
gr-rpitx: GNU Radio compatible general purpose SDR emitter using the Raspberry Pi(4) internal phase locked loop

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Abstract

`gr-rpitx` provides the support for the full GNU Radio signal processing framework when using the Raspberry Pi internal radiofrequency Phase Locked Loop (PLL) controlled by the Pulse Width Modulation (PWM) Direct Memory Access (DMA) for tuning the output frequency. Furthermore, the `librpitx` added amplitude tuning. Thanks to frequency and amplitude tuning capability, full IQ datastreams can be processed, here within the framework of a GNU Radio Sink block. We promote `gr-rpitx`, despite the multiple spurious spectral components preventing the emission over the air, for educational purposes including emitting and recording analog and digital communication mode or probing the transfer function of a device under test in a scalar vector network analyzer configuration.

1. Introduction

Emitting radiofrequency signals from one of the Raspberry Pi (RPI) General Purpose Input Output (GPIO) pins has been known since 2012 with the release of PiFm as described at http://www.icrobotics.co.uk/wiki/index.php/Turning_the_Raspberry_Pi_Into_an_FM_Transmitter. Incremental improvements have included adding amplitude A tuning to frequency f tuning, as described at (É. Courjaud, 2017), leading to full IQ stream controlling the radiofrequency output since $I = \text{Re}(I + jQ) = A \cos(\varphi)$ and $Q = \text{Im}(I + jQ) = A \sin(\varphi)$ with the phase being the integral of the frequency $\varphi = \int f \cdot dt$. Packaging such functionalities in a library with a blocking call to filling the DMA buffer makes the transition to GNU Radio trivial, and yet opens the doors to streaming any signal generated by a GNU Radio Companion flowchart.

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The educational benefits of this radiofrequency signal emission approach, when coupled with the RTL-SDR Digital Video Broadcast-Terrestrial (DVB-T) dongles used as general purpose Software Defined Radio (SDR) receivers, is significant as long as over-the-air emission is avoided and only short range communication is allowed by the poor impedance matching of the pin length with the radiofrequency wavelength of the emitted signal.

2. Basics of the sink block

The GNU Radio 3.8 Out Of Tree (OOT) module tree structure is generated with `gr_modtool` with two arguments shared with the constructor, the sampling rate defining the rate which DMA transfers will occur between the GNU Radio buffer and the hardware peripheral, and the carrier frequency. The constructor allocates the DMA buffer, defines the nature of the exchanged data and the carrier frequency. The main work function is reduced to a blocking call to filling the buffer with the data transferred from the previous block. The scheduler is informed of the timing capability of this sink block, thanks to the blocking call to the DMA filling function, with the `throttle` flag in the GNU Radio Companion YAML description of the block.

The Constructor initializes the DMA and datastream structure following the example provided by `sendiq` at <https://github.com/F50EO/rpitx/blob/master/src/sendiq.cpp>

```
1 #define IQSize 4096
2
3 namespace gr {
4     namespace rpitx {
5
6         rpitx_source_impl::rpitx_source_impl(float
7             samp_rate, float carrier_freq):
8             gr::sync_block("rpitx_source",
9                 gr::io_signature::make(1, 1, sizeof(gr_complex)),
10                gr::io_signature::make(0, 0, 0))
11             {iqtest=new iqdmasync(carrier_freq,samp_rate,
12                 14,IQSize*4,MODE_IQ);
13                 iqtest->SetPLLMasterLoop(3,4,0);
14             }
15
16 rpitx_source_impl::~rpitx_source_impl()
```

```

17 {iqtest->stop();
18   delete(iqtest);
19 }

```

which also includes the destructor definition to release resources. The work function is fed `noutput_items` to be transferred to the buffer as follows, using the blocking `iqtest->SetIQSamples` to regulate the datarate when filling the DMA buffer:

```

20 int rpitx_source_impl::work(int noutput_items,
21   gr_vector_const_void_star &input_items,
22   gr_vector_void_star &output_items)
23 {std::complex<float> CIQBuffer[IQSize];
24   int H=1; // Harmonic
25   int nbread=0,xferlen;
26   const gr_complex *in=\
27     (const gr_complex*)input_items[0];
28
29   while (nbread<noutput_items)
30     {if (nbread+IQSize<noutput_items)
31       xferlen=IQSize;
32       else xferlen=noutput_items-nbread;
33       iqtest->SetIQSamples((std::\
34         complex<float>*) &in[nbread],xferlen,H);
35       nbread+=xferlen;
36     }
37   return noutput_items;
38 }
39 } /* namespace rpitx */
40 } /* namespace gr */

```

This datarate regulation must be advertised to GNU Radio Companion to avoid the missing Throttle block warning: the YAML description file includes

```

id: rpitx_rpitx_source
label: rpitx source
category: '[Rpitx]'
flags: throttle
...

```

to let GNU Radio Companion know that this flow graph will regulate the datastream (Schroer, 2021).

3. Practical demonstration (1): analog FM broadcast

FM broadcasting is demonstrated at <https://www.youtube.com/watch?v=JIiKZ3UVAIw> in which the signal emitted by `gr-rpitx` (Fig. 1) is collected by a DVB-T dongle connected to the RPi4 and streamed through a 0MQ socket to the laptop PC used as a sound card to record the demodulated signal (Fig. 2).

In all these examples, “No GUI” flowcharts are assembled on the host PC generating the Python3 script which is transferred to the Raspberry Pi4 for execution on the target.

The maximum sampling rate we achieved on analog broad-

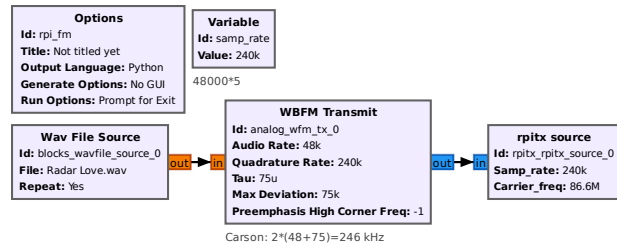


Figure 1. FM broadcast flowchart demonstrating the efficient integration of `gr-rpitx` with GNU Radio general purpose processing blocks.



Figure 2. Experimental setup for assessing FM broadcasting from `gr-rpitx` and reception using a DVB-T receiver used as general purpose Software Defined Radio receiver connected to the Raspberry Pi4 running GNU Radio. The demodulated output audio stream is transferred to the host PC acting as a sound card for playing the audio signal using a 0MQ publish-subscribe link.

cast wideband FM transmission with no audible loss of quality or pitch is $48000 \times 9 = 432$ kHz while $48000 \times 10 = 480$ kHz led to an obvious slow-down of the output stream. On the other hand, a continuous wave (CW) signal source streaming a 70 kHz sine wave at a rate of 3.42 MS/s at 87 MHz brought to baseband by Xlating FIR demonstrated a continuous transmission and no spreading by discontinuous acquisition, while no at all was transmitted at 3.43 MS/s.

4. Practical demonstration (2): digital (DRM) broadcast

As radiofrequency communication is shifting from analog to the more efficient spectrum occupation digital modulation schemes, we extend the analog FM broadcast demonstration to a digital mode. While Digital Audio Broadcast (DAB) requires excessive bandwidth to be compatible

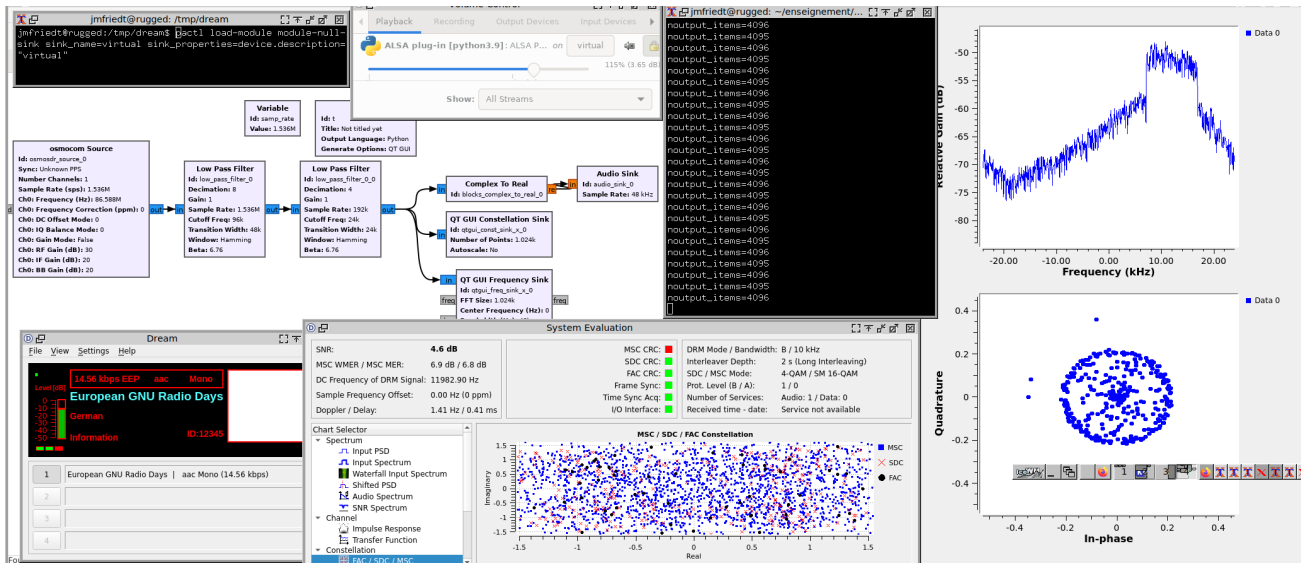


Figure 3. DRM (Digital Radio Mondiale) emission from `gr-rpitx` fed by `gr-drm` and reception using DREAM running on the host PC. Notice how a Pulse Audio virtual sink is used to feed DREAM with the output of GNU Radio. Right is the spectrum (magnitude) and raw constellation observed with GNU Radio, center-bottom is the constellation provided by DREAM, bottom left demonstrates how the encoding and station identified are decoded, top left is the host PC reception scheme and top left is the Pulse Audio virtual sink while top-middle is the Raspberry Pi 4 terminal emitting DRM using `gr-rpitx`. The signal to noise ratio is below 5 dB, preventing the constellation from locking on the audio signal.

with `gr-rpitx`, Digital Radio Mondiale (DRM (ETSI, 2009)) provides an acceptable tradeoff between simplicity, availability and bandwidth. Running `gr-drm` as found at <https://github.com/kit-cel/gr-drm> is as simple as replacing the UHD sink of the sample example – already clocking the datastream at an acceptable 250 kHz – to the `gr-rpitx` sink (Fig. 4). However, achieving such a result on the Raspberry Pi(4) requires that the `gr-drm` and its dependencies are installed on the embedded board. Buildroot is an efficient and light framework for generating dedicated images to embedded targets: `gr-drm` is packaged for Buildroot in an extension available at https://github.com/oscimp/oscimp_br2_external and more specifically in its package with the dependencies `faac`. A complete image running GNU Radio on the Raspberry Pi4 is generated by using the configuration file provided at https://github.com/oscimp/oscimp_br2_external/blob/master/configs/raspberrypi4_64_gnuradio_defconfig.

As demonstrated in Fig. 3, the simplest and sparsest modulation schemes are well decoded. Indeed, the Fast Acces Channel (encoded as 4-QAM, https://www.drm-sender.de/?page=drm&lang=en#2_2) and the Service Description Channel (SDR, also 4-QAM in this setting) exhibit good enough signal to noise ratio for analysis, while the Main Service Channel here encoded

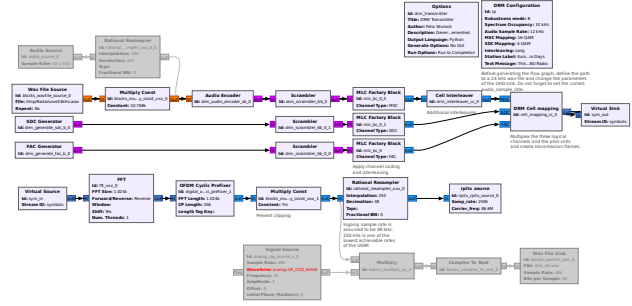


Figure 4. Demonstration DRM flowchart as provided by `gr-drm`, but replacing the USRP output with `gr-rpitx`. Three datastreams – FAC, SDC and MSC – are summed and transmitted as the DRM signal, but only the first two will be demodulated due to insufficient signal to noise ratio of the Raspberry Pi4 used as radiofrequency transmitter.

as 16-QAM and carrying the sound information cannot be decoded due to the insufficient signal to noise ratio to identify the symbols of this dense constellation. Indeed with only 3-bit (7-levels) of amplitude tuning, `gr-rpitx` lacks the flexibility to address more advanced modulation schemes. This reception scheme emphasizes how GNU Radio can benefit from external decoding software: here DREAM (version 2.2.1 compiled using the instructions at <https://gist.github.com/onetransistor/>

4cbe3a8ab5d47da22cde since all newer versions failed to run on a Debian/sid distribution as of this writing in Summer 2021) expects a sound card input while GNU Radio streams a sound card output. The link between the two is achieved with a virtual audio cable created with Pulse Audio using `pactl load-module module-null-sink sink_name=virtual sink_properties=device.description="virtual"`. The Pulse Audio control software `pavucontrol` then allows connecting the audio output of GNU Radio to this virtual sink and feeding DREAM with this input stream.

5. Dynamically tuning the carrier frequency: callback function

GNU Radio users expect to be able to define the carrier frequency of a sink block and dynamically tune this parameter e.g. through a slider or by sending the new value through a client-server link. Dynamically updating the parameter requires implementing a callback function: in this case the `set_freq()` callback function will de-activate the DMA stream, and re-activate the buffer with the new carrier frequency. Because the sampling rate must be provided as argument, this value is saved as a private variable shared by all functions of the class

```
1 samp_rate_=samp_rate;
```

but furthermore, the work function must be prevented from writing in the DMA buffer as reconfiguration is ongoing. A mutex (Mutually Exclusive) access is defined to make sure that whenever the callback function is reconfiguring the DMA buffer, the work function is prevented from writing as follows:

```
1 pthread_mutex_init(&th, NULL);
```

is defined in the constructor while the callback function defining the new carrier frequency is

```
1 void rpitx_source_impl::set_freq(float freq)
2 {pthread_mutex_lock(&th);
3   iqtest->stop();
4   delete(iqtest);
5   iqtest=new iqdmasync(freq,samp_rate_,\
6     14,IQSize*4,MODE_IQ);
7   iqtest->SetPLLMasterLoop(3,4,0);
8   pthread_mutex_unlock(&th);
9 }
```

with the main work function updated with

```
1 while (nbread<noutput_items)
2   {if (nbread+IQSize<noutput_items)
3     xferlen=IQSize;
4     else xferlen=noutput_items-nbread;
5     pthread_mutex_lock(&th);
6     iqtest->SetIQSamples((std::\
7       complex<float>*) &in[nbread],xferlen,H);
```

```
8   pthread_mutex_unlock(&th);
9   nbread+=xferlen;
10  }
```

This new structure is deleted in the destructor with

```
1 pthread_mutex_destroy(&th);
```

6. Practical demonstration (3): scalar network analyzer

As part of an undergraduate course on radiofrequency instrumentation, we aimed at characterizing the transfer function of a dual-resonator surface acoustic wave transducer designed to exhibit two resonances around 434 ± 1 MHz. Our initial investigation focused on a broadband noise source as widely available by polarizing a Zener diode (Sliwczynski, 1999; Maxim Application Note 3469, 2005), but due to remote teaching conditions, the 12 to 24 V high voltage needed to power the noise generator was not available to most students assumed to only have access to the 5 V output of a USB port. Hence, a noise source generated by the Raspberry Pi(4) provided as recording platform was needed: feeding a noise source IQ output to `gr-rpitx` configured to operate at 86.8 MHz – limited to 125 MHz based on (Pi, 2020) at p.82 “5.4.1 Operating Frequency” – would generate on its 5th overtone the required signal. Furthermore, the documented 200 kHz sampling rate at fundamental mode (86.8 MHz) would extend to 1 MHz on the 5th overtone, allowing to cover the whole Industrial, Scientific and Medical (ISM) band with only two carrier frequency shifts by $1 \text{ MHz}/5=200 \text{ kHz}$.

Dynamic carrier frequency tuning is demonstrated at http://jmfriedt.free.fr/gr-rpitx_set_freq.mp4 and a sample measurement is displayed in Fig. 5.

For comparison, the characterization of this same device using a Rohde & Schwarz vector network analyzer is displayed in Fig. 6.

7. Emitted spectra

The signal generated by the Raspberry Pi is a square wave and hence exhibits many more spectral components than expected. On a broad spectrum (Fig. 7) the harmonics are clearly visible and although they can be beneficial for reaching high radiofrequency (UHF) bands, analog filtering is needed for a single harmonic to probe the device under test.

On a narrower bandwidth, intermodulation is clearly observed when emitting an AM modulated sine wave at frequency f_{AM} over a carrier: while the theoretical spectrum would be two Dirac spectral characteristics spaced by twice

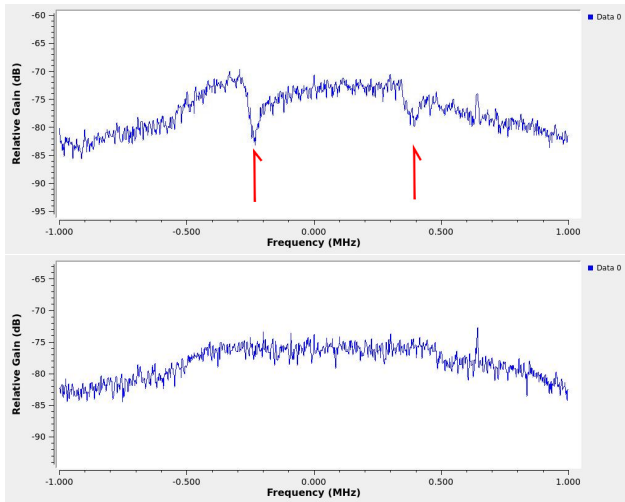


Figure 5. Top: through configuration of the dual resonator SENSEOR (France) SEAS10 transducer operating in the ISM band as cooperative target for passive, wireless sensing. Bottom: calibration with a through measurement as reference when no sensor is present between the radiofrequency output and the DVB-T receiver acting as general purpose software defined radio receiver. Arrows on the top chart indicate the frequency offsets at which the resonance modes are observed.

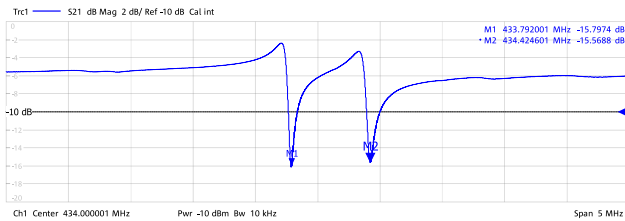


Figure 6. Reference measurement of the SEAS10 transducer used in transmission mode in this experiment. The 5 MHz frequency span is broader than the chart displayed in Fig. 5 to emphasize the lack of spurious resonance out of band.

the AM modulation rate, the practical spectrum exhibits a series of components separated by f_{AM} . Fig. 8 illustrates the emission of a 5-kHz amplitude modulation of a 86.6-MHz carrier: while the spectrum would be expected to be only two spectral components at ± 5 kHz when the modulation signal is a sine wave, a multitude of periodic components is visible, degrading the signal to noise ratio.

Fig. 8 also emphasizes how inaccurate the carrier frequency definition is with an offset of 20 kHz to the targeted 86.6 MHz or 230 ppm. Finally, the fractional PLL¹ (Fig. 9) converting the 700 MHz reference oscillator VCO divided by I to the GPIO output signal LO with a pre-

¹https://elinux.org/The_Undocumented_Pi#Clocks $dVCO = 2.7$ kHz.

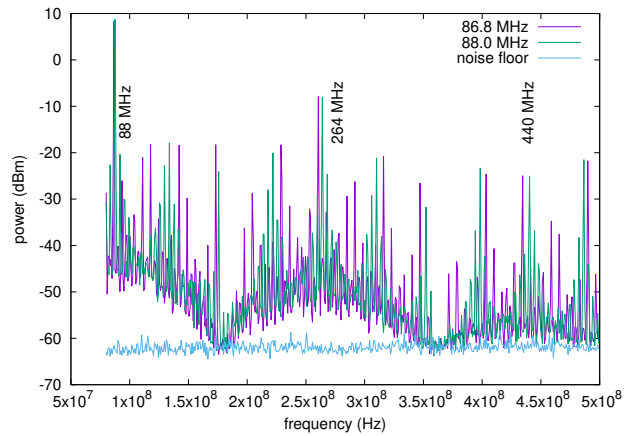


Figure 7. Multiple overtones are emitted, allowing to reach the 434 MHz ISM band with the 5th overtone of a 86.8 MHz signal, but also emphasizing that such a signal must not be emitted over the air. Bottom: zoom on the signal in the ISM band, exhibiting multiple spurious spectral features while a continuous sine wave is being emitted.

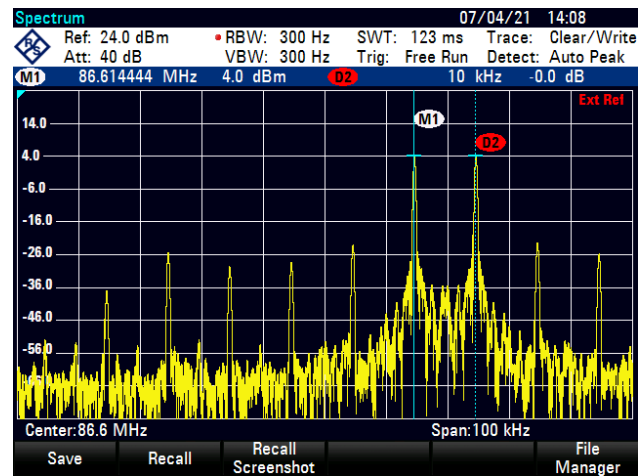


Figure 8. Spectrum of a 5 kHz sine wave being transmitted as an amplitude modulated carrier, emphasizing the many cross-modulation spectral components beyond the expected two Dirac components at ± 5 kHz from the carrier.

scaler of Q by comparing LO/Q with VCO/I : the description provided in the Raspberry Pi4 peripheral stating that $VCO = \frac{LO}{I+F/4096}$ (since F is defined on 12 bits) relates to the classical fractional PLL description by equating $Q = \left(1 + \frac{F}{4096 \times I}\right)^{-1}$. Considering that the denominator F is a 12-bit integer, $dVCO = LO/(4096 \times I^2)$ by tuning the fractional part of the PLL with unit steps, so that $dF/4096 = 2^{-12}$ and $I \simeq 8$ for a 86.8 MHz output and

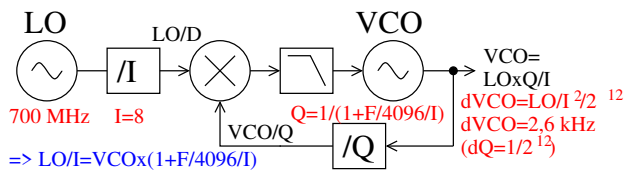


Figure 9. Schematic of the fractional PLL relating the classical PLL architecture with the quantities handled by the Raspberry Pi4 registers I and F (Pi, 2020) at p.81 “5.4 General Purpose GPIO Clock”.

8. Conclusion

We have extended the capability of the Raspberry Pi(4) as a radiofrequency source by providing compatibility with GNU Radio and hence all the signal processing blocks available to generate signals as simple as broadcast analog frequency modulated signals to as complex as Digital Radio Mondiale digital communication streams. The emphasis is on educational purposes to promote investigations of real signals plagued by practical issues such as fading and noisy communication channels between the source and an inexpensive receiver such as a digital video broadcast-terrestrial receiver used as general purpose software defined radio receiver on the Raspberry Pi or the host personal computer. The software is available at <https://github.com/jmfriedt/gr-rpitx>

Acknowledgement

Emitting digital mode broadcast signal and using DRM for that purpose rather than DAB(+) which would require excessive bandwidth was supervised by Hervé Boeglen (XLim, Poitiers, France) who also improved the manuscript by proofreading.

References

- É. Courjaud, F5OEO. Rpitx: Raspberry Pi SDR transmitter for the masses, 2017. https://www.youtube.com/watch?v=Jku4i8t_nPc.
- ETSI. Digital Radio Mondiale (DRM); system specification – final draft ETSI ES 201 980 V3.1.1, 2009. https://www.etsi.org/deliver/etsi_es/201900_201999/201980/03.01.01_50/es_201980v030101m.pdf.
- Maxim Application Note 3469. Build low cost white noise generator, Mar 14 2005. <https://www.maximintegrated.com/en/design/technical-documents/app-notes/3/3469.html>.

Pi, Raspberry. BCM2711 arm peripherals, 2020. <https://datasheets.raspberrypi.org/bcm2711/bcm2711-peripherals.pdf>.

Schroer, V., 2021. <https://www.mail-archive.com/discuss-gnuradio@gnu.org/msg73035.html>.

Sliwczynski, Lukasz. Zener diode and mmics produce true broadband noise, October 14 1999. <https://www.edn.com/zener-diode-and-mmics-produce-true-broadband-nois>