Efficient USB communication under GNU/Linux for a wideband L-band (GNSS) SDR receiver: getting familiar with the MAX2771

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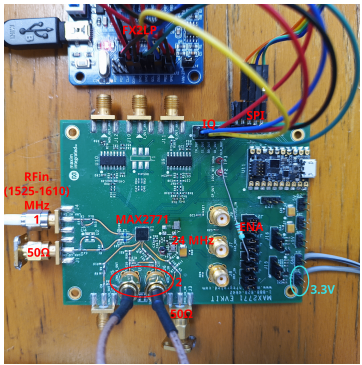
From



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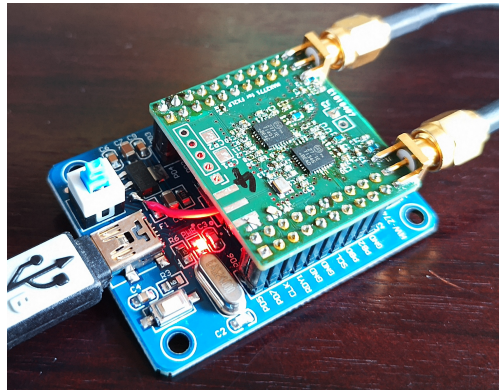
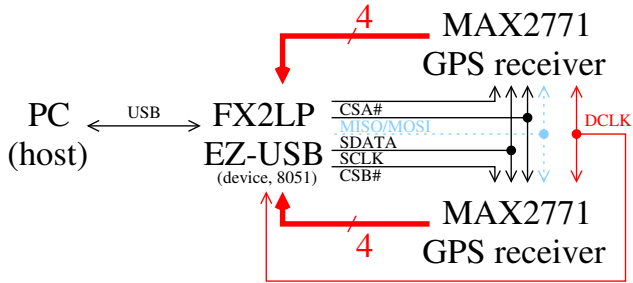


January 6, 2025

Getting familiar with the MAX2771 L-band receiver

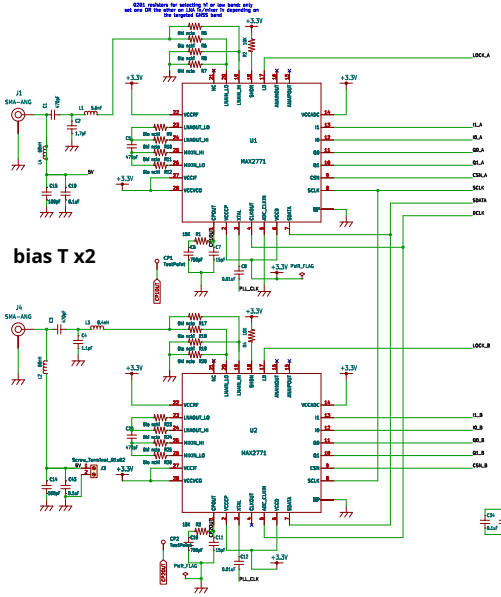
- FX2LP core based on a 8051 microcontroller ...
- ... for efficient conversion from parallel stream to USB and communication to PC (USB Bulk over endpoints EP2, EP4, EP6 or EP8)
- EP2 and EP6 buffer size: 1024 bytes, with half-full and full FIFO flags.
- EP2 = bulk out, EP6 = bulk in [1]
- MAX2771 L-band frontend converts radiofrequency signal to baseband IQ stream digitized on 2 or 3 bits (parallel in to USB, up to 44 MHz)
- MAX2771 registers are configured through a synchronous protocol



[1] page 176/460: https://www.keil.com/dd/docs/datashts/cypress/fx2_trm.pdf

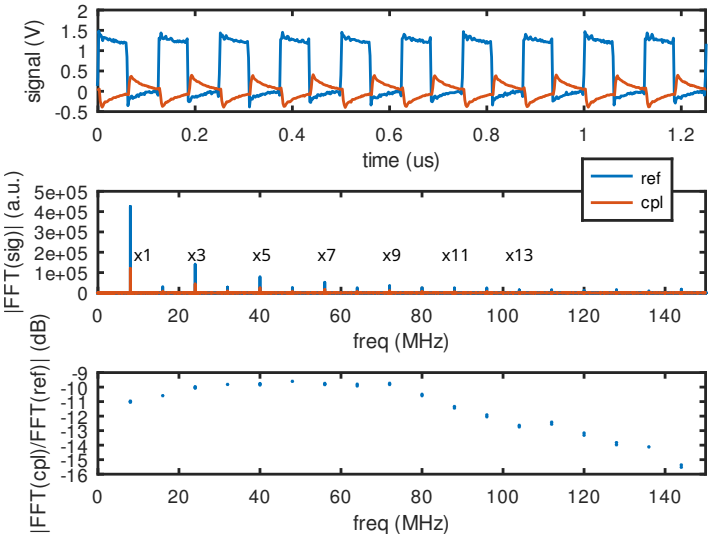
Getting familiar with the MAX2771 L-band receiver

- Maxim IC MAX2771 (now Analog Devices)
- "SPI"-like configuration (bitbanged since EZ-USB does not provide SPI)
- two chips for upper/lower L-band reception or CRPA [a] in one band ⇒ CS# selection of the chip
- few passive external components but propagating > 1 GHz signals ⇒ impedance matching



[a] Controlled Reception Pattern Antenna with two antennas separated by $\lambda/2$ for direction of arrival measurement

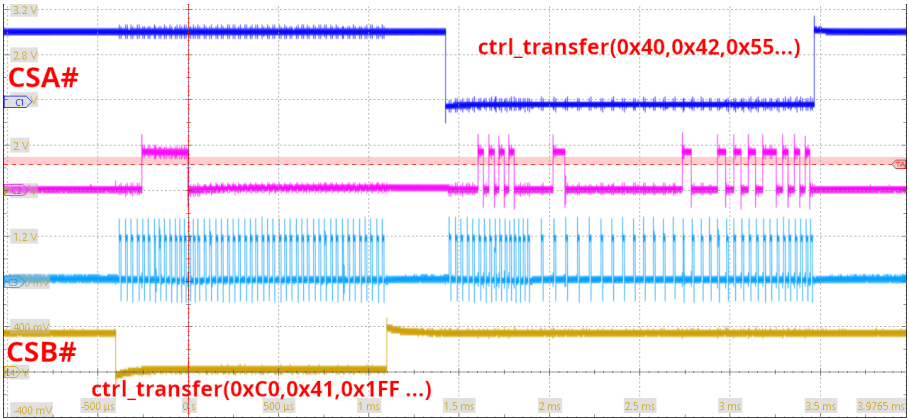
Why a dedicated PCB? (time-domain analysis)



- A square wave generates odd harmonics with the nth component amplitude decreasing as n
- Coupling between ajacent wires, here 21 cm-long wires a few millimeters apart, loaded on 50 Ω to ground
- Induced voltage might trigger a logic gate and result in an erroneous bit state

SPI implementation in the 8051 as user requests

- Reading and writing MAX2771 registers
- Synchronous protocol more or less compliant with SPI: clock generated by 8051 master, chip selected with CS#, but single two-way data signal
- PocketSDR: most significant byte of Vendor Request to select which chip is activated



- Test with a Python script for setting register values

PCB schematic

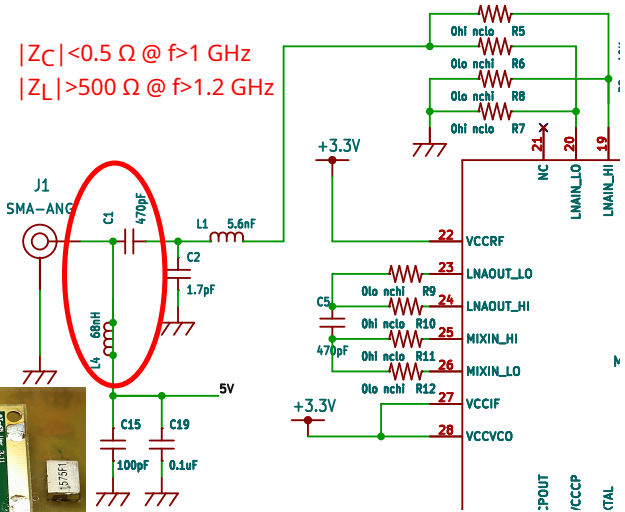
- Create a new symbol and footprint representing the FX2LP EZ-USB (symbol and footprint)
- Check DIL connector spacing (mechanical constraint on footprint)
- Check RF signal path depending on upper ($\in [1151 : 1214]$ MHz) or lower ($\in [1559 : 1610]$ MHz) GNSS L-bands [2], pre-amplifier and local oscillator/mixer
- Check IQ outputs from MAX2771 to FX2LP + clock feeding the FIFO input

[2] https://gssc.esa.int/navipedia/index.php/GNSS_signal

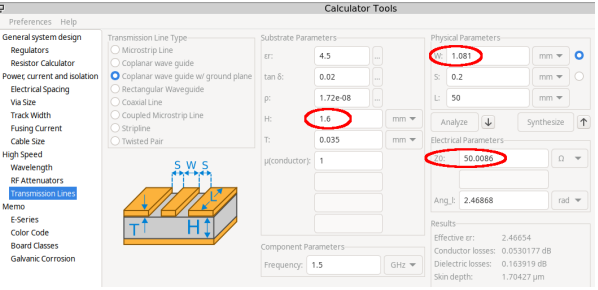
Bias T

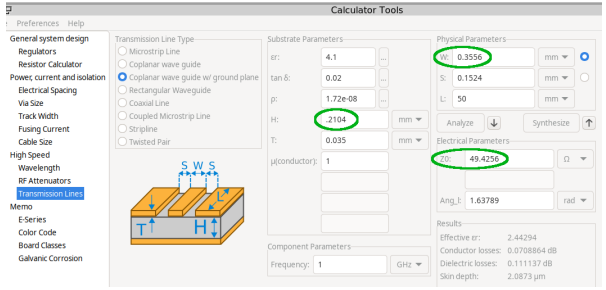
- GNSS antennas are usually active, *i.e* include an amplifier close to the receiving radiating element before propagating the L-band signal over a coaxial cable
- remote amplifier must be powered
- eliminate need for an additional wire by sharing one common coaxial cable to carry RF and DC signals
- separation using bias-T:
  - inductor in series with the DC signal (low resistance "wire") to block RF signal ($|Z_L| = L\omega$)
  - capacitor in series with the RF signal (low impedance path $|Z_C| = 1/(C\omega)$) while blocking the DC signal

$|Z_C|$<0.5 Ω @ f>1 GHz
$|Z_L|$>500 Ω @ f>1.2 GHz



Impedance matching





- KiCAD calculator to evaluate coplanar transmission line [3]
- geometry of the substrate and properties (thickness, relative permittivity, losses)
- geometry of the copper conducting line (thickness, width)

Make sure to match manufacturer characteristics (30 μm Cu, 1.6 mm FR4 ...)

[3] patterned on a dielectric printed circuit board substrate uniformly coated on the opposite side with a conducting ground plane and surrounded with a ground plane on both sides

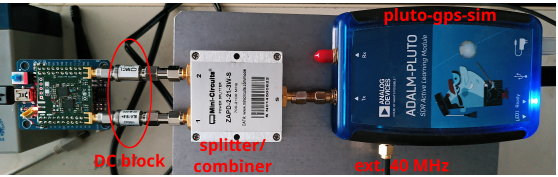
PCB routing

- Try to match 2-layer, 1.6 mm-thick FR4 PCB, to 50 Ω: what is the impact of line width at the MAX2771 pad spacing?
- Try to match 4-layer, 0.2-1.2-0.2 mm-thick FR4 PCB, to 50 Ω: what is the impact of line width at the MAX2771 pad spacing?
- separate as much as possible RF paths from digital paths
- check MAX2771 datasheet for decoupling capacitor specifications [4]
- Move component numbering (silkscreen) to avoid overlap with footprints
- BOM (supplier, reference v.s volume), manufacturing cost with volume and delay?

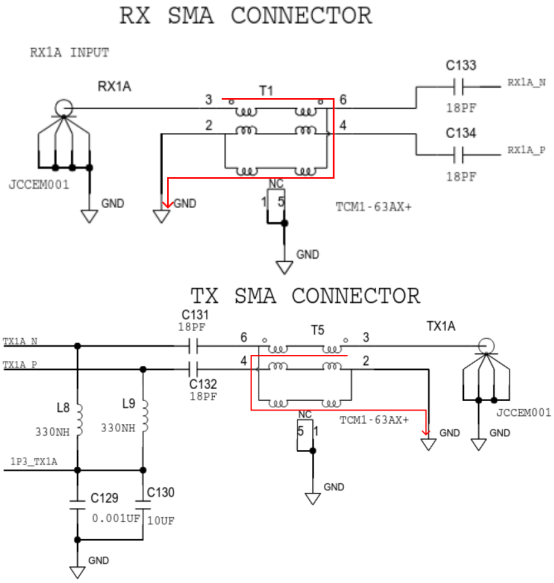
[4] See "General Layout Guidelines for RF and Mixed-Signal PCBs"

DC bias on antenna connector

⚠ DC-bias output to power active antenna ⇒ use DC-blocker (series capacitor[5] when feeding a RF signal in a wired configuration since diode to ground for ESD protection of RF port, or balun, will short-circuit DC bias.



T1 and T5 unbalanced center conductor are DC-coupled to ground through balun coils (PlutoSDR schematics[6]) ⟶

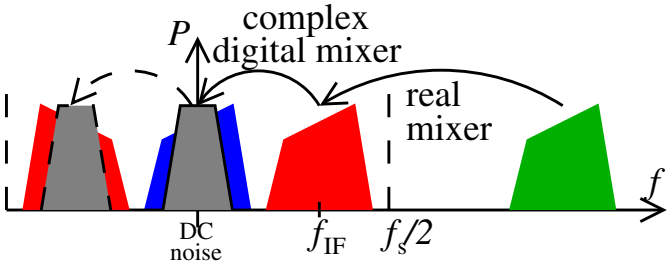


[5] e.g. Minicircuits BLK-18-S+ at https://www.minicircuits.com/WebStore/dashboard.html?model=BLK-18-S%2B

[6] https://wiki.analog.com/_media/university/tools/pluto/hacking/plutosdr_schematic_revb.pdf

Signal testing: 0-IF v.s super-heterodyne (IF) frequency layout

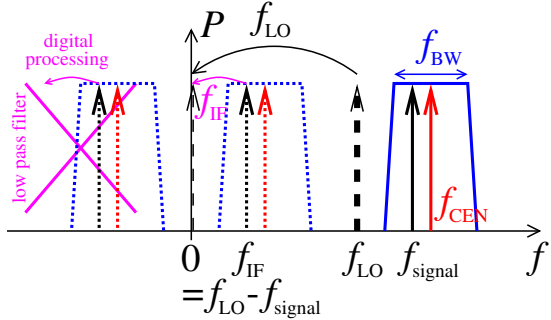
- Principle of super-heterodyne (IF) to get rid of DC-noise (e.g. power supplies)
- Check **compression point**, i.e. input power above which the output power is no longer proportional to input power = maximum allowed input power for proper operation



Understanding the various parameters of the frequency transposition

- local oscillator frequency:
  $LOBAND = \{0 \text{ or } 1\}$ for L1 (upper) or L2/L5 (lower)
  $F_{LO} = \frac{F_{XTAL}}{RDIV} \times \left(NDIV + \frac{FDIV}{2^{20}} \right)$
- bandpass filter bandwidth[a]:
  $f_{BW} = 000$ for 3.9 MHz center, 2.5 MHz bandwidth
  $f_{BW} = 010$ for 7.1 MHz center, 4.2 MHz bandwidth
  $f_{BW} = 001$ for 7.6 MHz center, 8.7 MHz bandwidth
  or
  lowpass filter bandwidth:
  $f_{BW} = 011$ for 11.7 MHz cutoff frequency
  $f_{BW} = 111$ for 8.2 MHz cutoff frequency
  $f_{BW} = 100$ for 18.0 MHz cutoff frequency
- bandpass filter center frequency:
  $f_{center} = \left(\frac{128 - f_{cen}}{2} \right) \times \begin{cases} 0.195 \text{ if } f_{BW} = 000 \\ 0.355 \text{ if } f_{BW} = 010 \\ 0.66 \text{ if } f_{BW} = 001 \end{cases}$
  with f_{cen} 7-bit long (0..127)
- **Challenge**: find the mistakes in MAX2771 datasheet!

[a] MAX2771 datasheet p. 8/50



- ADC sampling frequency (=basband bandwidth)

$$f_{ADC} = REFDIV(f_{XTAL}) \cdot \frac{LCOUNT}{4096 - MCOUNT + LCOUNT}$$

with [a]:
$REFDIV(\cdot) = \{\times 2, /4, /2, \times 1, \times 4\}$ for $0, 1, 2, 3, 4$
and $LCOUNT$, $MCOUNT$ 12-bit registers

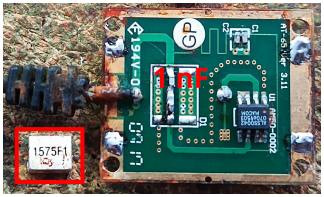
[a] MAX2771 datasheet p. 24/50

Data collection and characterization

- Broadcast various waveforms, record on the MAX2771 without and with IF, plot spectra
- software processing (Python/Octave) to remove the IF
  1. considering the known sampling frequency, create the "time" vector
  2. considering the known IF frequency, create the (complex) local oscillator vector
  3. multiply the recorded signal with the local oscillator to bring the IF to baseband
  4. low-pass filter to get rid of unwanted spectral components (where are they?)
  5. plot the time-domain and frequency-domain characteristics
  6. test on Iridium (requires a modified GNSS antenna without band-pass filter)

1. configure PocketSDR:
   ```
   sudo ./app/pocket_conf/pocket_conf conf/pocket_L1L1_4MHz.conf
   ```
2. check PocketSDR configuration:
   ```
   sudo ./app/pocket_conf/pocket_conf
   ```
3. collect samples, two binary files (IQ interleaved or I real only, 8 bit/sample) for the two channels:
   ```
   sudo ./app/pocket_dump/pocket_dump 1.bin 2.bin
   ```
4. for GNSS signals, decode:
   ```
   python3 ./python/pocket_acq.py -f 4 -fi 2 -sig L1CA -prn 1-32 -d 15000 2.bin
   python3 ./python/pocket_acq.py -f 4 -fi 2 -sig L5I  -prn 1-32 -d 15000 1.bin
   python3 ./python/pocket_acq.py -f 8 -fi 4 -sig E1B  -prn 1-32 -d 15000 2.bin
   python3 ./python/pocket_acq.py -f 8 -fi 4 -sig E5AI -prn 1-32 -d 15000 1.bin
   ```

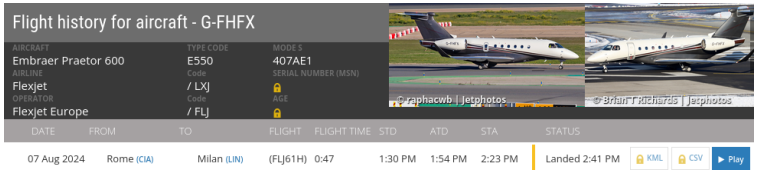
Sidenote exploration: Iridium reception

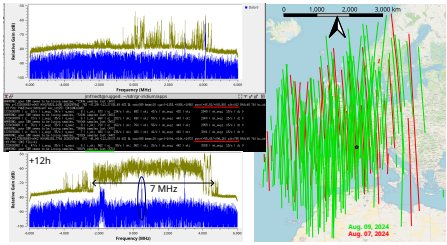


- LEO (780 km) satellite constellation broadcasting in the upper L-band,
  J. Bloom, *Eccentric Orbits: The Iridium Story – How a Single Man Saved the World's Largest Satellite Constellation From Fiery Destruction*, Grove Press (1998)
- signal well above thermal noise ...
- ... but (BPSK/QPSK) does not benefit from correlation to increase number of bits
- GPS L1 active patch antenna whose bandpass filter was replaced with a capacitor
- Fractional PLL of MAX2771: $RDIV \in [0:1023]$, $NDIV \leq 546$ ($f_{LO} = 1638 > 1622$ MHz) and $FDIV \in [36-32767]$,

  for $f_{LO} = \frac{f_{Xtal}}{RDIV} \times \left(NDIV + \frac{FDIV}{2^{20}}\right)$ with $f_{Xtal} = 24$ MHz

Settings: $f_{IF} = 6.5$ MHz, $f_s = 24$ MS/s ; MAX2771 spectrum around 1622 MHz $\longrightarrow$






```
2024-08-07T14:02:03 [hdr: 0339010100000001] Dir:DL Mode:2 REG:F-GXLI ACK:7 Label:_? (Demand mode) bID:F
2024-08-07T14:42:12                         Dir:DL Mode:2 REG:GFHFX  ACK:8 Label:_? (Demand mode) bID:Z
```

Result: ACARS message [7] from a plane between Rome and Milan (Italy), beyond the horizon from Besançon (France)

[7] https://thebaldgeek.github.io/Iridium.html