AERA filters of the RFI in cosmic rays radio detection

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ECRS, Barnaul, July 2018
Filtering by the FFT technique

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FPGA Based Signal-Processing for Radio Detection of Cosmic Rays

Adrian Schmidt, Hartmut Gemmeke, Member, IEEE, Andreas Haungs, Karl-Heinz Kampert, Christoph Rühle, and Zbigniew Szadkowski, Member, IEEE

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IIR filter currently in use

\[ \begin{align*}
y_i &= x_i - (2 \cos \omega_N \cdot x_{i-1}) + x_{i-2} \\
&\quad + (2r \cos \omega_N \cdot y_{i-1}) - (r^2 \cdot y_{i-2}).
\end{align*} \tag{1} \]

The normalized filter frequency \( \omega_N \) is given by the notch frequency \( f_N \) and the sampling frequency \( f_S \),

\[ \omega_N = 2\pi f_N / f_S, \tag{2} \]

and the width parameter \( r \) is a value strictly between 0 and 1, with higher values giving a narrower response function. \( r = 0.99 \) is typical for a narrow transmitter.

Data Acquisition, Triggering, and Filtering at the Auger Engineering Radio Array

J. L. Kelley\(^a\), for the Pierre Auger Collaboration\(^b,1\)

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IIR filter in the field

Extremely efficient, but Non-adaptive
Linear predictor

\[ \hat{s}(i) = \sum_{n=1}^{p} a_n s(i - D - n) \]

\[ e(i) = s(i) - \hat{s}(i) \]

\[ E = \frac{1}{N} \sum_{i=0}^{N-1} e^2(i) = \frac{1}{N} \sum_{i=0}^{N-1} \{s(i) - \hat{s}(i)\}^2 \]
Math. background

\[ \frac{\partial}{\partial a_i} E = 0 \]

\[ \sum_{i=0}^{N-1} s(i - D - n)s(i) = \sum_{i=0}^{N-1} \sum_{m=1}^{p} a_m s(i - n)s(i - m) \]

We can now define the covariances

\[ r^*(n) = \sum_{i=0}^{N-1} s(i - n - D)s(i) \]

\[ R(m, n) \equiv r(|m - n|) = \sum_{i=0}^{N-1} s(i - n)s(i - m) \]
FPGA data flow

FPGA/NIOS Implementation of an Adaptive FIR Filter Using Linear Prediction to Reduce Narrow-Band RFI for Radio Detection of Cosmic Rays

Zbigniew Szadkowski, Member, IEEE, E. D. Fraenkel, and Ad M. van den Berg

First Results from the FPGA/NIOS Adaptive FIR Filter Using Linear Prediction Implemented in the Auger Engineering Radio Array

Zbigniew Szadkowski, Member, IEEE, D. Gla, C. Timmermans, and T. Wijnen, for the Pierre Auger Collaboration
Example of filtered signals - cntd.

- 64 stages in the FIR filter,
- Many narrow band RFI suppressed by the factor of 3 – 5.
Improved FIR

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Adaptive Linear Predictor FIR Filter Based on the Cyclone V FPGA with HPS to Reduce Narrow Band RFI in Radio Detection of Cosmic Rays

Zbigniew Szadkowski, Member, IEEE, and Dariusz Głas

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A Hardware Implementation of the Levinson Routine in a Radio Detector of Cosmic Rays to Improve a Suppression of the Nonstationary RFI

Zbigniew Szadkowski, Member, IEEE for the Pierre Auger Collaboration
FPGA data flow

Covariances

Solving of linear equations – Levinson procedure

\[
r^*(n) = \sum_{i=0}^{N-1} s(i - n - D) s(i)
\]

\[
R(m, n) \equiv r(|m - n|) = \sum_{i=0}^{N-1} s(i - n) s(i - m)
\]
void levinson(double *r, double *y,
  double *x, double *a,
  unsigned int dim)
{
  unsigned int n,i;
  double e,z,xi,temp;

  // initialization step //
  e = r[0];
  a[0] = 1;
  x[0] = y[0]/e;

  // main loop //
  for (n = 1; n < dim; ++n)
  { // calculate xi //
    xi = 0;
    for (i = 0; i < n; ++i)
    { // loop A //
      temp = a[i];
      a[i] = temp + a[n-i] * xi;
      a[n-i] = a[n-i] + temp * xi;
    }
    if (n % 2 == 0)
    { // update a //
      a[n] = a[0] + a[n-i] * xi;
    }
    // calculate e //
    e = e * (1 - xi*xi);
    // calculate 1 //
    z = y[n];
    for (i = 0; i < n; ++i)
    { // loop C //
      temp = z - r[n-i] * x[i];
    }
    // update x //
    x[n] = 0;
    for (i = 0; i < n; ++i)
    { // loop B //
      temp = a[1];
      a[1] = temp + a[0] * xi;
      a[0] = a[0] + temp * xi;
    }
  }

  return;
}

---

**Levinson procedure**

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<table>
<thead>
<tr>
<th>Loop A</th>
<th>Loop B</th>
<th>Loop C</th>
<th>Loop D</th>
</tr>
</thead>
<tbody>
<tr>
<td>n=1</td>
<td>x[i] = 0;</td>
<td>a[1] = 0;</td>
<td>z = y[1];</td>
</tr>
<tr>
<td></td>
<td>x[i] = r[1] * a[0];</td>
<td>a[1] = a[0] * xi;</td>
<td>z = r[1] * x[0];</td>
</tr>
<tr>
<td></td>
<td>x[i] / e;</td>
<td>pm = z/e;</td>
<td>pm = z/e;</td>
</tr>
</tbody>
</table>

| n=2    | x[i] = 0; | a[2] = 0; | z = y[2]; | x[2] = 0; |
|         | x[i] / e; | pm = z/e; | pm = z/e; | x[2] = a[0] * pm; |

| n=3    | x[i] = 0; | a[3] = 0; | z = y[3]; | x[3] = 0; |
|         | x[i] / e; | pm = z/e; | pm = z/e; | x[3] = a[0] * pm; |

| n=4    | x[i] = 0; | a[4] = 0; | z = y[4]; | x[4] = 0; |
|         | x[i] / e; | pm = z/e; | pm = z/e; | } |
Hardware implementation
Adaptive IIR-Notch Filter for RFI Suppression in a Radio Detection of Cosmic Rays

Zbigniew Szadkowski, Member IEEE
4 IIR filters in a cascade way
Normalized Least Mean Square

- Each iteration of LMS algorithm involves:
  - Error estimation: 
    \[ e(i) = d(i) - \sum_{k=0}^{M} h_k(i)x(i - k - D), \]
  - Adaptation of coefficients: 
    \[ h_k(i + 1) = h_k(i) + \mu(i) \cdot e(i) \cdot x(i - k - D), \]
  - Updating of learning factors:
    \[ \mu(i + 1) = \frac{\mu}{\gamma + \sum_{j=0}^{M} x^2(i - j - D)}, \]

Division in the FPGA
A suppression of a single sine carrier for NLMS32 and 5CEFA9F31I7

12. The Least Mean Squares Adaptive FIR Filter for Narrow-Band RFI Suppression in Radio Detection of Cosmic Rays

By: Szadkowski, Zbigniew; Glas, Dariusz
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View Abstract
DLMS

Non-canonical FIR

Cropping of 7 LSB

\[ \mu = 1/32 \]

Additional pipeline + learning factor \( \mu \)
For $\mu = 1/128$, $1/256$ or $1/512$ the mono-carrier is suppressed to ZERO !!!
DLMS – 4mono-carriers

Suppression of 4 sine RFIs for 32-stage FIR ($\mu^{-1}=32,\ldots,256$)

Suppression of 4 sine RFIs for 32-stage FIR ($\mu^{-1}=512,\ldots,4096$)
DLMS – 32- vs. 64 stages

Suppression of RFIs turning on sequentially

Suppression of RFIs turning on sequentially (zoom)
DLMS32 – echoed signals

AERA pattern

A

Amplitude (ADC-units)

1\textsuperscript{st} pulse

2\textsuperscript{nd} pulse

3\textsuperscript{rd} pulse

4\textsuperscript{th} pulse

5\textsuperscript{th} pulse

6\textsuperscript{th} pulse

number of sample

AERA pattern contaminated by the RFI

B

Amplitude (ADC-units)

AERA pattern contaminated by the RFI and cleaned by the Delayed LMS32 algorithm

C

Amplitude (ADC-units)

number of sample
ILMS32
DLMS – measurements
DLMS – Front-End used for tests
DLMS – FM filtering

Spectrum of radio signal in the Łódź laboratory

Spectrum filtered by the FM band-reject filter
DLMS – 4 carriers

Spectrum of 4 mono-carriers

FREQUENCY

Center: 65.00000 MHz
Start: 10.0000 MHz
Stop: 120.000 MHz
TG ATT: 0 dB
TRACKING GEN.

Spectral amplitude (arb. units)

328 μs

0 25 50 75 100 MHz

0 5000 10000 15000 20000 25000 30000 35000 40000

Zbigniew Szadkowski
ECRS, Barnaul, July 2018
DLMS – exact and deviated

Spectrum of 4 mono-carriers

IIR FIXED

DLMS32 - $\mu = 1/32$

IIR FIXED - $f_2 += 1\%$, $f_3 += 0.5\%$
Filtered spectra of ILMS32

ILMS32 filter with $\mu=1/16$

ILMS32 filter with $\mu=1/64$

ILMS32 filter with $\mu=1/256$

ILMS32 filter with $\mu=1/1024$
ILMS32 for $\mu=1/256$, $\mu=1/1024$
IIR filter
\[ DF_{shift} = \sqrt{\frac{\sum_{j=0}^{M} \sum_{k=-12}^{12} (ROM_k - ADC(\text{filtered})_{k+\text{shift}})^2}{25^2 \times M^2}} \]
The first condition, attributed to Butterweck\textsuperscript{1} (1995), states that the convergence necessary condition can be expressed as:

- $0 < \mu < \frac{2}{\lambda_{\text{max}}}$

where $\lambda_{\text{max}}$ is the largest eigenvalue of the autocorrelation matrix $\mathbf{R}$.

\textsuperscript{1}Butterweck H. (1995), \textit{A steady-state analysis of the LMS adaptive algorithm without use of the independence assumption}, Proceedings of ICASSP, pp. 1404–1407
Stability for 2014-2015

rdm_2014_09_03

rdm_2015_03_26

histogram for rdm_2014_09_03

histogram for rdm_2015_03_26
Stability for 2016-2017

rdm_2016_07_20

histogram for rdm_2016_07_20

histogram for rdm_2017_08_02
Conclusions

- The ILMS32 is adaptive in contradiction to the IIR notch currently in use,
- The ILMS32 does not use a division operation as the NLMS. It guarantees faster registered performance and stability,
- For learning factors $\mu = 1/32 – 1/256$ the suppression of multi-carriers is efficient and very fast,
- The converge time is at the level of several microseconds in contradiction to previous FIR filters based on the linear prediction:
  - With FIR coefficients calculated in NIOS (~600 ms),
  - In HPS (20 ms)
  - Directly in the FPGA fabric (as Levinson algorithm) (600 $\mu$s).
- Laboratory measurements fully confirmed very high efficiency of the ILMS

- This ILMS filter as very efficient and adaptive should be tested in the field to be an potential alternative for non-adaptive IIR filter.
Adaptive IIR-Notch Filter for RFI Suppression in a Radio Detection of Cosmic Rays
Zbigniew Szadkowski, Member IEEE

The Least Mean Squares Adaptive FIR Filter for Narrow-Band RFI Suppression in Radio Detection of Cosmic Rays
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