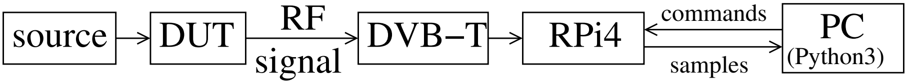
Outline

General context: embedded network analyzer architectured around the Raspberry Pi 4 and using an RTL-SDR DVB-T dongle as radiofrequency receiver.



Emitting a radiofrequency signal from the Raspberry Pi 4 clock

1. Investigating radiofrequency emission sources
2. Using the RPi4 internal PLL feeding a GPIO as radiofrequency source
3. Making sure the radiofrequency is controlled and understood by receiving with the DVB-T dongle

Objective: emitting an FM radio signal from the Raspberry Pi4 and listening to the resulting sound [1]

[1] sample video of one possible outcome: `https://www.youtube.com/watch?v=JIiKZ3UVAIw`

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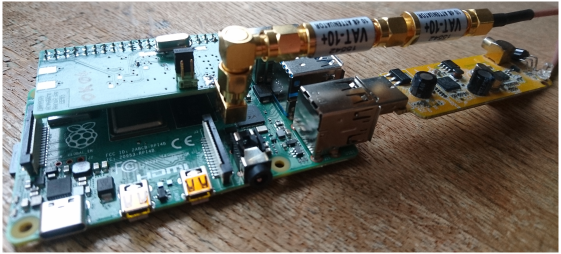

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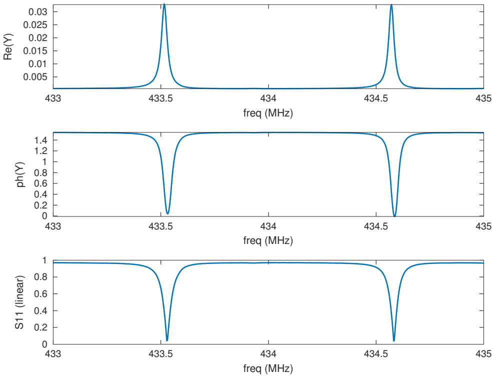
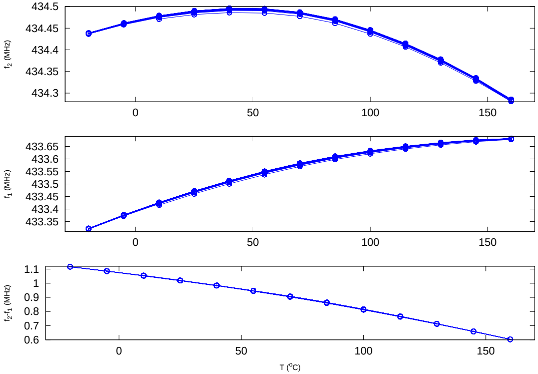
Device under test: dual resonator surface acoustic wave temperature sensor

Operating range; Industrial, Scientific and Medical (ISM) band, [433.05, 434.79] MHz





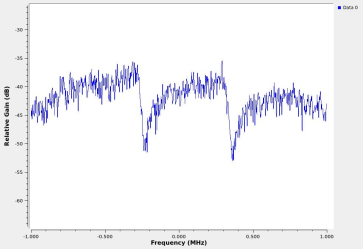
Radiofrequency sources

Characterize the transfer function of a passive Device Under Test

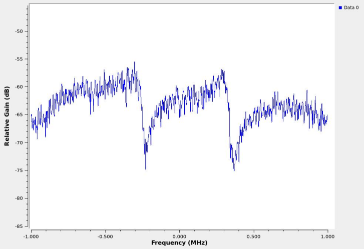
$\Rightarrow$ radiofrequency driving signal

- broadband = noise: Zener diode, but requires high (24 V) voltage for broadband signal + radiofrequency amplifiers
- pulse: must be short and sharp edges. Test with ADCMP fast comparators (e.g. ADCMP573 [2] for single supply operation): functional but requires an external trigger, e.g. RPi PWM

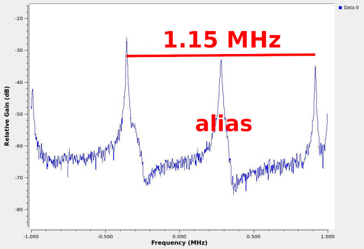
These solutions require additional, external hardware and are prone to artefacts ...



Broadband noise source



40 ns pulse every 160 ns



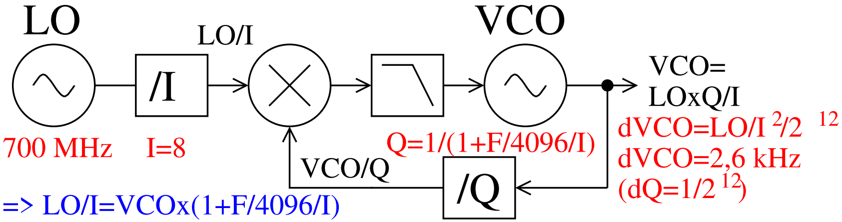
40 ns pulse every 800 ns

... but the RPi GPIO can be driven from a radiofrequency clock source ! See the PiFM project [3].

[2] https://www.analog.com/en/products/adcmp573.html

[3] http://www.icrobotics.co.uk/wiki/index.php/Turning_the_Raspberry_Pi_Into_an_FM_Transmitter

Fractional PLL



- Raspberry Pi single board computers provide a reference clock LO (700 MHz for RPi4, 500 MHz for others)
- LO feeds a fractional Phase Locked Loop (PLL [4]) with a pre-scaler of $I \in \mathbb{N}$
- the PLL Voltage Controlled Oscillator (VCO) is divided by $Q \in \mathbb{Q}$
- the phase comparator compares LO/I with VCO/Q: $VCO = LO \times Q/I = LO/I \times \left(1+\frac{F}{I\times 4096}\right)^{-1}$ (see [5])$= LO/\left(I + F/4096\right)$
- output frequency $<$ 125 MHz (GPIO limitation [6]) $\Rightarrow$ use overtone (5th overtone of FM band to reach 434 MHz ISM band)
- output frequency resolution: considering that $\boldsymbol{VCO = LO \times Q/I}$ and that the resolution $\boldsymbol{dF}$ on $\boldsymbol{F \in [0:4095]}$ is **1**, **what is the frequency resolution at 434 MHz? Is it enough for our application? How does it compare with a DDS?**

[4] https://elinux.org/The_Undocumented_Pi#Clocks

[5] https://datasheets.raspberrypi.org/bcm2711/bcm2711-peripherals.pdf p.81 "5.4 General Purpose GPIO Clock"

Fractional PLL

Many implementations derived from the original PiFM demonstration [7]:

- https://github.com/ChristopheJacquet/PiFmRds is easiest [8] to understand
- GPIO4 clock sourced from a fractional PLL is described pp.104–105 of https://www.raspberrypi.org/documentation/hardware/raspberrypi/bcm2711/rpi_DATA_2711_1p0.pdf
- a much more general (and complex [9]) implementation is available at github.com/F5OEO/rpitx relying on github.com/F5OEO/librpitx
- interfacing the latter with GNU Radio {I,Q} stream is explained at https://github.com/ha7ilm/rpitx-app-note
- http://abyz.me.uk/rpi/pigpio/pigs.html explains that "Access to clock 1 is protected by a password as its use will likely crash the Pi. The password is given by or'ing 0x5A000000 with the GPIO number."

Our application only requires a single continuous-wave (CW) tone for a Frequency Swept CW analyzer (FSCW)

[7] O. Mattos & O. Weigl, https://github.com/rm-hull/pifm described at http://www.icrobotics.co.uk/wiki/index.php/Turning_the_Raspberry_Pi_Into_an_FM_Transmitter

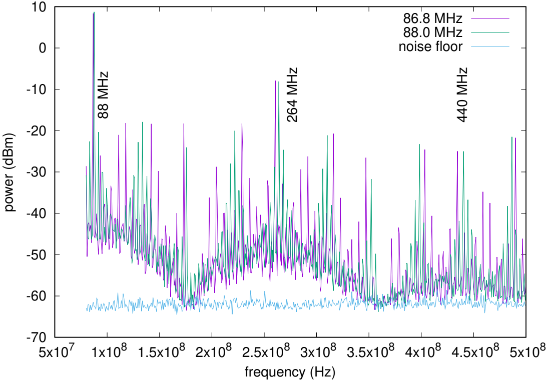
[8] github.com/ChristopheJacquet/PiFmRds/blob/master/src/pi_fm_rds.c#L534

[9] E. Courjaud *Rpitx: Raspberry Pi SDR transmitter for the masses*, SDRA (2017) at https://www.youtube.com/watch?v=Jku4i8t_nPc

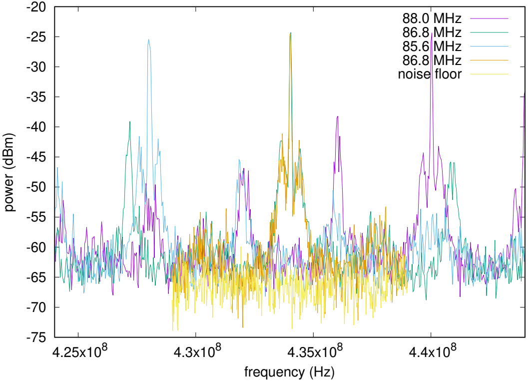
Overtone

The RPi GPIO has been observed to generate a strong signal up to 250 MHz.

We aim for the 434 MHz band $\Rightarrow$ use overtones



Broadband spectrum



Zoom on the (FM modulated) overtone signal

Square wave output $\Rightarrow$ overtone N scales as $1/N$. Emit at $434/5 = 86.8$ MHz

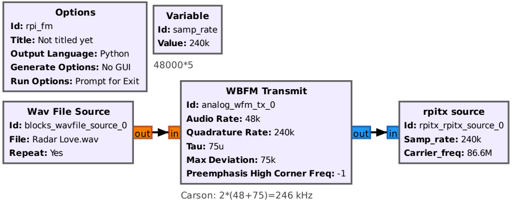
AM emission from the RPi4

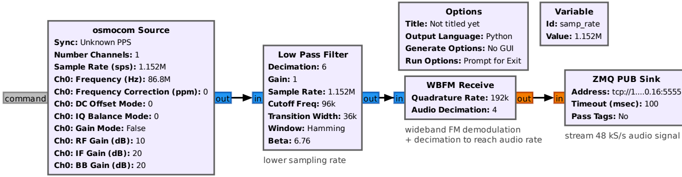
Assessing the spectrum of the signal broadcast by `gr-rpitx` modulated as AM:

- AM modulation at ω_m with modulation index $m \leq 1$: $s(t) = (1 + m\cos(\omega_m t)) \cdot \exp(j\omega_c t)$ on carrier ω_c
- since $\cos(\omega_m t) \propto (\exp(j\omega_m t) + \exp(-j\omega_m t))$ the spectrum must consist in three spectral components at ω_c and $\omega_c \pm \omega_m$
- emit an AM modulated signal from `gr-rpitx` (signal source $\rightarrow$ mag/phase to complex with constant phase $\rightarrow$ `rpitx sink`) and record using the RTL-SDR dongle
- 0MQ stream the RTL-SDR output to the host PC and display the spectrum to check the spectrum consistency on the fundamental carrier (ω_c) and fifth overtone ($5\omega_c$)

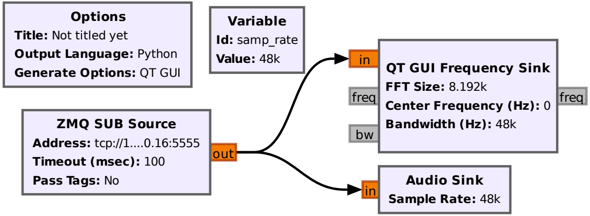
FM emission/reception from the RPi4 (sequel to week 2)

On the **embedded board**: **two** CLI flowchart for on the one hand emitting FM broadcast, and on the other hand acquisition, demodulation and streaming (lowering the sampling rate and hence the communication bandwidth)





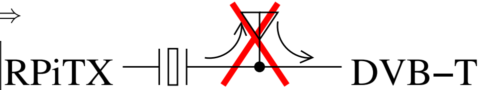
On the **host PC**: GUI for displaying the spectrum and playing audio on the sound card



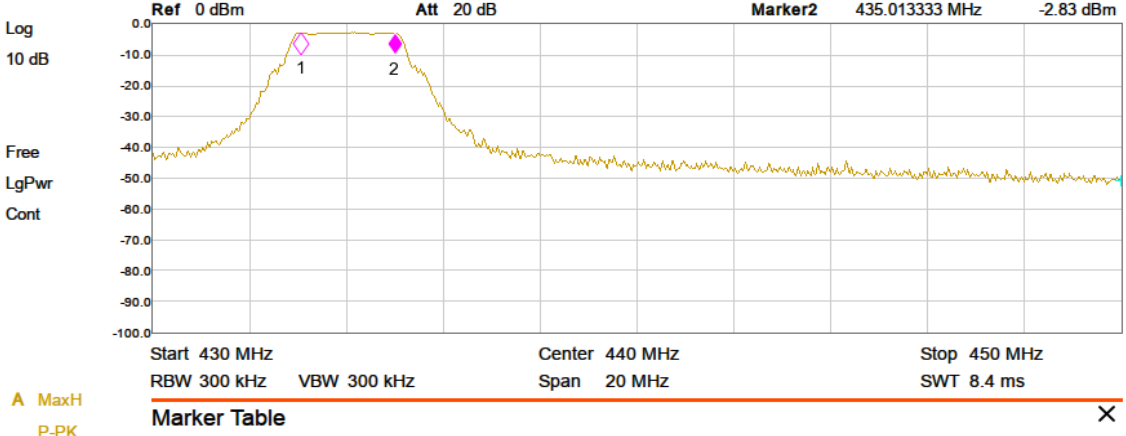
SAW resonator characterization

The SAW device is connected in parallel to the antenna ⇒

make sure to disconnect the antenna (MCX connector) when measuring the SAW device to avoid radiating the probe signal and collecting environmental noise !

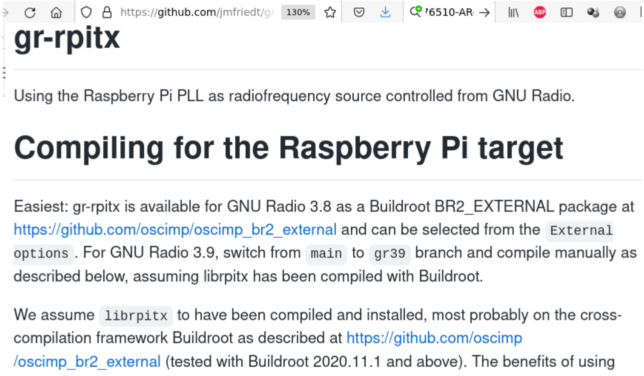


Example of radiated spectrum when seeping around the 434 MHz ISM band:



gr-rpitx general purpose sink

- Wrapping `librpitx` as a general purpose GNU Radio Sink
- Although targeted to the Raspberry Pi 4, must also be compiled on the host to be accessible from GNU Radio Companion
- datarate: 10000-250000 Hz so that fourth overtone will span 1 MHz
- compiles and tested on 3.8 and 3.9, compiles with 3.10:
  1. `git clone https://github.com/jmfriedt/gr-rpitx/`
  2. `cd gr-rpitx`
  3. `mkdir build && cd build`
  4. `cmake ../ && make`
  5. `sudo make install`
  6. reload processing block list in GNU Radio Companion



https://github.com/jmfriedt/gr

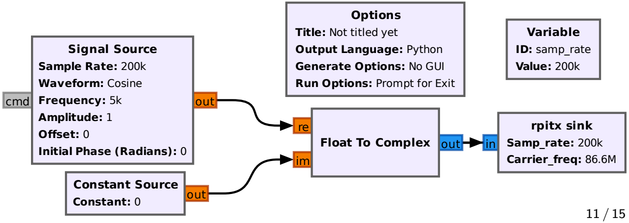
gr-rpitx

Using the Raspberry Pi PLL as radiofrequency source controlled from GNU Radio.

Compiling for the Raspberry Pi target

Easiest: gr-rpitx is available for GNU Radio 3.8 as a Buildroot BR2_EXTERNAL package at https://github.com/oscimp/oscimp_br2_external and can be selected from the `External options`. For GNU Radio 3.9, switch from `main` to `gr39` branch and compile manually as described below, assuming librpitx has been compiled with Buildroot.

We assume `librpitx` to have been compiled and installed, most probably on the cross-compilation framework Buildroot as described at https://github.com/oscimp/oscimp_br2_external (tested with Buildroot 2020.11.1 and above). The benefits of using



Consistency issue between GNU Radio version (host v.s target)

Consistency issues between flowgraph generated on PC and run on the Raspberry Pi:

- Debian/stretch (oldoldstable): 3.7.10.1 ; buster (oldstable): 3.7.13.4 ; **bullseye (stable): 3.8.2.0** ; bookworm (testing) and sid (unstable): 3.10.1.1
- Ubuntu/bionic (18.04LTS): 3.7.11 ; focal (20.04LTS): 3.8.1.0 ; **hirsute (21.04) and impish (21.10): 3.8.2.0** ; jammy: 3.9.4.0
- For GNU Radio 3.8 as provided by the official Buildroot release:
  - PyBOMBS at `https://github.com/gnuradio/pybombs` produces with the `gnuradio-default` recipe generates a local copy of GNU Radio 3.8 (`source setup_env.sh` after completion [10] to use this version)
- For GNU Radio 3.9 as provided by most current binary distributions:
  - use the `gnuradio39` recipe: `pybombs prefix init pybombs-3.9 -R gnuradio39`
- after completing GNU Radio PyBOMBS compilation:
  - in the PyBOMBS directory: `source setup_env.sh`
  - `pybombs install gr-osmosdr` [11]
  - a temporary Buildroot is available from the BR2_EXTERNAL at `https://github.com/oscimp/oscimp_br2_external/` (see `package/gnuradio39` for the recipe)
  - GNU Radio 3.9 will never be part of Buildroot, shifting straight to GNU Radio 3.10

[10] watch for conflicting libuhd function prototypes: `https://github.com/gnuradio/pybombs/issues/612`

[11] in case of error with `gr-fcdproplus`, remove this entry from `$HOME/.pybombs/recipes/gr-recipes/gr-osmosdr.lwr` since it is not needed.

Reading a 0MQ stream from Python

Initialize the ZeroMQ socket, receive a byte array and convert to the appropriate format:

```
import numpy as np
import zmq
import array

Nt=1024
context=zmq.Context()
sock1=context.socket(zmq.SUB)
sock1.connect("tcp://127.0.0.1:5556"); # replace with RPi4 IP and port
sock1.setsockopt(zmq.SUBSCRIBE, b"")
vector1=[]
while (len(vector1)<Nt):
  raw_recv=sock1.recv()
#  recv=array.array('f',raw_recv) # float
  recv=array.array('l',raw_recv) # integer
  print(recv)
```

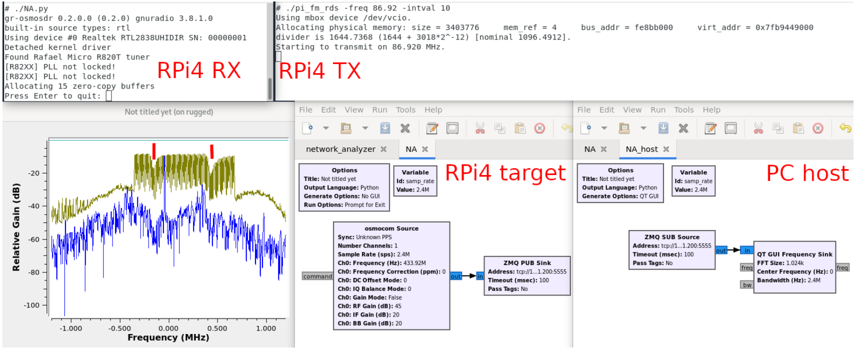
Conclusion

PiFM is provided as Buildroot external package (BR2_EXTERNAL) at `https://github.com/oscimp/oscimp_br2_external/`
`rpitx` has been converted to a library compatible with a GNU Radio sink: `https://github.com/jmfriedt/gr-rpitx` [12]

1. Compile PiFM and its dependencies for the RPi4
2. Generate signals and check that their spectra are consistent with expectations (tone, chirp, FM)
3. Listen to the generated signals
4. Control the emitted signal, in addition to the received signal, from the Python server

Do not add a wire to GPIO4: the pin will radiate a low enough power to be detected by the DVB-T receiver without bothering neighbours

Conclusion: characterize the SAW resonator transfer function, either using a noise generator or a frequency sweep, either using RPiTX (standalone program) or `gr-rpitx`



[12] main branch for GNU Radio 3.8, gr39 branch for GNU Radio 3.9

Executing a processing flowchart when inserting the RTL-SDR dongle

1. flowchart runs to completion (*not* prompt)
2. remove `dvb-usb-rtl28xxu.ko` and `dvb_usb_v2.ko`
3. add in `/etc/udev/rules.d/rtl-sdr.rules`:

```
SUBSYSTEMS=="usb", ATTRS{idVendor}=="0bda", ATTRS{idProduct}=="2838", \
ENV{ID_SOFTWARE_RADIO}="1", MODE="0660", GROUP="plugdev", \
RUN+="/root/rpi_fm_auto.py"
```

with `/root/rpi_fm_auto.py` the GNU Radio flowchart to be executed.

Take care that GNU Radio Companion flowcharts are **not** backward-compatible.