Radiofrequency spectrum painting, and the frequency modulation capture effect – or why do planes still communicate using AM

J.-M Friedt, April 1, 2018

We present painting patterns from bitmap images on the radiofrequency spectrum by emitting an audiofrequency signal whose spectal components carry the color intensity of each pixel when displayed as a waterfall chart – time evolution of the spectrum of the signal acquired using a DVB-T receiver used as a general purpose software defined radio receiver. This project brings us to the re-discovery of the frequency modulation (FM) capture effect in which the strongest emitting station locks the demodulator and weaker stations are rejected, explaining the use of amplitude modulation (AM) in aeronautical fields in which a pilot must know of any possible interference of its radiofrequency communications. All experiments use a DVB-T receiver used as general purpose software defined radio driven by GNURadio, for an investment of less than 20 euros.

1 Painting on the radiofrequency spectrum

Two presentations during the 2018 edition of the FOSDEM Software Defined Radio (SDR) devroom included messages painted on the radiofrequency spectrum [1]. By emitting a signal whose spectral components represent the color intensity of each pixel, a demodulation followed by a display of the spectra as a function of time in a waterfall chart exhibits the message being transmitted as a picture. Mathematically, each signal is simply the inverse Fourier transform of each line being transmitted, since the waterfall will take care of computing the Fourier transform of the received signal and hence display the transmitted line. This concept is practically implemented with the GNURadio block named `gr-paint` (`https://github.com/drmpeg/gr-paint`) in which the rule we just described is seen as (`https://github.com/drmpeg/gr-paint/blob/master/lib/paint_bc_impl.cc#L160-L166`)

```
pixels = image_width * pixel_repeat;
volk_32f_cos_32f(angle_cos, angle_line, pixels);
volk_32f_sin_32f(angle_sin, angle_line, pixels);
volk_32f_x2_multiply_32f(angle_cos, angle_cos, magnitude_line, pixels);
volk_32f_x2_multiply_32f(angle_sin, angle_sin, magnitude_line, pixels);
volk_32f_x2_interleave_32fc(out, angle_cos, angle_sin, pixels);
out += pixels;
```

The author of `gr-paint` calls this modulation OFDM (Orthogonal Frequency Division Multiplexing) since all components of the spectrum are transmitted simultaneously. Our interest in this artistic expression medium lies in the fact that, as is, `gr-paint` generates a set of complex coefficients I, Q feeding an IQ modulator as found in the Ettus Research emitters. Lacking such equipment, ca we still paint on the spectrum ?

As a first step, we can analyze the parameters defining the properties of the transmitted signal. The signal source exhibits a bandwidth f_s equal to the sampling frequency (the Fourier transform spreads from $-f_s/2$ to $+f_s/2$ for the complex emitted signal). This means that each N pixel wide line is observed as the spectral components of a N sample Fourier transform, which hence requiers a duration of N/f_s to be transmitted. This duration defines the rate at which the waterfall scrolls, *i.e.* at which rate the successive lines are displayed. As an example, using a sound card sampling at $f_s = 192$ kHz, each line of a 1920 pixel-wide image requires 10 ms to be transmitted, and a full 2770-line high image requires 27.7 s to be transmitted. Practically, `gr-paint` uses a `ofdm_fft_size = 4096` variable which defines the number of frequencies generated during the Fourier transform by zero-padding each image line at the left and the right: the 4096 samples require $4096/f_s$ seconds to be transmitted, and in our numerical application each line requires 21.3 ms to be transmitted, hence a total 2770-line picture transmission duration of 1 minute, in excellent agreement with our observations (Fig. 4, right).

Figure 1: Emission using an FM-modulated radiofrequency synthesizer whose external input is connected to the PC sound card output. The FM excursion is a few kHz/V. We shall describe later in the text how other circuits better suited to the general public will be used.

Our investigations have focused on emitting on a PC sound card the real part of the signal generated by the inverse Fourier transform of each line of the picture to be transmitted, wasting half of the needed information. Indeed, the modulation input of a radiofrequency emitter can only be driven by a single signal which can only be the real or imaginary part of the Fourier transform. The alternative option found in I/Q modulators – which would allow generating the sum of the real and imaginary components driving two carrier signals in quadrature – is not available in most radiofrequency emitters (Fig. 1). Hence, we must provide a picture in which half of the information is equal to 0, in order to avoid mixing the positive and negative parts of the spectra: these two halfs are initially separated by the imaginary part of the complex coefficients, but overlap when only the real part is kept since the Fourier transform of a real signal is an even function (Fig. 2).

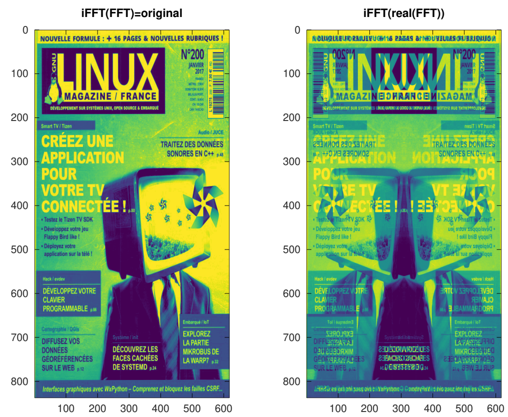

Figure 2: Illustration of the impact of keeping only the real part of the Fourier transform of each picture line during the transmission: the even spectrum is clearly visible on the right picture, while the left picture in which all information was kept during the transforms is recovered identical to the original image.

The transmission and reception scheme using GNURadio is shown in Fig. 3.

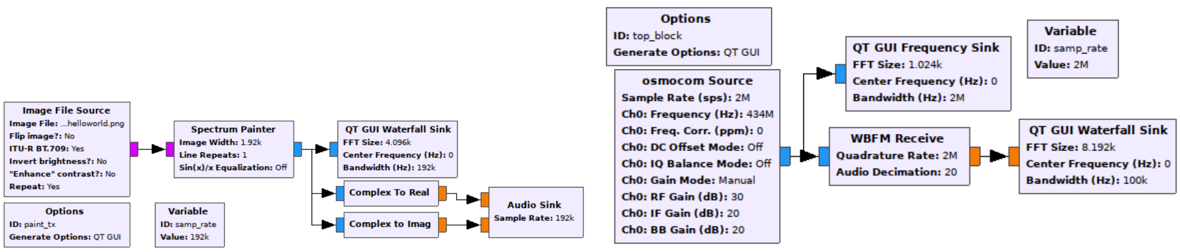

Figure 3: Emission (left) and reception (right) charts. The transmitted signal feeds the external FM modulation input of a Rohde & Schwartz SMA100 synthesizer through the sound card output (Fig. 1): the FM deviation is set to 300 to 500 kHz/V. Right: reception using a DVB-T receiver used as a general purpose software defined radio.

Tuning the sampling rate and the input signal amplitude, a convincing result is achieved, as shown in Fig. 4.

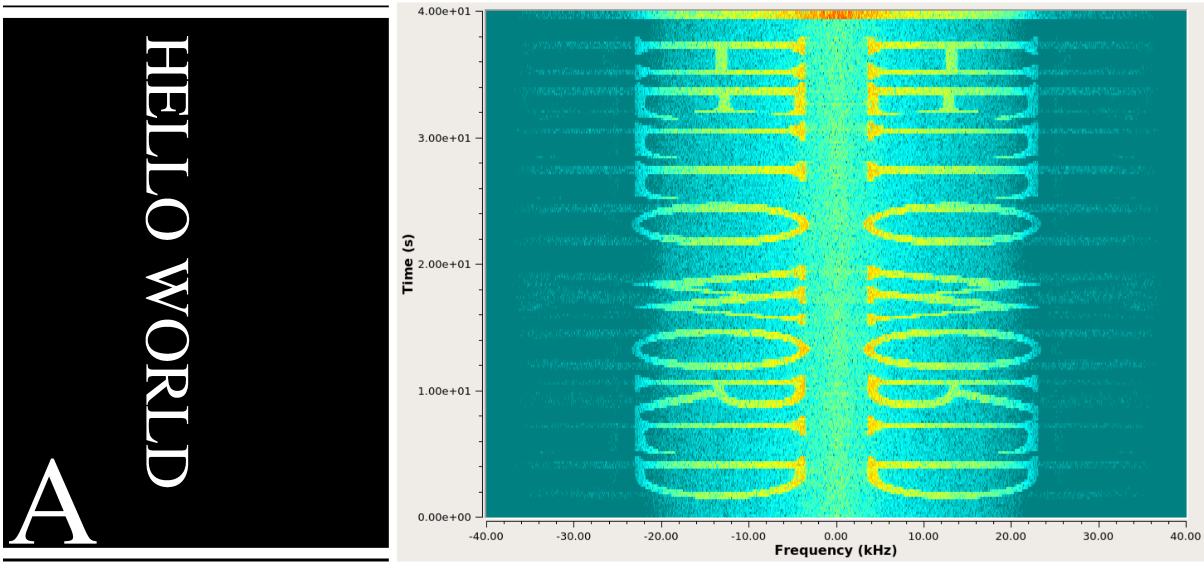

Figure 4: Left: image transmitted by `gr-paint`. Keeping only the real part of the I, Q coefficients generated by the modulator requires the introduction of a large empty part in the transmitted picture (right half) in order to prevent disturbing the demodulated image with aliasing due to the loss of half of the information. The left quarter of the image ("A" letter) will not be visible considering the modulation and demodulation parameters. Right: signal demodulated by the FM detector and displayed as a waterfall.

2 Practical implementation

Few readers have access to a high quality frequency synthesizer such as Rohde & Schwartz's SMA100 with its frequency modulation input. Can we demonstrate the concept of painting on the radiofrequency spectrum using affordable equipment ? The two solutions we have investigated use an integrated FM emitter, or a single chip radiofrequency emitter manufactured by Maxim IC under reference MAX2606. The former solution demonstrates painting on the spectrum by feeding the audio input of a Radiometrix TX2-433-160-5V emitter operating in the European ISM (Industrial, Scientific and Medical) band centered around 434 MHz, with the output of a sound card emitting the signals generated by `gr-paint` (Fig. 5).

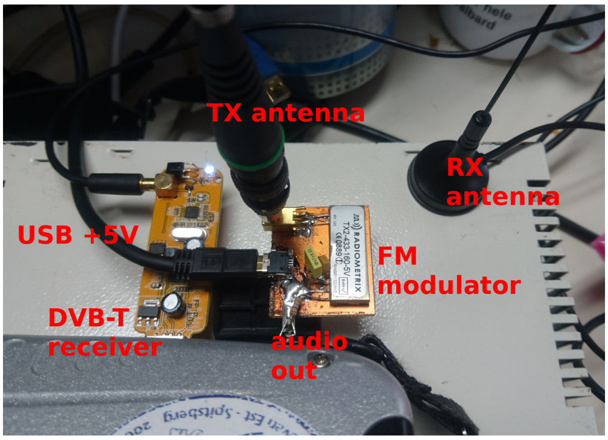

Figure 5: Using a commercial FM emitter working in the 434 MHz ISM band for painting on the radiofrequency spectrum, and receiving using a DVB-T dongle.

The second implementation uses the MAX2606, an emitter working from 70 to 150 MHz, again feeding its audio input with the output of the sound card defined by the signals generated by `gr-paint` (Fig. 6). This component was selected for its ability to emit in the commercial broadcast FM band, and hence to check its proper operation with an FM receiver, not requiring dedicated laboratory equipment (spectrum analyzer), as well as its availability as free samples from the manufacturer [1] (Fig. 7). The circuit is strongly inspired from the associated application note [2], even though the lack of control on the VCO only provides a poor stability carrier signal. This is an opportunity to demonstrate how useful

[1]actually, other versions of this chip operating out of the FM band are available as free samples, otherwise its cost is 1.71 euros when ordering from Farnell

modulation schemes are to recover, on the receiver, the transmitted information, whatever the offset between the emitter and receiver local oscillators, within the acquisition bandwidth (Fig. 8).

These two implementations are interesting since beyond their low cost which allows anyone to reproduce the experiement, they demonstrate the redundancy of information introduced by the modulation, providing the FM communication its immunity to multipath destructive interferences or local disturbances on the spectrum (Fig. 6).

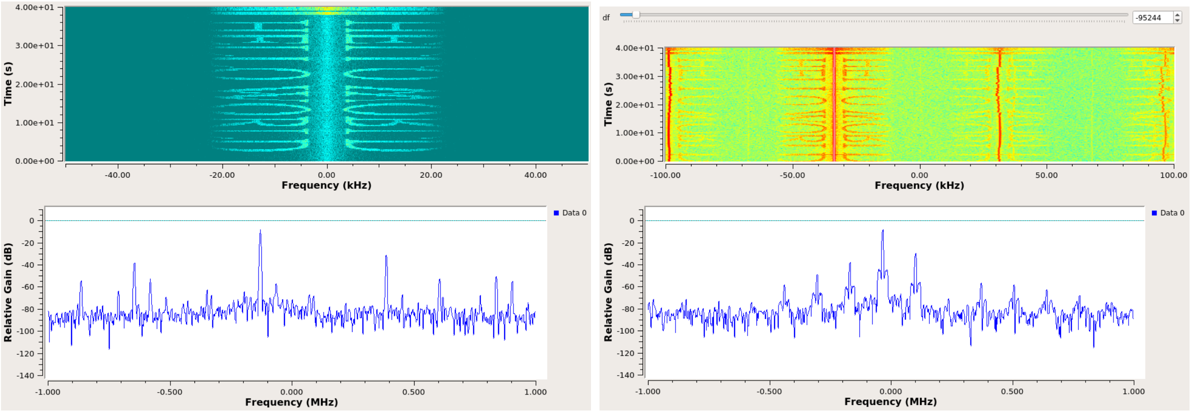

Figure 6: Left: *waterfall* of the GNURadio WBFM output, which compensates for any offset between the emitter (Fig. 5) and receiver local oscillators. Right: waterfall of the raw modulated signal, before being processed by GNURadio's WBFM block, illustrating the redundancy of information carried by the various components of the FM modulated signal.

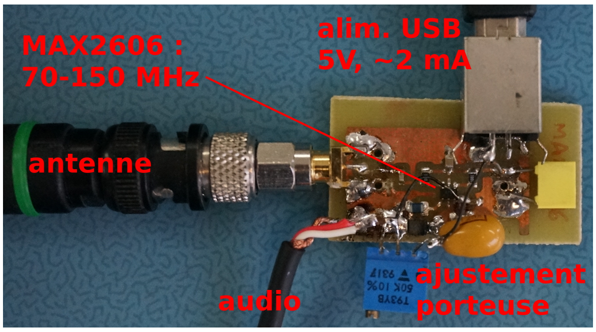

Figure 7: Radiofrequency emitter designed around the Maxim MAX2606: an inductor coarsely defines the frequency in the 70-150 MHz range, and the voltage offset introduced by the potentiometer over the audio signal decoupled by a 470 nF capacitor finely defines the operating frequency.

3 FM "capture" effect

While investigating the impact of a parasitic signal emitted close to the frequency modulated signal, we observed a binary behaviour if no efficient filtering of this interfering signal was implemented: either the parasitic signal was weaker than the signal encoding the image is the frequency domain, and the reception of the pattern was excellent, or the parasitic signal was stronger than the signal transmitting the pattern, and the image was completely lost during the demodulation. This binary behaviour of the FM demodulation, without intermediate state in which the quality of the demodulated image is simply degraded, is called the "capture effect" of the frequency modulation (Fig .9). It is again a very well known effect thoroughly investigated between 1950s and 1980s [3], but somewhat forgotten in the current era obsessed with digital communication using highly efficient modulation schemes.

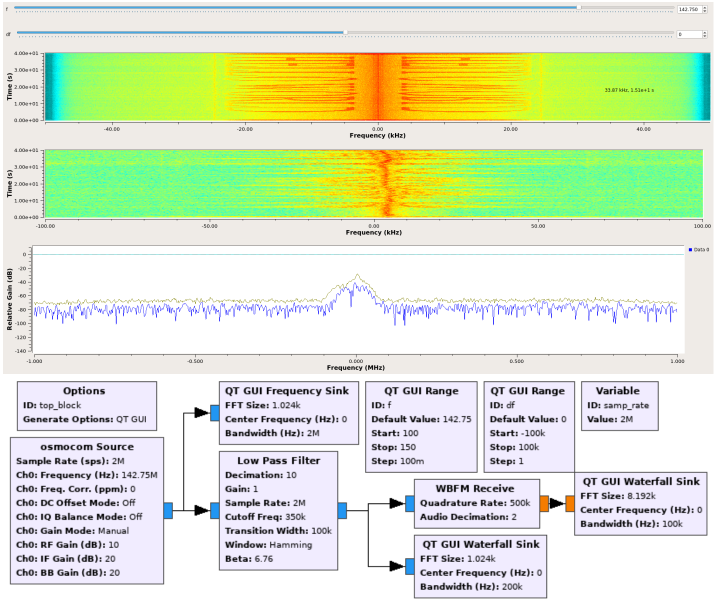

Figure 8: Lacking a lock of the oscillator on a stable source such as a quartz oscillator, the huge drift of the poor quality emitter local oscillator (Fig. 7) is clearly visible on the middle waterfall. After demodulation by the WBFM block, the message has become clearly visible, again thanks to the correction of the offset between the emitter and receiver frequencies. The GNURadio processing chart for generating these figures is shown on the bottom.

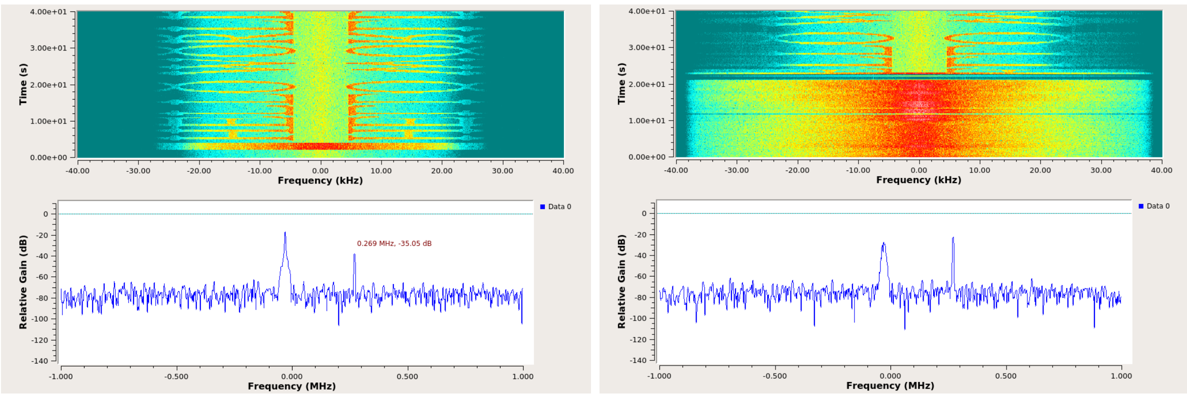

Figure 9: Left: the signal transmitting the image – close to 0 Hz – is stronger than the parasite signal shifted by 300 kHz. The message is perfectly visible on the waterfall. Right: while the parasite signal is initially weak, its power is gradually increased until it becomes stronger than the signal propagating the information with the picture. Suddenly, the image disappears, the demodulator locking on the parasite signal as soon as its power exceeds that of the information containing the image.

During his plenary talk at the 2016 edition of FOSDEM [4], Tom Rondeau concluded on the social impact of pirate FM broadcast in the New-York area, and emphasized on the property of an FM emitter stronger than other emissions on the same carrier frequency to crush the latter. FM modulation hence exhibits the property that a demodulator receiving two signals from two emitters on the same carrier frequency will amplify the strongest signal and reject the weakest: this is the same FM capture effect we have just discussed. We wish to use GNURadio to explore this effect on synthetic signals, analyze its consequences, and especially understand the underlying cause. A manual implementation of the demodulation algorithm with GNU/Octave will validate this analysis.

Let us notice right now, before investigating the details of signal processing, that his analysis will answer a question that was bothering us since discovering that aeronautical bands (108–137 MHz) are using amplitude modulation (AM) despite its inefficiency in using the amplifier stage and its low spectral bandwidth meaning it has long been disused by most users of the radiofrequency spectrum. Why do aeronautical communications between planes and air traffic controllers still use amplitude modulation rather than frequency modulation, more robust and providing better audio quality ? The answer lies in the capture effect of FM: while a pilot can hear two simultaneous emissions on the same carrier and detect interferences, and hence attempt to overcome the issue by requesting a new transmission, the FM capture effect attenuates the weaker signal and amplifies the strongest to make it dominant. The pilot is no longer informed of a possible interfering signal, and hence cannot solve the conflict in the use of the radiofrequency spectrum.

3.1 GNURadio

Now that the problem has been stated, let us first model it using GNURadio. Two processing chains are considered: two emitters generate signals at different frequencies, with their relative contributions tunable before being added, and the demodulator output feeding on the one hand a spectrum analyzer and on the other hand the sound card. Such a signal processing scheme is emplemented for frequency modulation on the one hand, and amplitude modulation on the other hand. Notice that there is no “amplitude modulation” block: indeed, amplitude modualtion is achieved by multiplying the carrier with a modulating signal (a sine wave with different frequency for each emitter, shifted by an offset so that the voltage never goes below 0). The FM modulator is a bit more challenging, since the output datarate must be a multiple of the input audiofrequency datastream rate.

Figs. 10 and 11 display two signal processing schemes applied to synthetic data generated with GNURadio in order to experiment with the FM capture effect, and the lack of such an effect with AM. In both cases, the two information datastreams are periodic signals whose freqency has been arbitrarily selected at 480 and 1170 Hz.

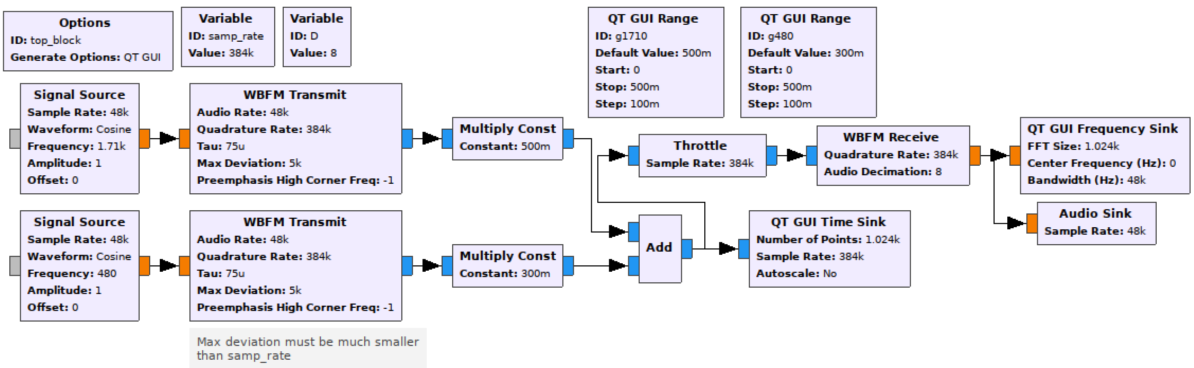

Figure 10: GNURadio signal processing scheme for an FM modulation of two sources transmitted simultaneously and demodulated using a single wideband FM (WBFM) block.

The result of such simulations, whose output is more dramatic if the reader reproduces the signal processing schemes and emits the resulting signals on the sound card, are summarized in Fig. 12 for the FM modulation and Fig. 13 for the AM modulation. In order to help the reader analyze these somewhat crowded charts, all figures display on top the time evolution of the modulated signals, and on the bottom the spectral characteristics of the demodulated signals. The time-domain signals are not easily interpreted in the case of the FM modulation, but the sum of the two periodic components is well visible on the envelope in the case of amplitude modulation. In the frequency domain, we easily see that a single spectral component is visible, either at 1710 or 480 Hz, in the case of FM modulation, but never both at the same time (Fig. 12, bottom left and middle). When generating synthetic signals, generating two periodic waves with the same power yields a failure of the demodulator (Fig. 12, bottom-right, on which we notice that the two sliders selecting the output power on top of the figure are tuned to the same level). In the case of amplitude modulation (Fig. 13), we always observe both spectral components at 1710 and 480 Hz, with relative levels representative of the power injected in each component (as selected

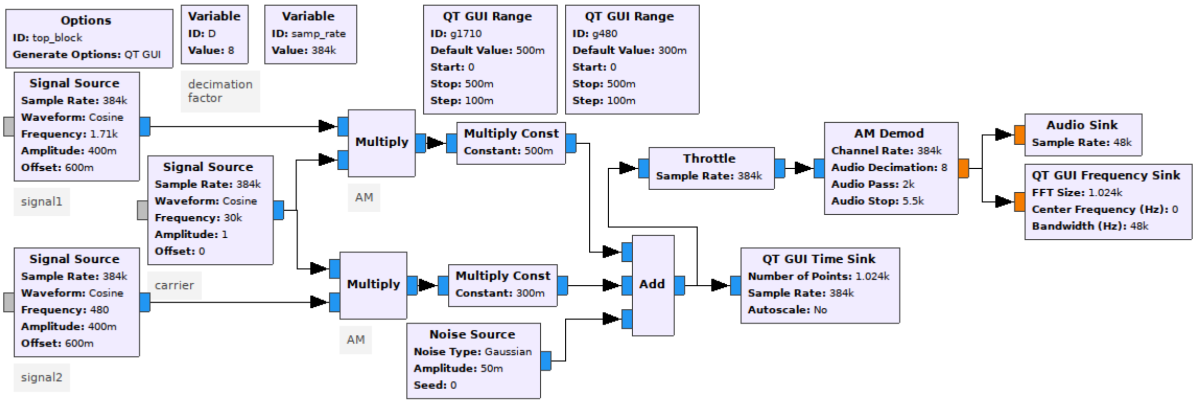

Figure 11: Similar signal processing scheme than presented in Fig. 10, but applied to amplitude modualtion. The amplitude modulator does not exist: a carrier is multiplied by both information made of sine waves offset by a voltage selected for the output to always be positive.

by the slider position on top of each figure).

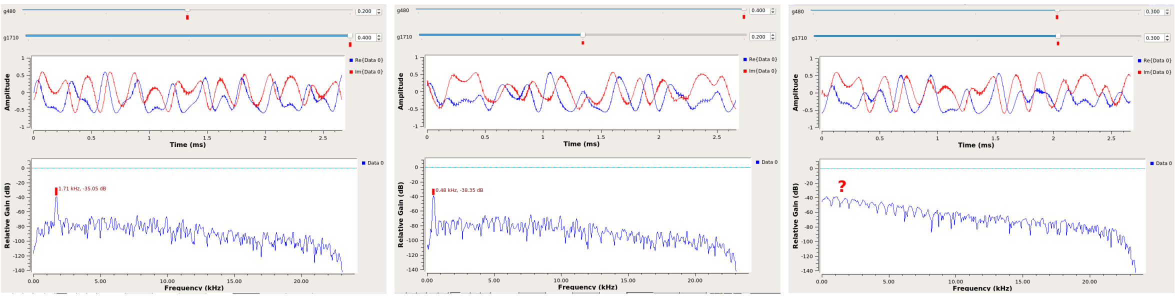

Figure 12: Result of processing FM modulated data streams. Only the spectral component of the most powerful signal (bottom) appears after the demodulation, while the time domain signal (top) hardly provides any information of each component. If both signals are characterized with exactly the same power (right), the demodulator fails and no spectral component representative of any of the signals is visible. The red marks are added for guiding the eye of the reader on the significant features of each figure.

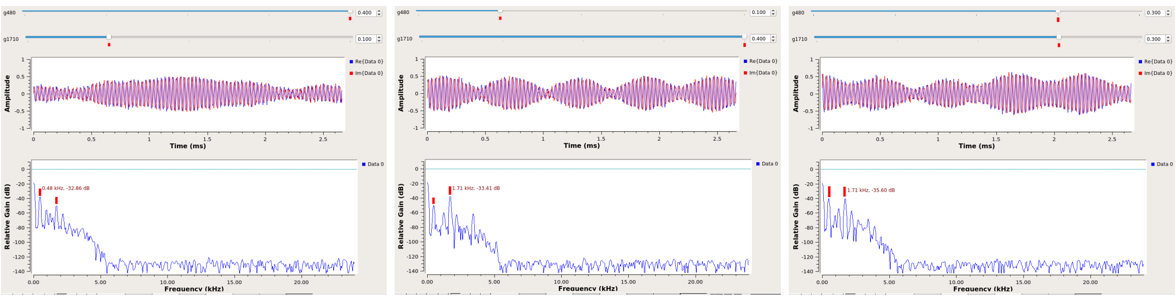

Figure 13: Result of processing AM modulated data streams. Both spectral components of the information transmitted appear after demodulation, whatever their relative power. The time domain signal (top) allows for identifying each of the two components of the signals. The red marks are added for guiding the eye of the reader on the significant features of each figure.

While the AM demodulator is easily analyzed – a rectifier and a low pass filter implemented digitally as absolute value and a sliding average – the digital implementation of the FM demodulator is not a "simple" implementation of the analog phase locked loop, but uses at best the complex values of the digital signal.

In order to avoid the GNURadio “WBFM” black box which does not help us in understanding the capture effect of this modulation scheme, we shall implement the digital demodulation of frequency modulated signals and hence see that the phase locked loop has nothing to do with the capture effect, which happens to be an intrinsic effect of the modulation characteristics. Doing so will be achieved by analyzing synthetic frequency modulated signals with GNU/Octave.

3.2 GNU/Octave

A first idea on the capture effect would be based on the classical analog FM demodulation scheme using a phase locked loop (PLL): such a circuit can only lock on a single frequency, rejecting the second weaker signal. Such an analysis is however not consistent with the digital implementation of the FM demodulator, exhibiting no feedback loop but only simple multiplications between successive samples of the complex I and Q signals obtained from the frequency transposition of the signal collected by the antenna.

We indeed observe in `gr-analog/lib/quadrature_demod_cf_impl.cc` which is called by `gr-analog/python/analog/wfm_rcv.py` that the GNURadio implementation of the FM demodulator follows the equation mentioned by D. Bederov in his presentation at `https://archive.fosdem.org/2015/schedule/event/sdr_arithmetic/`, namely

```
volk_32fc_x2_multiply_conjugate_32fc(&tmp[0], &in[1], &in[0], noutput_items);
for(int i = 0; i < noutput_items; i++) {
   out[i]=d_gain*gr::fast_atan2f(imag(tmp[i]), real(tmp[i]));
```

which actually implements the fact that a message $m(t)$ with maximum frequency f_m, frequency modulated in a signal $s(t)$ with a deviation Δf, is expressed as

$$s(t) = \frac{\Delta f}{f_m} \int_0^t m(\tau) d\tau$$

and that the demodulation of this signal sampled at discrete times $k \cdot T_s$, $k \in \mathbb{N}$ and T_s the sampling period, is obtained by computing

$$m_k \propto \arg(s_k \cdot s_{k-1}^*)$$

No feedback loop is needed in this formula that would explain locking on the most powerful signal and reject weaker spectral components. On the opposite, AM demodulation is restricted to rectifying and low-pass filtering, which allows for all spectral components to be generated at the output, whatever their relative power. We observe on Fig. 14 (left) that the FM demodulation indeed only exhibits the strongest signal and the rejection of the weaker ones. However, the time domain signal additionnaly is polluted with multiple artefacts, making the comparison with the initially emitted signal difficult. A frequency characterization is easier to interpret, as shown in Fig. 14 (right). In this case, we immediately see that only the strongest component is visible in the spectra, with the addition with some high-frequency artefacts which become weaker as the interfering signal is weaker.

```
kf=.0628; % Modulation index
f=100;    % Carrier frequency
fs=1000;  % Sample frequency
N=1000;   % Number of samples
R1=.9     % ratio of one channel v.s other
R2=.6     % ratio of one channel v.s other
t=[0:1/fs:(N/fs-1/fs)];

msg1=sin(2*pi*20*t);  % first signal (f=20)
msg2=sin(2*pi*5*t);   % second signal (f=5)
subplot(311);plot(msg1);hold on;plot(msg2)
S1=exp(j*2*pi*(f*t+kf*cumsum(msg1))); % FM modulation
S2=exp(j*2*pi*(f*t+kf*cumsum(msg2))); % FM modulation
subplot(312);plot(real(S1+.8*S2));    % sum of FM modulated signals
S=S1+R1*S2; demod11=angle(S(2:end).*conj(S(1:end-1))); % FM demod
S=S1+R2*S2; demod12=angle(S(2:end).*conj(S(1:end-1))); % FM demod
S=R1*S1+S2; demod21=angle(S(2:end).*conj(S(1:end-1))); % FM demod
```

```
S=R2*S1+S2; demod22=angle(S(2:end).*conj(S(1:end-1))); % FM dmeod
dref1=angle(S1(2:end).*conj(S1(1:end-1))); % FM demod of signal 1 alone
dref2=angle(S2(2:end).*conj(S2(1:end-1))); % FM demod of signal 2 alone
subplot(313)
plot(demod12,'b');hold on;plot(demod22,'r') % compare outputs in the time domain
plot(dref1,'c');hold on;plot(dref2,'m')     % ... with the raw signals

figure(2)
subplot(311)  % same analysis, in the frequency domain ... easier to read
plot(abs(fft(dref1-mean(dref1))),'c');hold on;plot(abs(fft(dref2-mean(dref2))),'m')
subplot(312);plot(abs(fft(demod11-mean(demod11))),'b');
hold on     ;plot(abs(fft(demod12-mean(demod12))),'g');
subplot(313);plot(abs(fft(demod21-mean(demod21))),'r')
hold on     ;plot(abs(fft(demod22-mean(demod22))),'k')
```

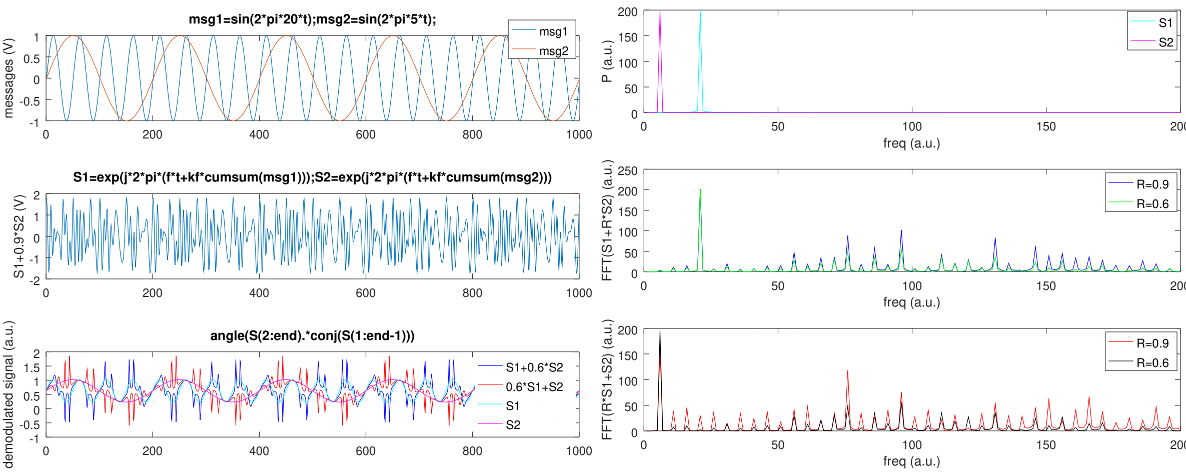

Figure 14: Left: time evolution of the reference signals (top), frequency modulated signal in the case of two input signals with the same power (middle), and result of the demodulation (bottom) for various weighing of the two transmitted signals, including pure input signals. Right: frequency domain analysis is easier, since we clearly see that the strongest signal dominates the weaker one (bottom, middle) with spectral characteristics close to those observed for each pure signal (top), with the second components vanishing. The parasitic spectral components (middle, bottom, right half of each spectrum) are the same in both cases.

This analysis is in excellent agreement with the investigation summarized in [5] which indeed exhibits some sharp spikes in the instantaneous frequency after demodulation, and matches the analysis in [6] which states that the capture effect is magnified with lower bandwidth induced by the low-pass filtering of the demodulated signal.

Intuitively, [7] argues that the difference in the behaviour between the AM and FM demodulators arrises from the fact that the latter is based on a frequency measurement, or the time of zero-crossing, as opposed to AM which is based on an amplitude measurement. A periodic signal, polluted by a weaker signal, still crosses at “about the same” time the abscissa, the zero-crossing point exhibiting the sharpest voltage slope as a function of time. Analyzing such a behaviour in a complex plane phasor diagram, [8] considers an analysis on the vector addition of the two complex components, and indeed demonstrates that the angle of the resulting vector (whose zero-crossing defines the frequency) is hardly affected by the weaker component while the strongest component dominates the phase behaviour.

4 Conclusion

After painting on the radiofrequency spectrum patterns observed through the time-evolution of the spectra in a waterfall display, we have met the capture effect of frequency modulated signals when an interfering signal more powerful than the one carrying the information lies in the demodulation bandwidth. Modeling this effect allows us to identify the cause as not being related to the demodulation scheme – classically based on a phase locked loop approach in the analog implementation, but not used in the digital approach – but on the intrinsic properties of the modulation scheme. Indeed, FM modulation is based on encoding the information on a frequency and hence a time of zero-crossing of the emitted signal, rather than on the amplitude which is immune to this capture effect. The need for a robust aeronautical communication link, and especially the ability to detect an interfering signal rather than hiding it under the most powerful signal, dictates the use of the latter modulation scheme, despite its inefficient use of the amplifier stage of the transmitter.

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