Adaptive Analog Nonlinear Algorithms and Circuits for Improving Signal Quality in the Presence of Technogenic Interference

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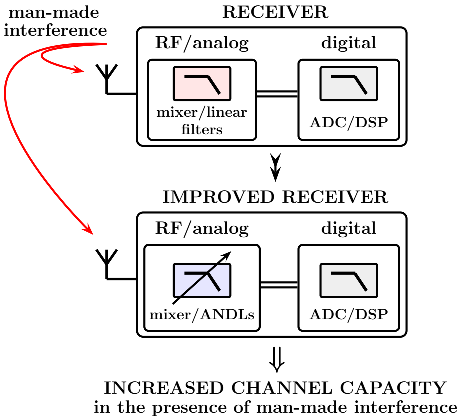
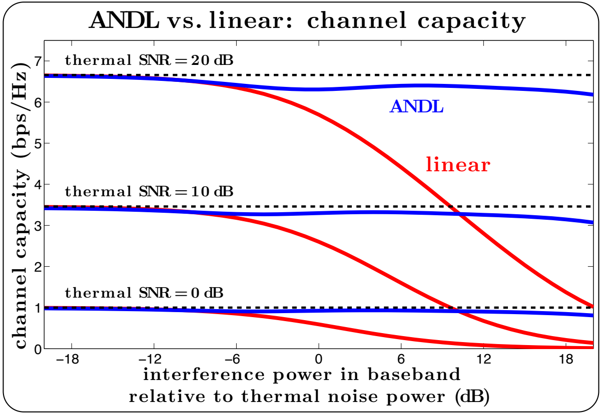
Motivation

Communications receivers resistant to technogenic interference





Replacing certain analog filters in communications receiver by ANDLs provides resistance to man-made interference

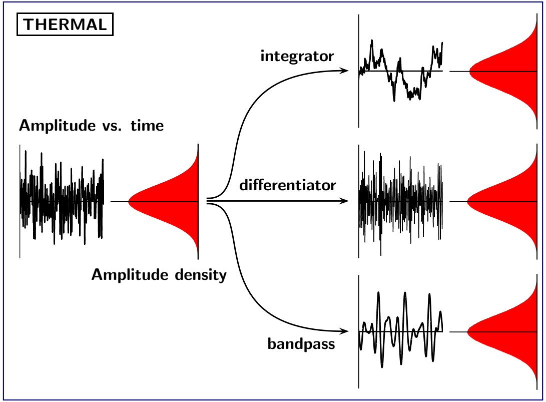
▸ ANDLs vs. linear: baseband SNR (14/15)

Motivation

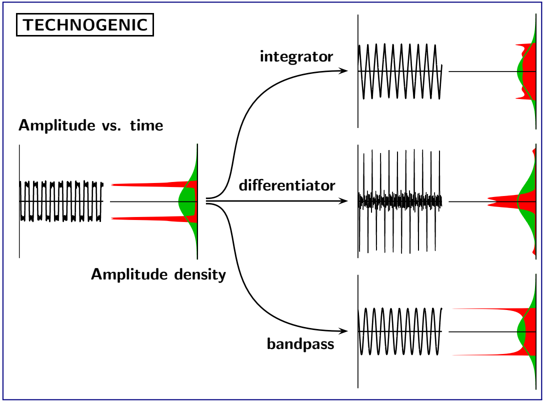
Nonlinear vs. linear: The rationale

- 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 to state-of-art interference mitigation methods

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

Distributional differences between thermal noise and technogenic signals

Measures of peakedness

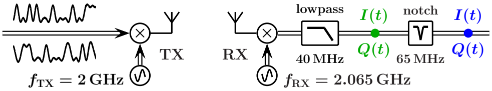
Convenient measure of *peakedness* for $z(t) = I(t) + \mathrm{i}Q(t)$:

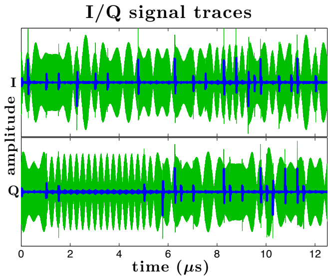
$$K_{\mathrm{dBG}}(z) = 10 \lg \left(\frac{\langle |z|^4 \rangle - |\langle zz \rangle|^2}{2\langle |z|^2 \rangle^2} \right)$$

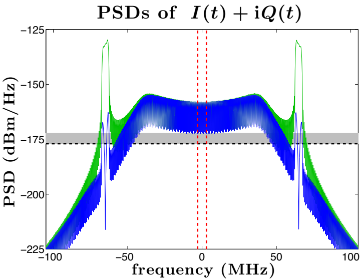
- angular brackets denote time averaging
- based on definition of *kurtosis* for complex variables
- "decibels relative to Gaussian" (dBG) – in relation to Gaussian distribution
- K_{dBG} vanishes for Gaussian distribution
- $K_{\mathrm{dBG}} < 0$ for sub-Gaussian, $K_{\mathrm{dBG}} > 0$ for super-Gaussian
- high peakedness $\Rightarrow$ frequent occurrence of outliers (impulsive)

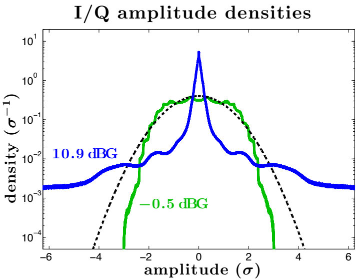
Distributional differences between thermal noise and technogenic signals

Practical example of increasing peakedness







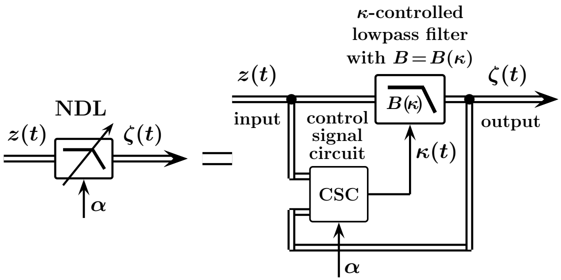


Green lines and text: before notch **Blue lines and text:** after notch

Notch filter reduces sub-Gaussian part of interference without affecting signal of interest and/or PSD of mpulsive interference around baseband, enabling its effective mitigation by NDLs

Nonlinear Differential Limiters (NDLs)

NDLs are designed for mitigation of impulsive interference
(i.e. characterized by relatively high occurrence of outliers)



Block diagram of Nonlinear Differential Limiter

Example of sub-circuit topologies (11/15)

- Dynamic modification of filter bandwidth based on magnitude of difference signal $z(t) - \zeta(t)$
- "Bandwidth" B of NDL = bandwidth of linear filter with same coefficients
  - just convenient computational proxy
- B is non-increasing function of $|z - \zeta|$
  - monotonically decreasing for $|z - \zeta| > \alpha$
  - α is resolution parameter
- Linear filter when $\alpha \to \infty$

Nonlinear Differential Limiters (NDLs)

2nd order NDL example

$\zeta(t) = z(t) - \tau\,\dot{\zeta}(t) - (\tau Q)^2\,\ddot{\zeta}(t)$ – second order linear lowpass filter

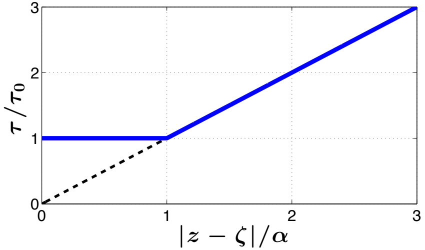
- τ is time parameter, Q is quality factor
- "bandwidth" is *decreasing* function of τ, *increasing* function of Q

Constant-Q NDL:

$$\tau(|z-\zeta|) = \tau_0 \times \begin{cases} 1 & \text{for } |z-\zeta| \le \alpha \\ \left(\frac{|z-\zeta|}{\alpha}\right)^{\beta} & \text{otherwise} \end{cases}$$

- $\beta > 0$
- Canonical Differential Limiter (CDL) for $\beta = 1$
- Differential over-Limiter (DoL) for $\beta > 1$

CDL time parameter $\tau(|z-\zeta|)$

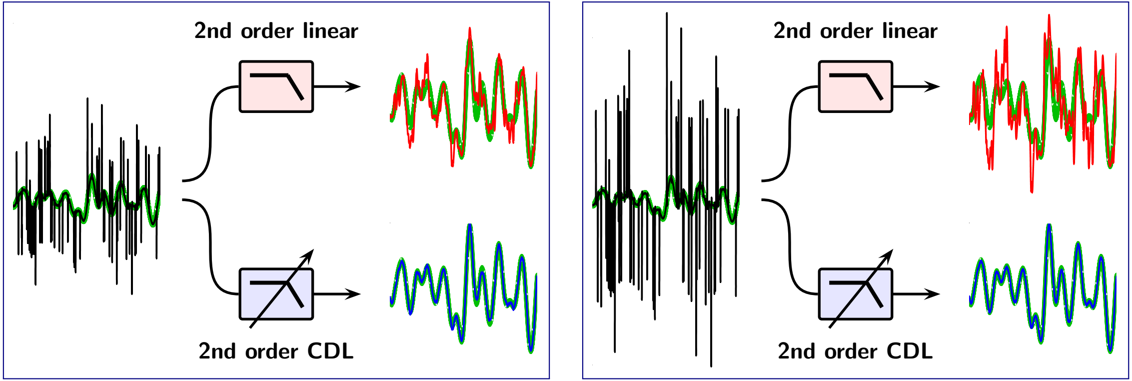


More on NDLs: US patent 8,489,666 (16 July 2013)

Nonlinear Differential Limiters (NDLs)

2nd order CDL: 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

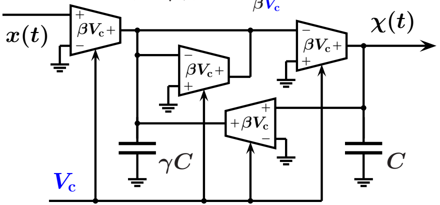
Nonlinear Differential Limiters (NDLs)

Example of sub-circuit topologies

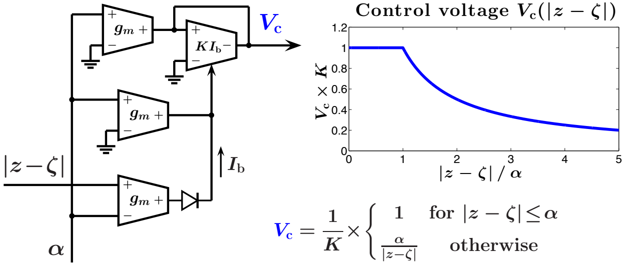
OTA-based 2nd order CDL

$$\chi(t) = x(t) - \tau\,\dot{\chi}(t) - (\tau Q)^2\,\ddot{\chi}(t)$$

$$Q = \sqrt{\gamma}\,, \quad \tau = \frac{C}{\beta V_c}$$



Voltage-controlled 2nd order lowpass



$$V_c = \frac{1}{K} \times \begin{cases} 1 & \text{for } |z-\zeta| \le \alpha \\ \frac{\alpha}{|z-\zeta|} & \text{otherwise} \end{cases}$$

CDL control voltage circuit

Nonlinear Differential Limiters (8/15)

Adaptive NDLs (ANDLs)

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

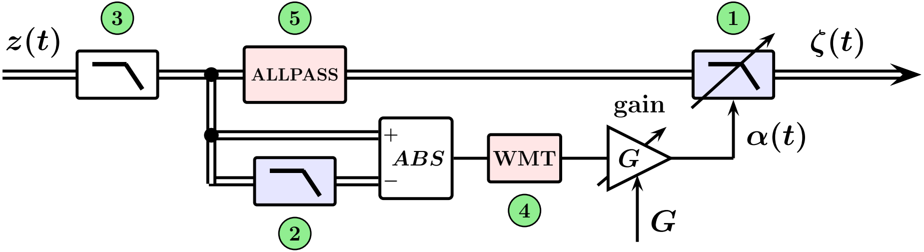
- suitable for improving quality of non-stationary signals under time-varying noise conditions

More on NDLs/ANDLs:

- Nikitin AV: **Method and apparatus for signal filtering and for improving properties of electronic devices.** WO 2013/151591 (10 October 2013)
- This MILCOM'13 paper
- http://www.avatekh.com

Adaptive NDLs (ANDLs)

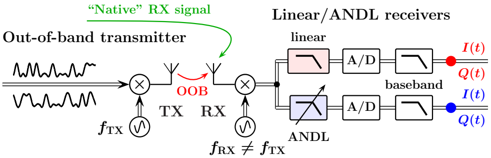
ANDL example

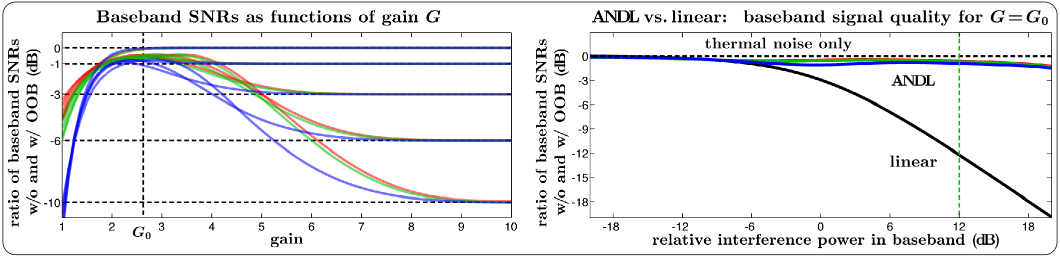


1. 2nd order constant-Q DoL ($\beta = 2$) with $\tau_0 = \frac{1}{2\pi f_0}$
2. 2nd order lowpass with $\tau = \tau_0$ (same Q)
3. Higher-order lowpass with $\tau \ll \tau_0$
4. WSMR circuit w/ 2nd order Bessel window ($\tau_b = 2\tau_0/\sqrt{3}$, $Q = 1/\sqrt{3}$)
5. Allpass with delay $2\tau_0$

Adaptive NDLs (ANDLs)

ANDLs at work



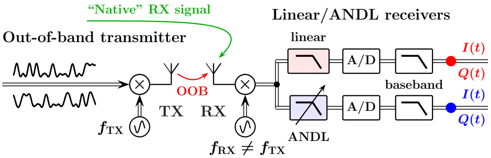


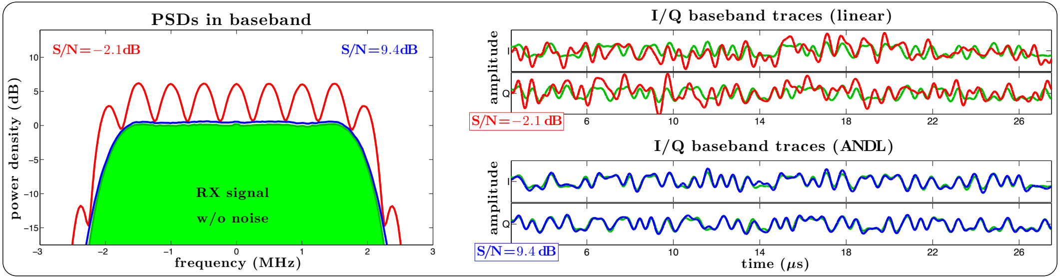
RED: 0 dB thermal SNR GREEN: 10 dB thermal SNR BLUE: 20 dB thermal SNR

Communications receivers resistant to man-made interference (3/15)

Adaptive NDLs (ANDLs)

ANDLs at work



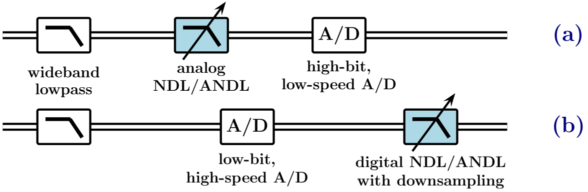


LEFT: Interference PSD reduction in passband **RIGHT:** Baseband time domain I/Q traces

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 relevant work

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Out-of-band and adjacent-channel interference reduction by analog nonlinear filters
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