non-exhaustive, please contact Satlab for further information if needed.

Table 12: Qualification Parameters

Parameter	Value
Thermal soak (RX)	−40 ℃ to 85 ℃
Thermal soak (RX+TX)	−40 ℃ to 70 ℃
Vibration	14.1 G_{rms}
TID	20 kRad(Si) board level

It should be noted that the levels which are listed in table 12 is a superset of the different tests the receiver has been through during various test campaigns.

7.1 Calibration and Acceptance Testing

All units are production calibrated at 20 ℃. Calibration includes adjusting default gain values for different output levels over the full TX band and adjusting the VCTCXO to a reference frequency source. The RF power sensors are calibrated against a reference sensor. As part of acceptance testing, each board is subject to a full RF performance test covering RX and TX over the temperature interval from −40 ℃ to 70 ℃.

7.2 Connector Pinout

P1, P2 and P3 are latching, high-reliability Harwin Gecko connectors with 1.25 mm pitch and gold-plated contacts. P1 (G125-MH11605L3P) is the main connector for power and communication interfaces. P3 (G125-MH11005L3P) is used for LVDS communication with the SRS-4. P2 (G125-MH10605L3P) is the EGSE connector used for the debugging shell and programming via SWD. Typically, the P2 connector is only used for test and firmware upgrade on ground and left unconnected in flight configuration. The debug UART can be connected to another system in the spacecraft if desired, as the board includes protection against reverse supply from these pins. It is strongly recommended to leave the SWD pins unconnected in flight configuration.

The S-band transceiver is supplied with termination resistors on the CAN-bus (120 Ω) and on the RS-422 receive pair (100 Ω). The unit has built-in magnetics on the Ethernet interface, and can be used in systems both with and without magnetics.

The coaxial RF connectors are full detent type SMP according to MIL-STD 348B.

The P1, P2 and P3 connector pinouts are shown here together with the pin numbering of the male connectors. “TX” pins denote output pins from the SRS-4 and “RX” pins are inputs to the SRS-4.

All pins in P1, P2 and P3 use TVS diodes for additional ESD suppression. The two RF connectors are DC grounded. However, proper care should still be observed while handling the device.

P1 — Main Connector

VIN	16	8	VIN
DNC	15	7	DNC
GND	14	6	GND
RS-422 RX-	13	5	RS-422 RX+
RS-422 TX-	12	4	RS-422 TX+
CAN-L	11	3	CAN-H
ETH RX-	10	2	ETH RX+
ETH TX-	9	1	ETH TX+

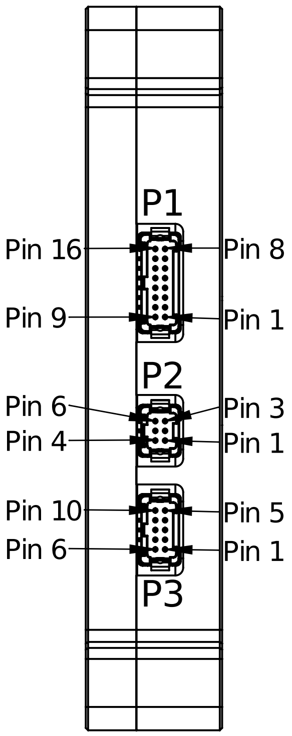
P2 — EGSE connector

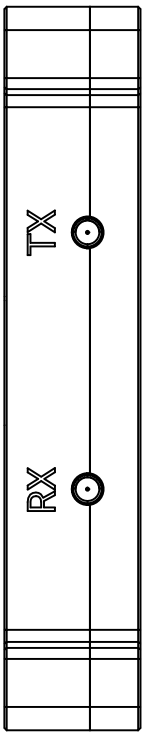
Debug TX	6	3	SWDCLK
V_{Target} (sense)	5	2	GND
Debug RX	4	1	SWDIO

P3 — LVDS connector

RX_2-	10	5	RX_2+
RX_1-	9	4	RX_1+
GND	8	3	GND
TX_2-	7	2	TX_2+
TX_1-	6	1	TX_1+

DNC = Do Not Connect





ATTENTION: Although all external interfaces on the SRS-4 are protected against ESD, proper precautions and grounding must still be observed when handling the device.

8 Mechanical Specifications

The PCB material is polyimide (Tg >250 ℃).

Table 13: Mechanical Specifications

Parameter	Min	Typ	Max	Unit
Mass	248	253	258	g
X-dimension	87.10	87.20	87.40	mm
Y-dimension	92.90	93.00	93.20	mm
Z-dimension	17.90	18.00	18.10	mm

8.1 Mechanical Interface

Figure 16 shows the transceiver from the top side (Z+) and first angle projections from the connector sides (X+ and X-) and thermal interface side(Y+). Note that the four mounting holes use the PC/104 layout and are not symmetrical. CAD models are available on the Satlab website.

8.2 Thermal Interface

On the bottom projection in figure 16, two M3 attachment points are provided for thermal interfacing. Internally the structure provides a good thermal path to these two points and it is advised to use these for thermal interfacing. The 4 corner holes provide a secondary thermal interface. The unit has a thermal capacity of approximately 230 J/K.

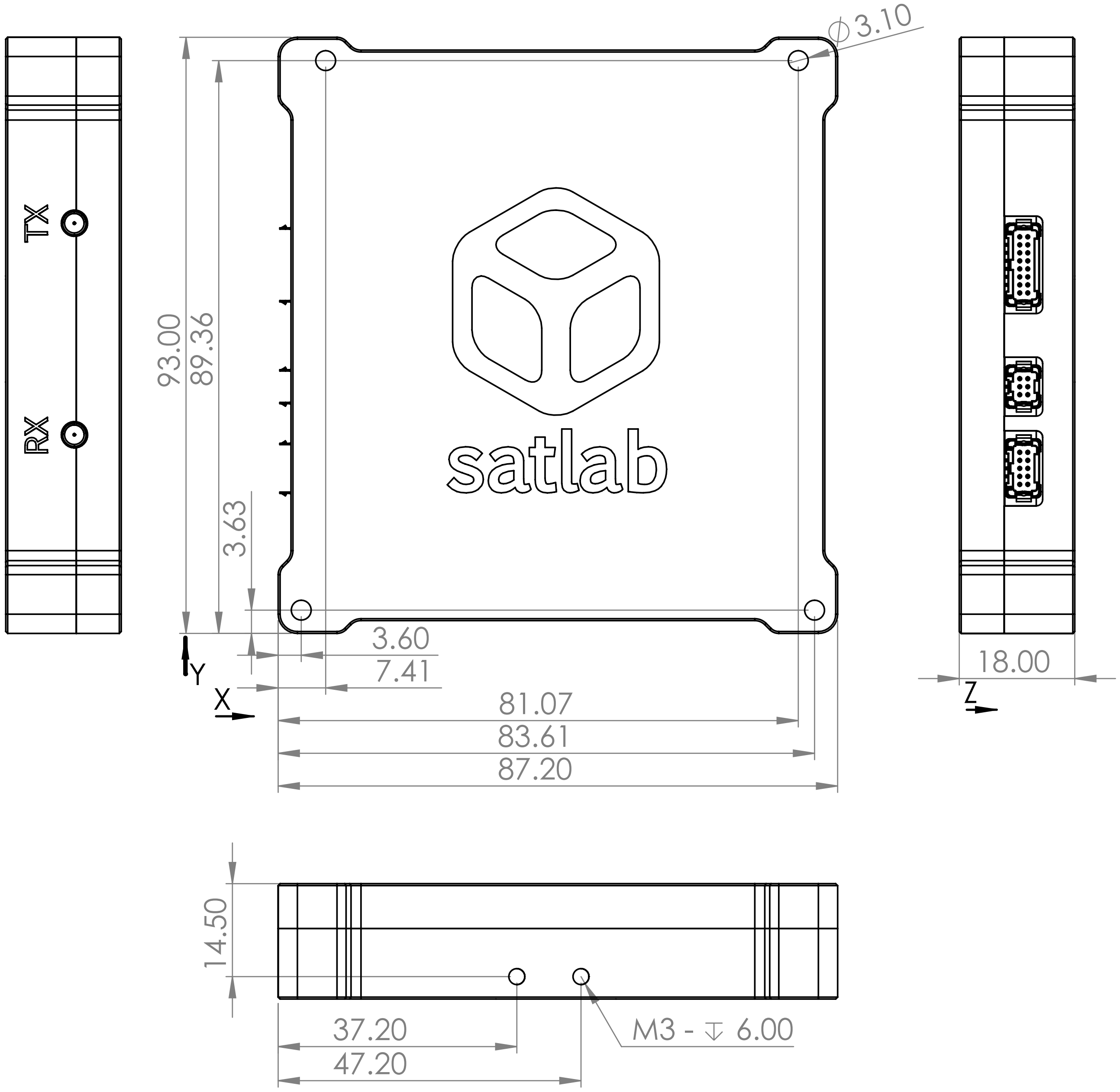


Figure 16: Board outline and side views showing the Z+, X+, X-, and Y+ faces. All dimensions in mm and ±0.1 mm tolerance.

9 Ordering Options

As default, the SRS-4 S-band transceiver is delivered with a PTFE flying leads cable for the main connector (P1) with all pins included and the connector potted. A USB EGSE adapter for SWD and serial interface is included for on-ground programming and testing on first order.

For contamination control and vibration protection, the PCB is coated with *Nusil CV-1152* conformal coating. If to be omitted, this can be selected below

The aluminum enclosure is normally delivered with *SurTec 650 ChromitAL TCP* chromate conversion coating (MIL DTL 5541, type II), but can optionally be delivered with *Henkel/Bonderite Alodine 1200S* coating instead (MIL DTL 5541, type I).

Satlab can deliver additional and/or customized cables upon request.

SRS-4 Order Options		
CAN-bus termination	Do not include 120 Ω resistor	☐
RS-422 termination	Do not include 100 Ω resistor	☐
Conformal Coating	Do not conformal coat PCB	☐
Conversion Coating	Alodine 1200S (additional charge)	☐

10 Customization

Customized versions of SRS-4 hardware and/or software tailored for specific customer requirements can be delivered at additional NRE cost. Please contact Satlab for more information about this option.

11 Revision History

The document ID of this datasheet is **SLDS-SRS4-1.2** and the revision number is **1.2**.

Revision	Issue date	Description
1.0	2021-02-23	First released version.
1.1	2023-01-06	Sec. 8: Updated mechanical drawing.
1.2	2024-08-16	Document frame header and compliant CCSDS frame sizes in section 4.

12 Disclaimer

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