# OPTIMIZATION OF SQUELCH PARAMETERS FOR EFFICIENT RESOURCE ALLOCATION IN SOFTWARE DEFINED RADIOS

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## ABSTRACT

The squelch function is an important element in almost every radio, especially the airborne radio. It suppresses the audio output of the radio receiver when the desired signal does not have sufficient SNR and/or signal strength.
In legacy radios the squelch characteristic has usually evolved through many iterations stemming from customer feedback as well as extensive lab and field tests, so that the user finally experiences the most convenient squelch behaviour. If the computation of the squelch algorithm has to be changed, for example due to efficiency reasons, it must be ensured that the carefully obtained squelch characteristic remains the same, preferably without being forced to redo all iterations mentioned above. This paper describes an optimization-based approach which allows to meet these requirements.

## 1. INTRODUCTION

The squelch function of a radio connects the desired signal to the audio output of the radio receiver when the desired signal exhibits the required characteristics such as sufficient SNR and/or signal strength. It suppresses the audio output in case these characteristics are not met. Hence the proper function of the squelch is imperative for the communication between the pilot and the air traffic controller. Since the squelch controls the incoming signal, it is implemented in the receiver of a radio. The main components for digital signal processing in the receiver module of a radio are a Digital-Down-Converter (DDC), a Field-Programmable-Gate-Array (FPGA), the Digital Signal Processor (DSP), and a flash memory. We are mainly interested in the DSP where the absolute value of the in-band signal and its differential phase are used to compute the squelch criteria for muting the AF output as illustrated in Figure 1.1 and Figure 1.2.
Note that the receiver module includes two receiving blocks: a main receiver (the primary block for voice and data communication) and a guard receiver (for emergency calls), which operate concurrently. Both main and guard receivers

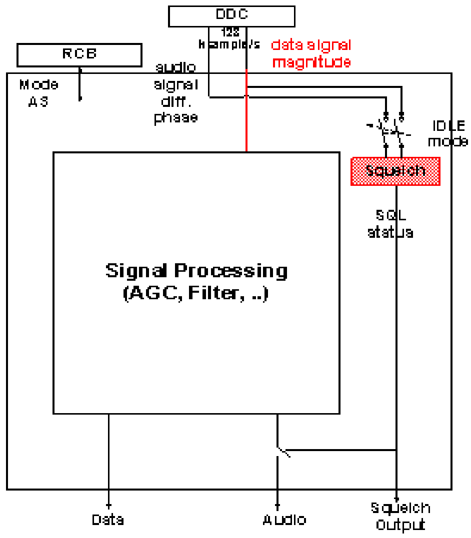


**Figure 1.1**: The squelch in the receiver module of the airborne radio (A3E Mode).

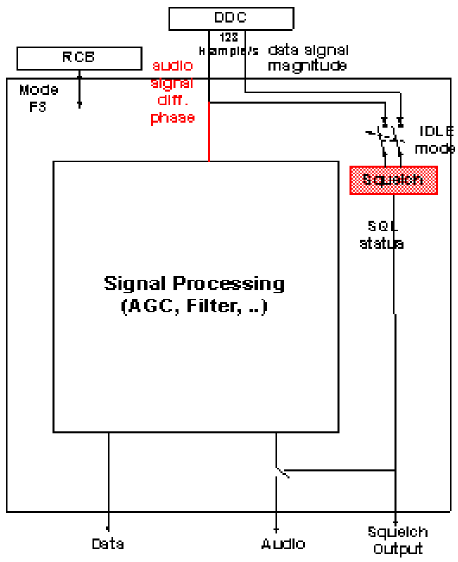


**Figure 1.2**: The squelch in the receiver module of the airborne radio (F3E Mode).

 

have a main block for signal processing and a separate block for squelch calculation. In this work, we only focus on the main receiver. The information-bearing input of the signal processing block is, in case of frequency modulation, the differential phase of the signal, and the absolute value of the in-band signal in case of amplitude modulation (compare Figure 1.1 and Figure 1.2). While the output of the squelch block controls the audio output of the receiver, the data output is not under squelch control.

## 2. A CLOSER LOOK AT THE SQUELCH

There are many state-of-the-art squelch techniques, and Figure 2.1 shows two of them: the S/N squelch and the carrier squelch. Both of them are illustrated for the F3E-mode [1]. We will investigate the S/N squelch more deeply because the carrier squelch has a much simpler implementation and is less challenging in terms of optimization.

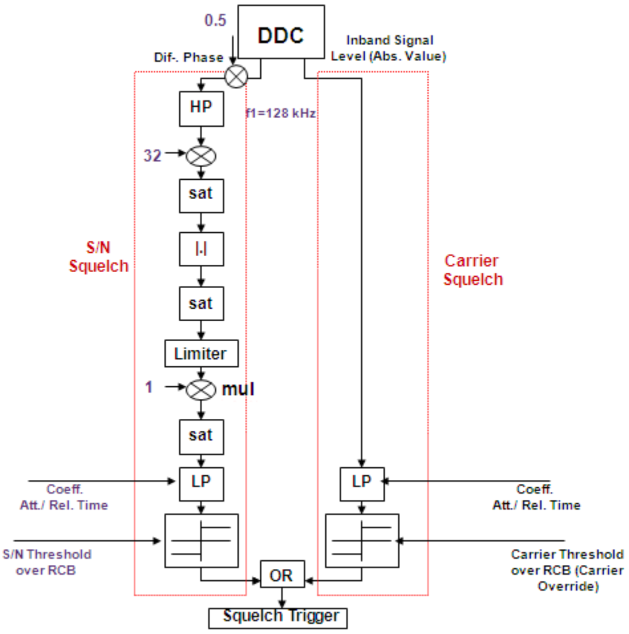


**Figure 2.1**: Fixed point implementation of the squelch in F3E Mode.

The S/N squelch detects valid radio signals which have a certain signal-to-noise ratio. Before that, the received RF signal is sampled and demodulated in the receiver. The demodulated signal is then fed into the squelch. In this work, the squelch receives the signal from the digital down converter (DDC), which converts the signal to a complex basebanded signal centered at zero frequency and represented in polar coordinates (absolute value and differential phase). The squelch gating of received signals, represented in polar coordinates, is a method that was introduced and patented in [2]. In this approach the noise is estimated and compared to thresholds which are determined by the characterization of the front-end to get meaningful signal-to-noise ratio estimates.

To this end the differential phase from the DDC is considered as a basis of the S/N squelch decision where it is assumed that an increase in noise power leads to an increase in the differential phase. This can be shown as follows:

Suppose we receive a 1 kHz noiseless tonal sound signal, which can be written as

$$y(t) = e^{j\omega t} \tag{2.1}$$

The amplitude of the signal is constant, while the phase is a linear function $\Phi = \omega t$. Hence, the differential phase is a constant $d\Phi/dt = \omega$. Let's suppose that a white Gaussian noise is added to the tonal sound. This random process also propagates into the differential phase of the signal which henceforth exhibits increased phase noise. The phase is no longer linear, and consequently the differential phase is not a constant any more. With increased noise level, also the variance of the phase noise is increased and therefore the energy of the differential phase. Therefore, the high-pass filtered differential phase can be considered as a measure for the noise level. In [3], the monotonic relation between noise in the complex baseband and in polar coordinates was shown.

## 3. MODES OF THE S/N SQUELCH

An airborne radio operates in different modes: fixed frequency modes, TRANSEC modes or other special modes. Each mode has a different payload routing for the signal transmission and reception. In this work, we are only interested in the signal reception for the fixed frequency modes. They can be classified into two categories: amplitude-modulated AM and frequency-modulated FM modes, depending on the modulation technique used to convey the signal.

The signal processing chain of the squelch is similar for all fixed frequency modes (cf. Fig. 2.1): the differential phase goes through a high-pass, so that the remaining noise can be estimated afterwards. However, the channel filter differs from mode to mode, allowing either narrow-band or wide-band signals to pass through. For instance, the amplitude-modulated AM A3E mode has a channel filter with bandwidth equal to 25000 Hz while the AM A1D mode has 50000 Hz , allowing both audio and data signals to be processed.

For each mode, the S/N squelch has a specified threshold function: the squelch estimates the signal-to-noise ratio of the received signal. If the measured S/N value is above the desired S/N ratio, the received signal is treated as a meaningful signal and is applied to the pilot's headphones or data modem.

In order to be able to perform an efficient development of the squelch algorithm a simulation in MATLAB® is available. When feeding a simulated differential phase into both the actual DSP implementation of the target radio MR6000A [4] and the simulation we obtain the result shown in Figures 3.1 and 3.2 verifying the validity of the simulation.

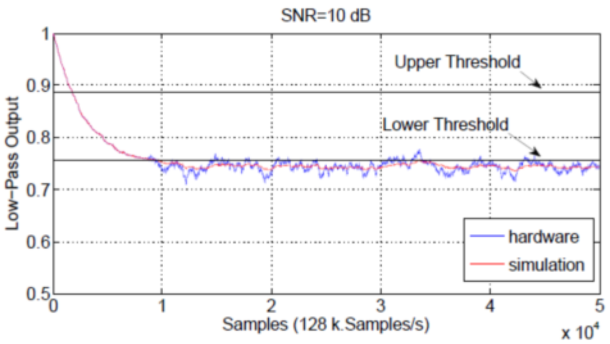


**Figure 3.1**: SNR=10dB in AM mode A3E.

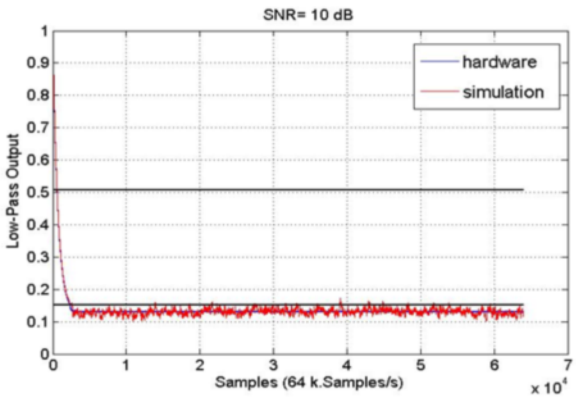


**Figure 3.2**: SNR=10dB in FM mode F3E.

### 4. SQUELCH ALGORITHM OPTIMIZATION

In this chapter, we focus on the task of preserving the S/N-squelch behavior while reducing the processing load that the S/N-squelch computation imposes upon the DSP. The latter may be necessary in order to free up DSP cycles for further functionality that needs to be added to the radio. The former, i.e. the preservation of the squelch algorithm behavior, is important since it has been optimized by means of exhaustive measurements and customer feedback. For instance, we consider the following situation: the squelch operates in A3E mode on signals with a sample rate of fa = 128 kHz. Consequently, all IIR filters (HP,LP) also have a clock rate of 128 kHz. In order to reduce the computational complexity, we want to perform down sampling on the LP filter. After a down sampling of factor 4, the low-pass filter will have a clock rate of 32 kHz, i.e., only every fourth sample will be considered by the LP filter. Hence, the output of the LP filter will deviate from the original one. With the appropriate optimization algorithm, we optimize the release- and attack- time coefficients of the low-pass filter so that its output approaches the one with the initial sampling rate (fa = 128 kHz).

The most critical function of the S/N-squelch is to estimate the SNR of the received signal. This is done by estimating the noise power and subsequently inverting it so that the SNR in the complex baseband can be computed [3]. Since the LP output of the squelch is a measure for the noise it is strictly decreasing with increasing SNR. Figure 4.1 confirms the decreasing behavior of the average squelch output as a function of the SNR, and also shows that the output changes considerably for the different lowpass sampling frequencies (initial frequency 128kHz and modified frequency 32kHz).

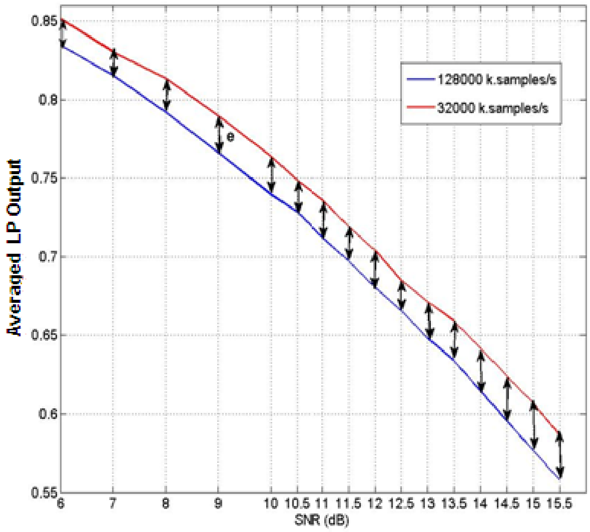


**Figure 4.1**: Averaged LP output of the squelch before and after downsampling.

The goal is now to alter the LP coefficients for a sampling frequency of 32kHz such that the noise estimation behaves in the same way as for the sampling frequency of 128kHz.

The optimization problem consists of minimizing the squared error between the two curves shown in Figure 4.1, i.e.

$$\min_{a_{lp}, b_{lp}} (f) = \sum_{i=1}^{16} (e_i)^2 \tag{4.1}$$

where $e_i$ represents the difference between the outputs at $SNR_i$, and $a_{lp}$ and $b_{lp}$ are the optimized coefficients of the IIR low-pass filter.

It has to be noted that the LP is not a simple fixed coefficient LP but has two sets of coefficients instead. One set determines the attack time of the squelch, the other set determines the release time. For this reason we have to split the minimization task of Eq. 4.1 into two which is expressed in the two equations Eq. 4.2 und Eq. 4.2. Hence we first minimize

$$\min_{a_{lp,att},\, b_{lp,att}} (f_{att}) = \sum_{i=1}^{16} (e_i)^2 \tag{4.2}$$

and then we minimize

$$\min_{a_{lp,rel},\, b_{lp,rel}} (f_{rel}) = \sum_{i=1}^{16} (e_i)^2 \tag{4.3}$$

where $a_{lp,att}$ and $b_{lp,att}$ are the attack time coefficients, i.e., the coefficients of the low-pass which control how quickly the filter modifies the open state of the squelch, and $a_{lp,rel}$ and $b_{lp,rel}$ are the release time coefficients, i.e., those coefficients of the low-pass which determine how quickly the modification comes to an end.

A longer attack time means that a longer period of time is used to lower the noise output, and a longer release time means that a longer time is taken for the noise to increase again in case of an abrupt decrease of the SNR. This allows separate control of the smoothing of the signal depending upon whether it is increasing or decreasing in amplitude.

In the following the Differential Evolution (DE) algorithm is described which is used to solve the minimization problems stated above.

## 5. DIFFERENTIAL EVOLUTION (DE)

The error functions introduced in Eq. (4.2) and Eq. (4.3) exhibit the following difficulties:

1) The error functions have regions of non-differentiability, because the filter coefficients are quantized.
2) The error functions are potentially multimodal, i.e. there may be more than one minimum, so there is a chance that the optimization gets stuck in a local minimum if the optimization method does not have mechanisms to escape local minima.
3) The optimization has to deal with constraints enforced by the stability criterion required for IIR-filters.

DE belongs to the direct search methods, is very simple to implement and use, possesses global optimization capability, and is able to deal with nonlinear as well as mixed-integer optimization problems [5], [6]. Hence it has been chosen for the minimization of the error functions stated in Eq. (4.2) and Eq. (4.3).

The optimization problem in chapter 4 aims to minimize the squared difference of the LP output before and the LP output after the sample rate reduction.

We already mentioned that the optimizers are the coefficients of the LP. For the first order IIR low-pass filter, these coefficients have the form $a_{lp}$ = [1;-(1 -$c_0$); 0] and $b_{lp}$ = [$c_0$, 0, 0], which means that we can optimize over one variable $c_0$ ex [0,1[. The optimization problem has two constraints: First, the IIR LP filter should be stable, i.e., the absolute value of the pole 1 - $c_0$ should be in [0,1]. Secondly, the filter parameters are represented as internal program variables, i.e. the values need to be from the interval [0, 1].

Initialization of the population ($g = 0$): $c_{0i,0} = rand(1) * (c_{0U} - c_{0L}) + c_{0L}$, $i = 1, .., N_p$
Initialization of the optimum $c_{0opt} = c_{01,0}$
**while** $f(\text{modified rate}, c_{0opt}) > \epsilon$ **do**
  **for** every element $i$ of the population **do**
    $r_0 = rand(Np)$
    $r_1 = rand(Np)$
    $r_2 = rand(Np)$
    //Mutation
    $\mathbf{v}_{i,g+1} = c_{0r_0,g} + F(c_{0r_1,g} - c_{0r_2,g})\ (F = 0.85)$
    //Crossover
    $u_{i,g+1} = \begin{cases} v_{i,g+1}, & \text{if} \quad rand(1) \leq CR \\ c_0(i,g), & \text{otherwise.} \end{cases}$
    //Bounce Back
    **if** $u_{i,g+1} > c_{0U}$ **then**
      $u_{i,g+1} = c_{0r_1,g} + rand(1)(c_{0U} - c_{0r_1,g})$
    **end if**
    **if** $u_{i,g+1} < c_{0L}$ **then**
      $u_{i,g+1} = c_{0r_1,g} + rand(1)(c_{0L} - c_{0r_1,g})$
    **end if**
    //Selection
    **if** $f(\text{modified rate}, v) < f(\text{modified rate}, c_0(i))$ **then**
      $c_0(i) = v$
    **end if**
  **end for**
  choose the best $c_{0opt}$ from the new generation
**end while**

**Figure 5.1**: Pseudo code for DE applied to the squelch optimization problem.

From the two constraints, we conclude that $0 < c_0 < 1$. Fig. 5.1 shows the pseudo-code of the DE-algorithm applied to the problem stated in this chapter.

The function to be minimized in Figure 5.1 is f(modified_rate, $c_0$) which is regarded in the SNR-interval [6dB,…,15.5dB].

## 6. RESULTS FOR AMPLITUDE MODULATION

As discussed in chapter 4, we optimize over attack coefficients and release coefficients separately, i.e., we minimize the function f(modified_rate, $c_{0attack}$) and f(modified_rate, $c_{0release}$), then we combine the results to obtain the optimal $c_0$ for both attack and release time. If the DE algorithm of Fig. 5.1 is applied to the A3E and the A1D modes the optimization yields the results depicted in Fig. 6.1 and Fig. 6.2.

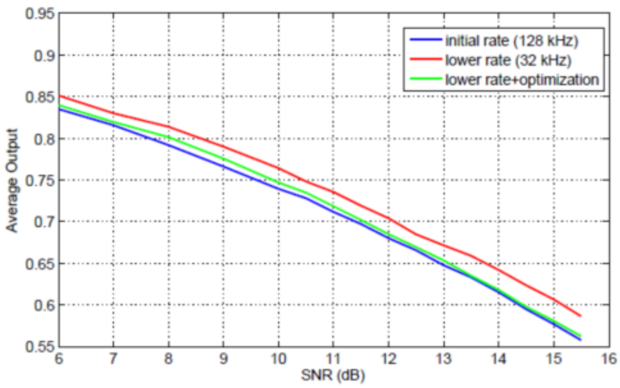


**Figure 6.1**: Average output of the squelch after 5 iterations for A3E and A1D using a population size Np = 5.

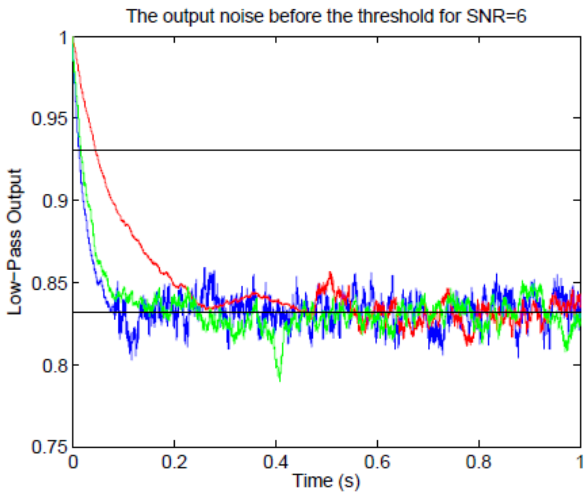


**Figure 6.2**: Lowpass output for SNR=6dB after 5 iterations of DE. Color coding is the same as in Fig. 6.1.

Obviously DE works very well for the optimization in the amplitude modulated modes. Only five iterations are needed to achieve good results.

## 7. RESULTS FOR FREQUENCY MODULATION

For the F3E Mode DE fails to find an optimal solution with optimizing only parameter $c_0$: Figure 7.1 shows the results after 50 iterations. It can be seen that the blue curve to be fitted is not approximated sufficiently.

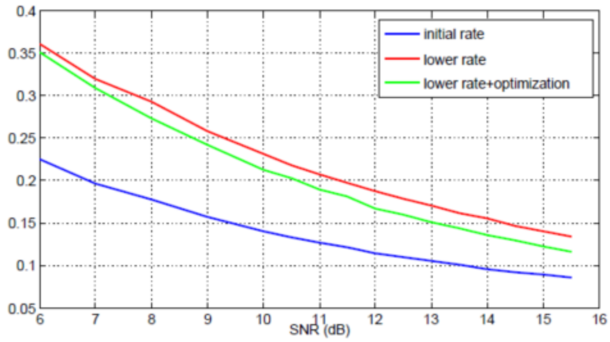


**Figure 7.1**: Optimization result after 50 iterations in case of one parameter $c_{0attack}$ (attack time coefficient) in F3E mode after minimizing f(rate, $c_{0attack}$).

In order to improve the optimization we increase the number of parameters for the frequency modulated modes: we now optimize with respect to $c_0$, the limiter bounds $lim_{min}$ and $lim_{max}$ and the multiplier mul (shown in Fig. 2.1). For this optimization we are faced with a mixed integer optimization problem, because the multiplier coefficients are powers of 2, i.e., the multiplier only performs right or left shifting of the input.

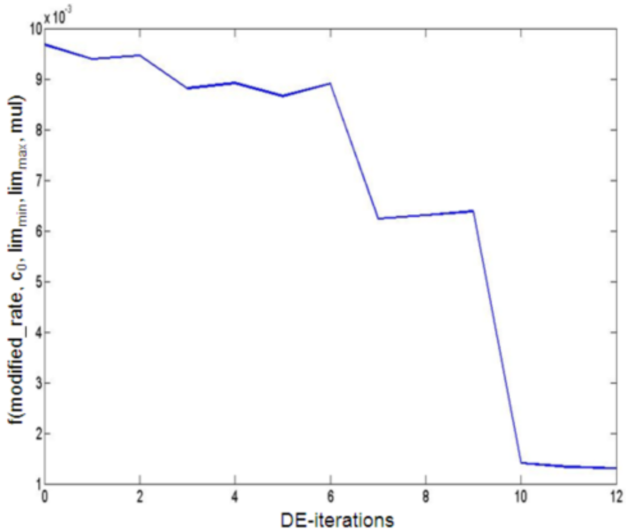


**Figure 7.2**: Convergence graph of the error function f(modified_rate, $c_0$, $lim_{min}$, $lim_{max}$, mul) while being minimized by DE. DE employed a population size Np = 20.

Since DE does not employ any gradient-based techniques the extension of the optimization to accommodate an error function f(modified_rate, $c_0$, $lim_{min}$, $lim_{max}$, mul) with four parameters is straightforward, and the results are depicted in Fig. 7.2, Fig. 7.3 and Fig. 7.4. It is evident that the optimization has been much more effective than in the previous attempt where only one parameter $c_0$ was adjusted.

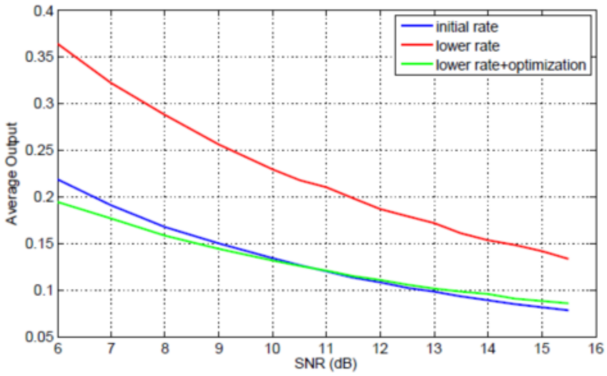


**Figure 7.3**: Optimization result in F3E mode after minimizing f(modified_rate, $c_0$, $lim_{min}$, $lim_{max}$, mul). The optimization took only 12 iterations of DE using a population size of Np = 20.

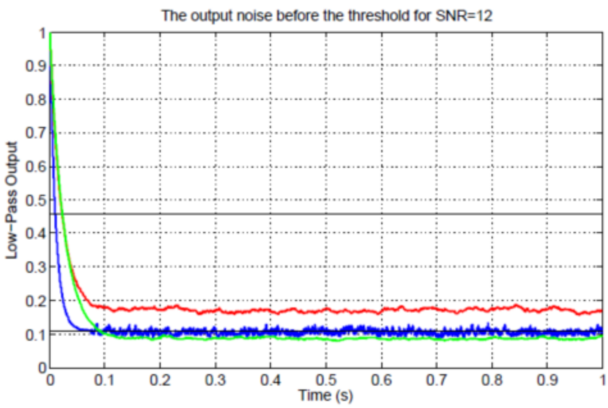


**Figure 7.4**: Lowpass output for SNR=12dB for F3E after minimizing f(modified_rate, $c_0$, $lim_{min}$, $lim_{max}$, mul). Color coding is the same as in Fig. 7.2.

## 8. CONCLUSION

The squelch algorithm of a radio is a component of the auditory user interface and therefore its behavior has direct influence on the acceptance of the radio by the user. If, for example for efficiency reasons, the sequelch algorithm needs to be changed it is very important that the behavior perceivable by the user remains the same. In this contribution it has been demonstrated that it is feasible to alter the squelch algorithm of an established implementation with very little effort while still maintaining its behavior. This was possible using an optimization procedure which is able to cope with nonlinear and mixed integer minimization problems which potentially exhibit multiple minima. The optimization algorithm of choice was Differential Evolution (DE).

## 8. ACKNOWLEDGEMENT

The help of and discussions with R. Arnaoudov are greatfully acknowledged.

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