Blind Adaptive Analog Nonlinear Filters for Noise Mitigation in Powerline Communication Systems

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   - Nonlinear vs. linear
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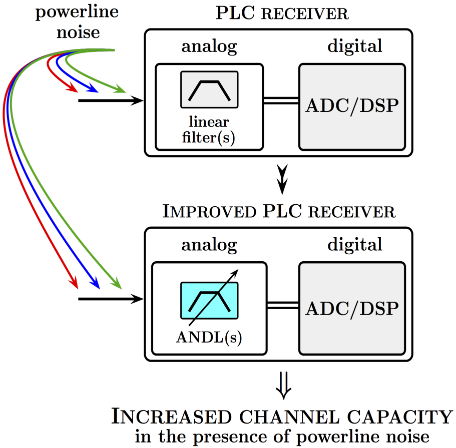
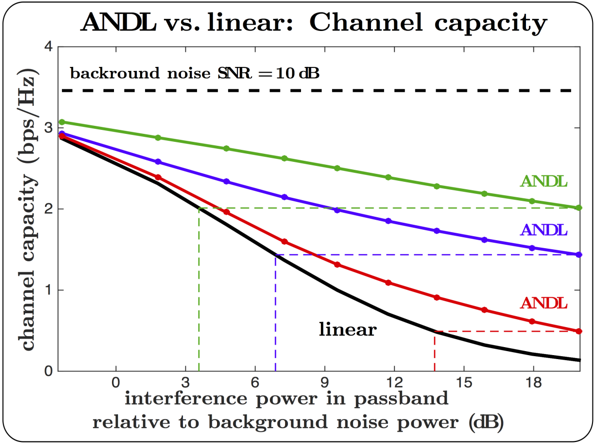
Motivation

PLC receivers resistant to powerline noise





Replacing front-end analog filters in PLC receiver by ANDLs provides resistance to powerline noise

RED, BLUE, or GREEN – different noise compositions

ANDLs vs. linear: Simulations (13/15)

Motivation

Nonlinear vs. linear

- Technogenic (man-made) signals are typically distinguishable from purely random (e.g. thermal)
  - specifically, in terms of amplitude distributions/densities (non-Gaussian)
- At any given frequency, linear filters affect power of both noise and signal of interest proportionally, and cannot improve SNR in passband
- Nonlinear filters can reduce PSD of non-Gaussian interference in passband without significantly affecting signals of interest
  - increasing passband SNR and channel capacity
- Linear filters are converted into Nonlinear Differential Limiters (NDLs) by introducing feedback-based nonlinearities into filter responses
  - NDLs/ANDLs are fully compatible with existing linear devices and systems
  - enhancements/low-cost alternatives for state-of-art interference mitigation methods

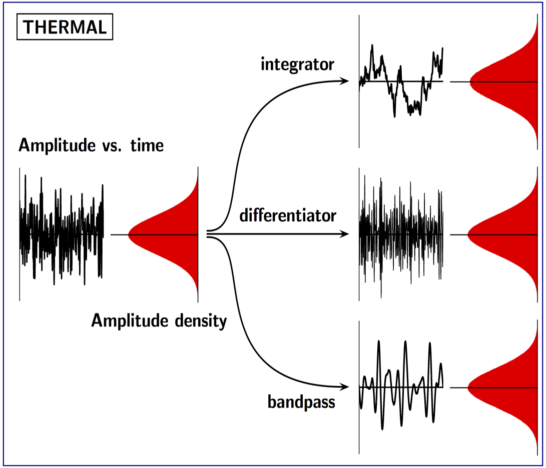
Motivation

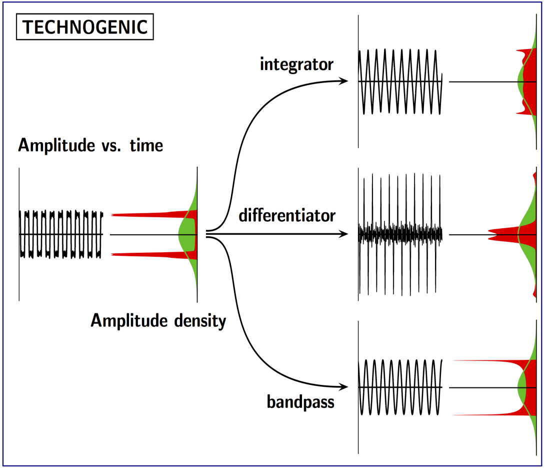
Analog vs. digital and "blind" vs. model-based

- *Digital* filtering is performed after ADC, when bandwidth of signal+interference mixture is reduced and non-Gaussian nature of interference is obscured
  - effectiveness is reduced and memory and DSP burden is exacerbated
- *Analog* NDLs combine bandwidth reduction with mitigation of interference
  - can simply replace respective linear filters in the analog front end
  - provide means to increase effectiveness by modifying peakedness of interference
- Model-based approaches may be limited by parameter estimation schemes
  - e.g. sensitive to inaccuracies in obtaining derivatives
  - may not be robust under a model mismatch
- "Blind" approaches do not rely on underlying noise distribution assumptions

Motivation

Distributional differences between thermal noise and technogenic signals





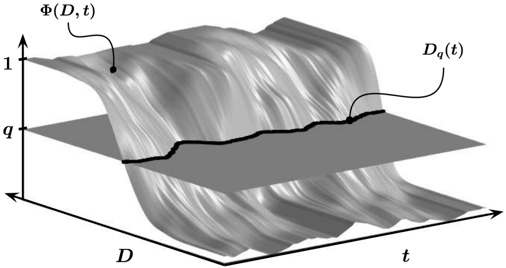
For Gaussian (e.g. thermal) signals, amplitude distribution remains Gaussian regardless of linear filtering

Amplitude distributions of non-Gaussian signals are generally modifiable by linear filtering

Nonlinear Differential Limiters

Theoretical foundation

Proc. R. Soc. Lond. A, 2003, 459(2033):1171-1192



- $\Phi(D,t) = w(t) * \mathcal{F}_{\Delta D}[D - x(t)]$
  - time-dependent amplitude distribution
  - $\mathcal{F}_{\Delta D}(D)$ is *discriminator function*
  - $w(t)$ is time window
- $\Phi(D_q(t),t) = q, \qquad 0 < q < 1$
  - level (contour) curve

$$\frac{\mathrm{d}D_q}{\mathrm{d}t} = -\frac{\partial\Phi(D_q,t)/\partial t}{\partial\Phi(D_q,t)/\partial D_q} + \nu\,[q - \Phi(D_q,t)], \qquad \nu > 0$$

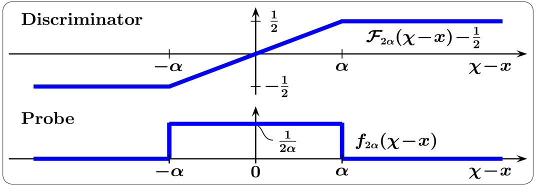
- corresponds to a variety of nonlinear filters with desired characteristics
  - depending on shape of $\mathcal{F}_{\Delta D}(D)$
- e.g. for $q=1/2$ and $\Delta D \to 0$ describes *analog median filter* in time window $w(t)$
  - becomes **linear filter** when $\Delta D \to \infty$

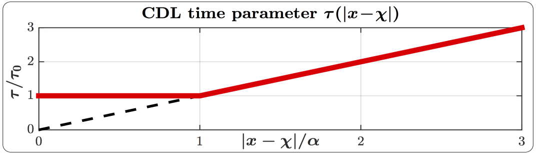
Nonlinear Differential Limiters

1st order Canonical Differential Limiter

$$\dot{\chi}(t) = \lim_{\alpha\to 0} \frac{\frac{1}{2} - \mathcal{F}_{2\alpha}\left[\chi(t) - x(t)\right]}{\int_{-\infty}^{t} ds\, \exp\left(\frac{s-t}{\tau_0}\right) f_{2\alpha}\left[\chi(t) - x(s)\right]}$$

- "true" analog median filter in exponential time window with time constant τ_0
  - $f_{2\alpha}(x) = \mathrm{d}\mathcal{F}_{2\alpha}(x)/\mathrm{d}x$, $\lim_{\alpha\to 0} \mathcal{F}_{2\alpha}(x) = \theta(x)$, and $\lim_{\alpha\to 0} f_{2\alpha}(x) = \delta(x)$





- $\chi = x - \tau(|x - \chi|)\,\dot{\chi}\,,$ where

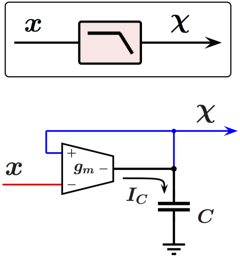
$$\tau(|x-\chi|) = \tau_0 \times \begin{cases} 1 & \text{for } |x - \chi| \leq \alpha \\ \frac{|x-\chi|}{\alpha} & \text{otherwise} \end{cases}$$

- α is **resolution parameter**
- linear 1st order lowpass filter when $\alpha \to \infty$

Nonlinear Differential Limiters

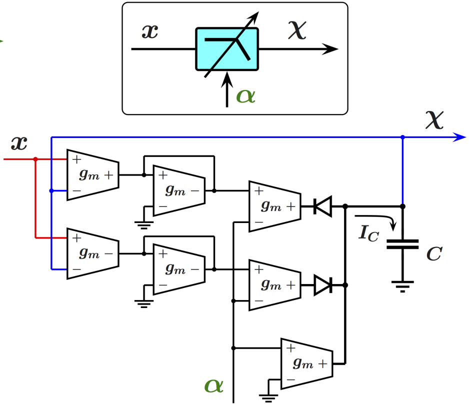
1st order CDL: Implementation

1st order linear



$$I_C = g_m(x - \chi)$$

1st order CDL

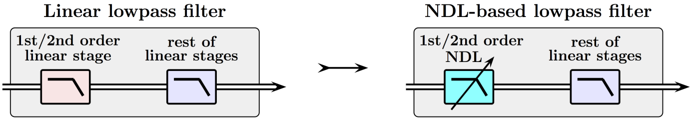


$$I_C = g_m \times \begin{cases} x - \chi & \text{for } |x - \chi| \leq \alpha \\ \alpha \, \text{sign}(x - \chi) & \text{otherwise} \end{cases}$$

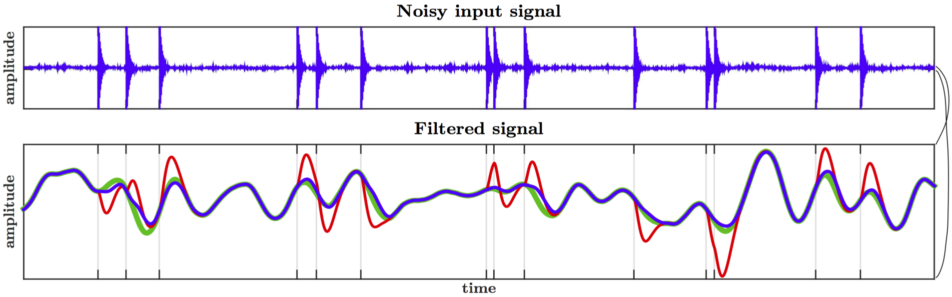
Example of idealized OTA-based implementation topology for 1st order CDL

Nonlinear Differential Limiters

Higher order NDLs



Linear-to-NDL conversion: Replace 1st/2nd order front-end lowpass stage with 1st/2nd order NDL



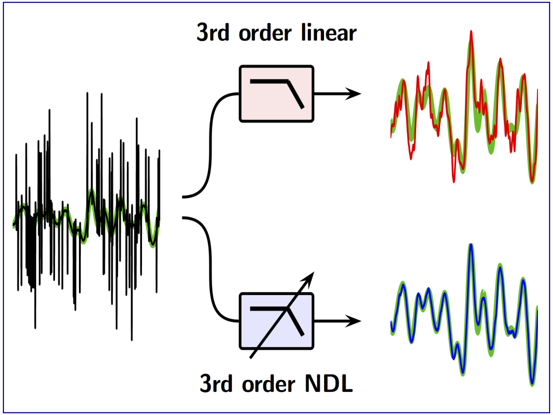
GREEN: Linear/NDL for background noise only RED: Linear 3rd order lowpass BLUE: 3rd order NDL

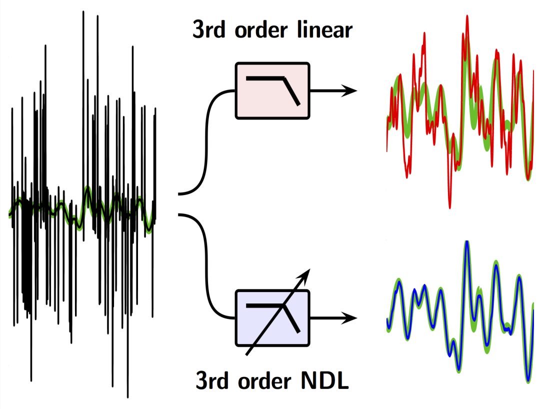
Example for PLC noise (14/15)

Nonlinear Differential Limiters

Higher order NDLs: Nonlinear suppression of impulsive noise

"Disproportional" (nonlinear) suppression of impulsive noise by NDLs



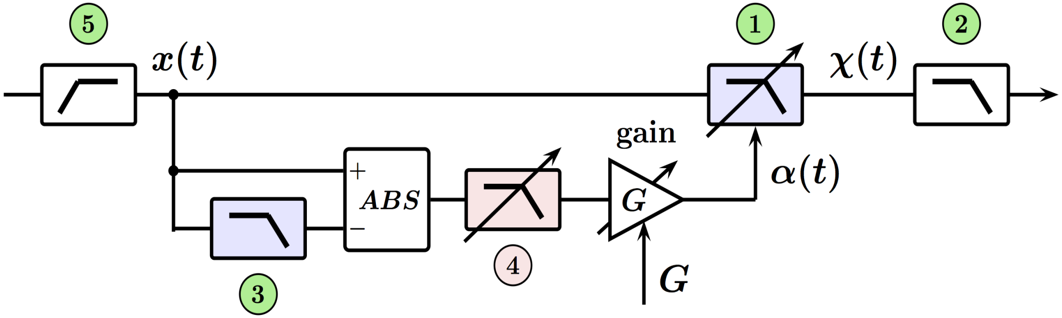


Linear filter: Output noise is proportional to input noise NDL: Output is insensitive to impulsive noise

Nonlinear Differential Limiters

Adaptive NDLs

An ANDL contains a sub-circuit (characterized by a *gain* parameter) that monitors a chosen measure of the signal+noise mixture and provides a time-dependent resolution parameter $\alpha = \alpha(t)$ to the main NDL circuit

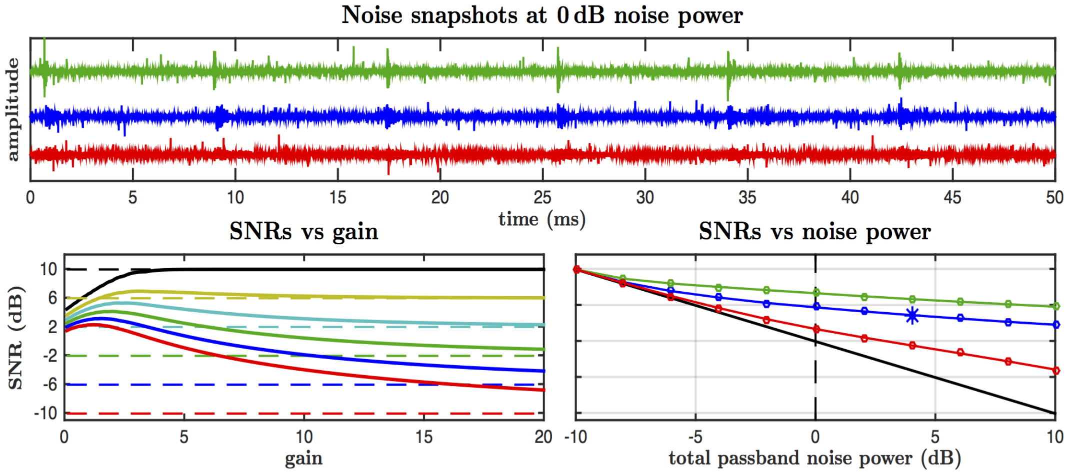


4 1st order CDL with $\tau_0' \sim 10\,\text{ms}$ and $\alpha' \lesssim$ RMS for background noise only

Example for PLC: $\alpha(t)$ corresponds to magnitude of difference signal for background noise only

ANDLs in PLC systems

Qualitative illustration of powerline noise mitigation

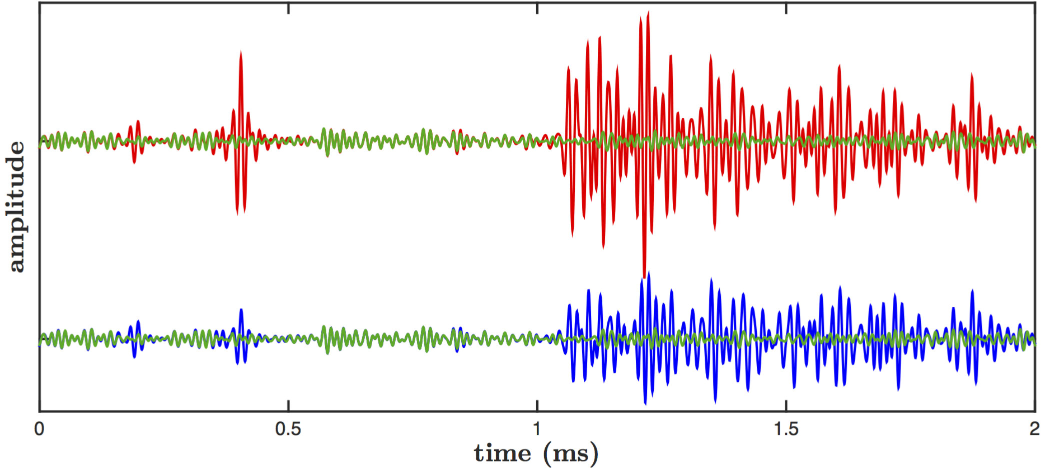


RED – “wide” ($\sim$2.5 ms), BLUE – “mid-range” ($\sim$500 μs), and GREEN – “narrow” ($\sim$100 μs) cyclostationary noise bursts

▸ PLC receivers resistant to powerline noise (3/15)

ANDLs in PLC systems

Example of signal traces



GREEN: Without/with NDL for background noise only RED: Without NDL BLUE: With NDL

Higher order NDLs (10/15)

ANDLs in PLC systems

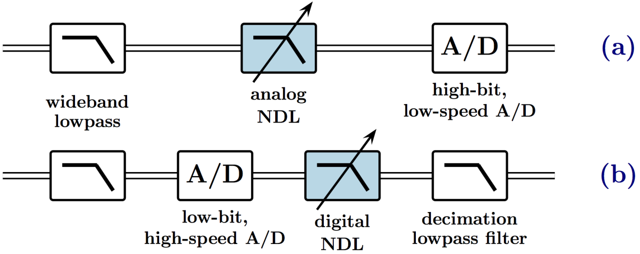
NDLs' ability to disproportionally reduce PSD of impulsive noise in signal passband provides opportunity for noise mitigation in PLC systems that deserves further investigation

NDLs/ANDLs:

- combine bandwidth reduction (e.g. when used as anti-aliasing filters) with mitigation of interference
- can be used as **enhancement** or **alternative** to other interference mitigation methods
- can be implemented in both **analog** and **digital** forms
- have appealing methodological advantages

Appendix I
Digital NDLs/ANDLs

- NDLs/ANDLs are *analog* filters
  - combine bandwidth reduction with mitigation of interference
- Also allow for near-real-time finite-difference (digital) implementations
  - relatively simple
  - computationally inexpensive
  - low memory requirements
- Digital NDLs/ANDLs require high sampling rates
  - should use multi-rate processing



Analog (a) and digital (b) NDL/ANDL deployments

Appendix II: References to NDL-related work

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