Blind adaptive nonlinear filters for mitigation of man-made noise in communication systems

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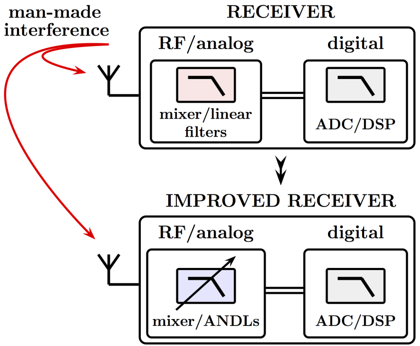
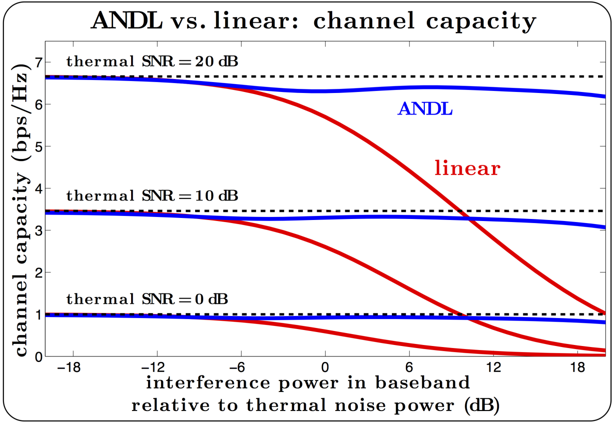
Motivation

Communications receivers resistant to technogenic interference



INCREASED CHANNEL CAPACITY
in the presence of man-made interference



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

▸ ANDLs vs. linear: baseband SNR (18/30)

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

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

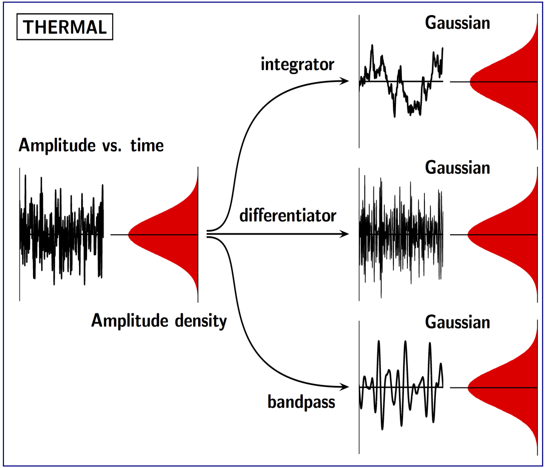
– Model-based approaches may be limited by parameter estimation schemes

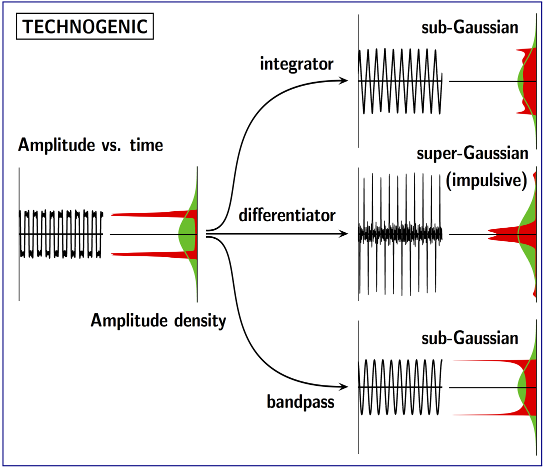
- e.g. sensitive to inaccuracies in obtaining derivatives
- may not be robust under a model mismatch

\+ "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

Motivation

Measures of peakedness

Various measures/statistics can be used

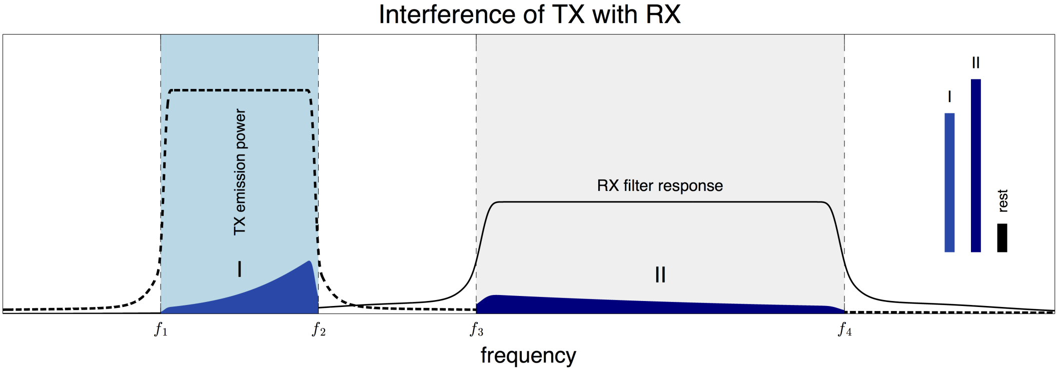
Measure of *peakedness* for $z(t) = I(t) + \mathrm{i}Q(t)$ used in this presentation:

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

- 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)

Motivation

Example: Interchannel interference *EURASIP J Adv. Signal Process.* (2011:137, 2012:79, and 2015:12)



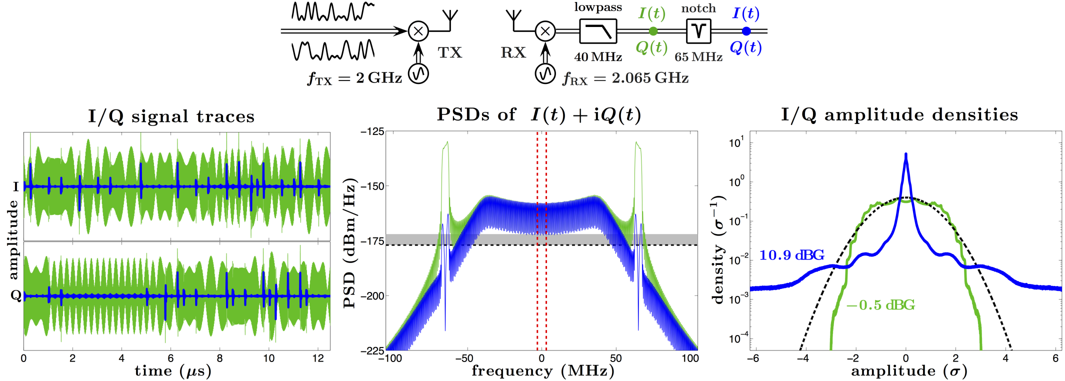
Qualitative illustration of different contributions into the interference which a receiver (RX) experiences from a transmitter (TX)

TX OOB interference in the RX channel (part II of the total interference) can appear impulsive under a wide range of conditions, and can degrade the RX communication signal as it raises the noise floor in the RX band

Increasing peakedness (9/30)

Motivation

Peakedness and interchannel interference



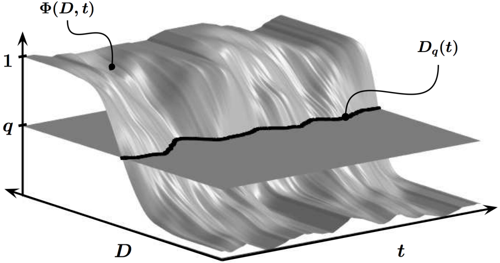
Green lines and text: before notch **Blue lines and text:** after notch

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

▸ TX RX interference (8/30)

Nonlinear Differential Limiters (NDLs)

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



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

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

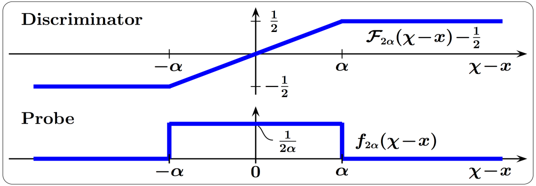
- corresponds to a variety of nonlinear filters with desired characteristics
  - depending on shape of $\mathcal{F}_{\Delta D}(D)$
- e.g. for $q = 1/2$ and $\Delta D \to 0$ describes *analog median filter* in time window $w(t)$
  - becomes **linear filter** when $\Delta D \to \infty$

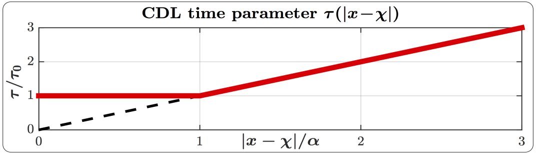
Nonlinear Differential Limiters

1st order Canonical Differential Limiter

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

- "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

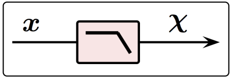
$$\tau(|x-\chi|) = \tau_0 \times \begin{cases} 1 & \text{for } |x-\chi| \le \alpha \\ \frac{|x-\chi|}{\alpha} & \text{otherwise} \end{cases}$$

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

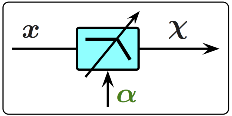
Nonlinear Differential Limiters

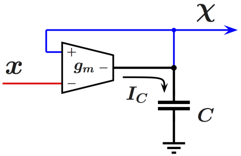
1st order CDL: Implementation

1st order linear

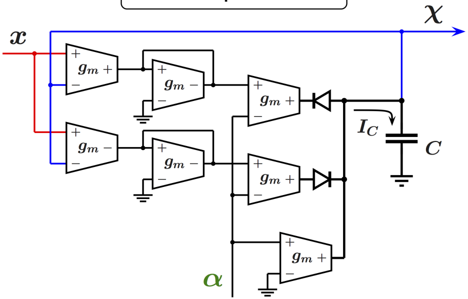


1st order CDL





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

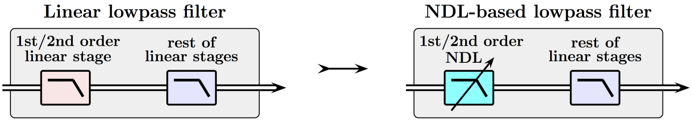


$$I_C = g_m \times \begin{cases} x - \chi & \text{for } |x - \chi| \leq \alpha \\ \alpha \,\mathrm{sign}(x - \chi) & \text{otherwise} \end{cases}$$

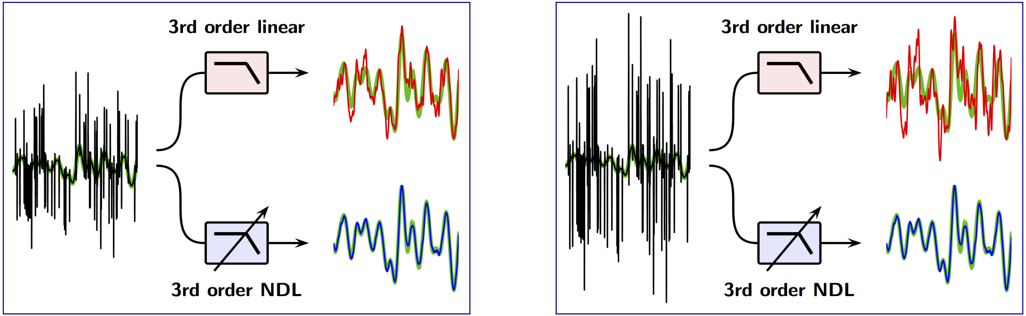
Example of idealized OTA-based implementation topology for 1st order CDL

Nonlinear Differential Limiters

Higher order NDLs



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



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

Nonlinear Differential Limiters

Adaptive NDLs (ANDLs)

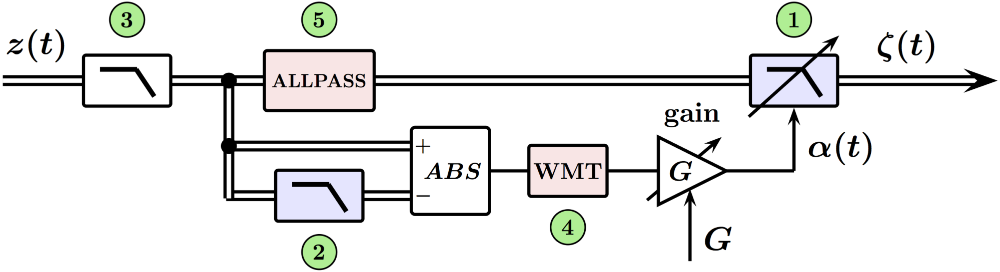
An ANDL contains a sub-circuit (characterized by a *gain* parameter) that monitors a chosen measure of the signal+noise mixture and provides a time-dependent resolution parameter $\alpha = \alpha(t)$ to the main NDL circuit

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

More on NDLs/ANDLs:

- **Out-of-band and adjacent-channel interference reduction by analog nonlinear filters.** *EURASIP J Adv. Signal Process.*, 2015, 2015:12
- **Adaptive analog nonlinear algorithms and circuits for improving signal quality in the presence of technogenic interference.** In: *Proc. IEEE Military Communications Conference* (MILCOM 2013), San Diego, CA, 18-20 November 2013
- **Blind Adaptive Analog Nonlinear Filters for Noise Mitigation in Powerline Communication Systems.** In: *Proc. IEEE International Symposium on Power Line Communications and Its Applications* (ISPLC 2015), Austin, TX, March 29-31, 2015
- **US Patents 8,489,666 and 8,990,284** **US Patent Application Publications 2013/0339418 and 2014/0195577**

Nonlinear Differential Limiters
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 $2\tau_0$

Digital ANDL (25/30)

Nonlinear Differential Limiters

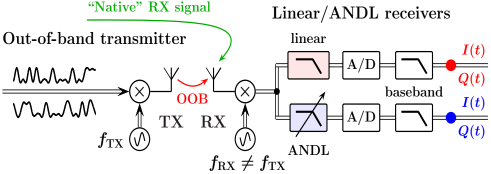
ANDLs at work: “Disproportional” (nonlinear) suppression of impulsive noise by ANDLs

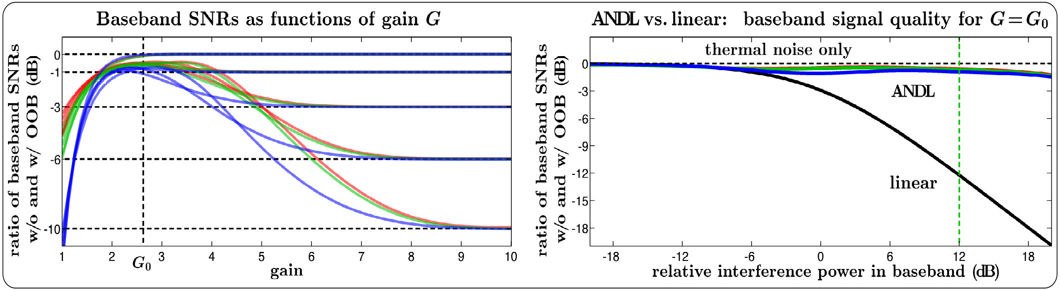
Nonlinear Differential Limiters

ANDLs at work: ANDL suppression of sub-Gaussian noise

Nonlinear Differential Limiters

ANDLs at work: Mitigation of out-of-band interference – SNRs



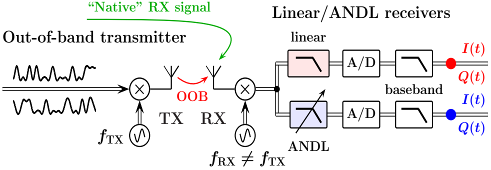


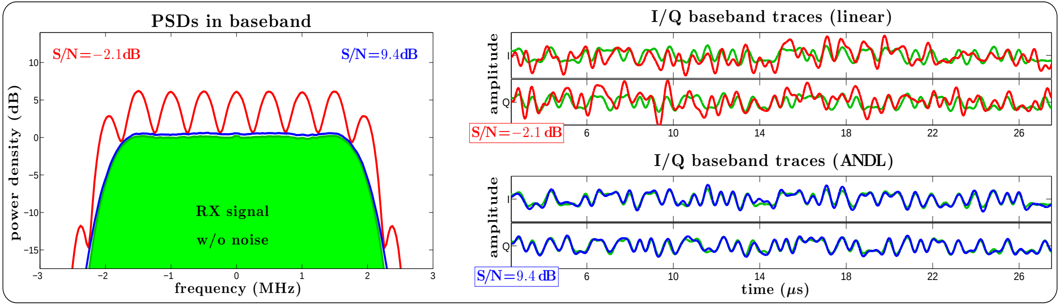
RED: 0 dB thermal SNR GREEN: 10 dB thermal SNR BLUE: 20 dB thermal SNR

Communications receivers resistant to man-made interference (3/30)

Nonlinear Differential Limiters

ANDLs at work: Mitigation of out-of-band interference – PSDs and signal traces

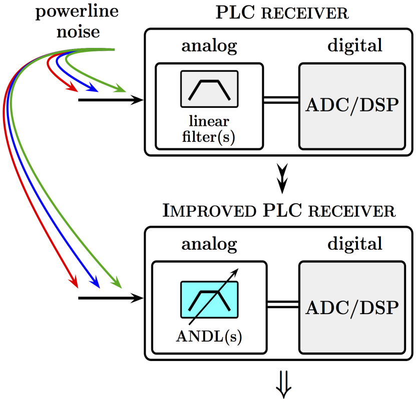




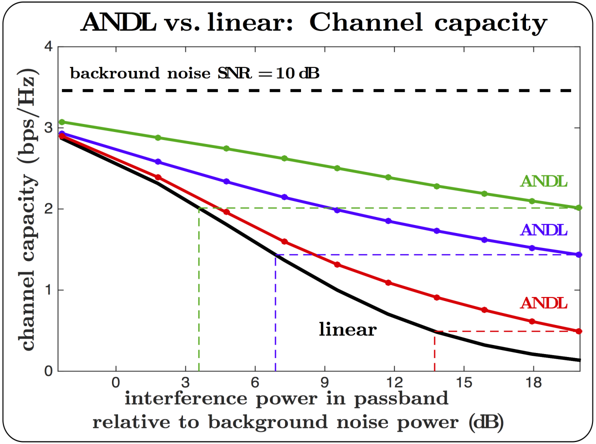
LEFT: Interference PSD reduction in passband **RIGHT:** Baseband time domain I/Q traces

Nonlinear Differential Limiters

ANDLs at work: PLC receivers resistant to powerline noise



INCREASED CHANNEL CAPACITY
in the presence of powerline noise



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

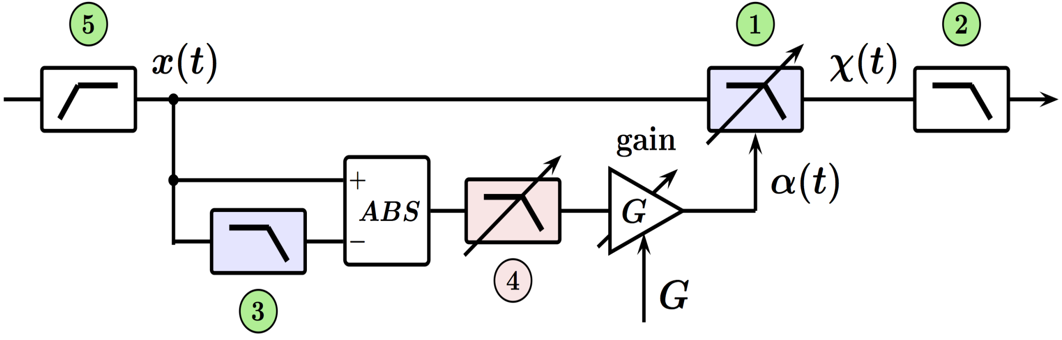
RED, BLUE, or GREEN – different noise compositions

ANDLs vs. linear: Simulations (22/30)

Nonlinear Differential Limiters

ANDLs at work: Example for PLC systems

Due to cyclostationary nature of PLC noise delay is not necessary, WMT circuit can be simplified, and filter is real-valued:

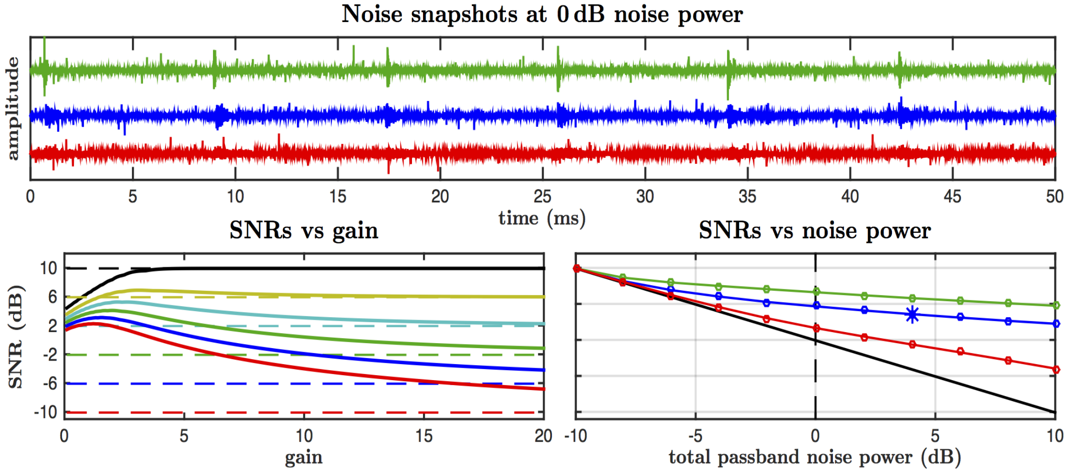


4 1st order CDL with $\tau_0' \sim 10\,\mathrm{ms}$ and $\alpha' \lesssim$ RMS for background noise only

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

Nonlinear Differential Limiters

ANDLs at work: Powerline noise mitigation – SNRs

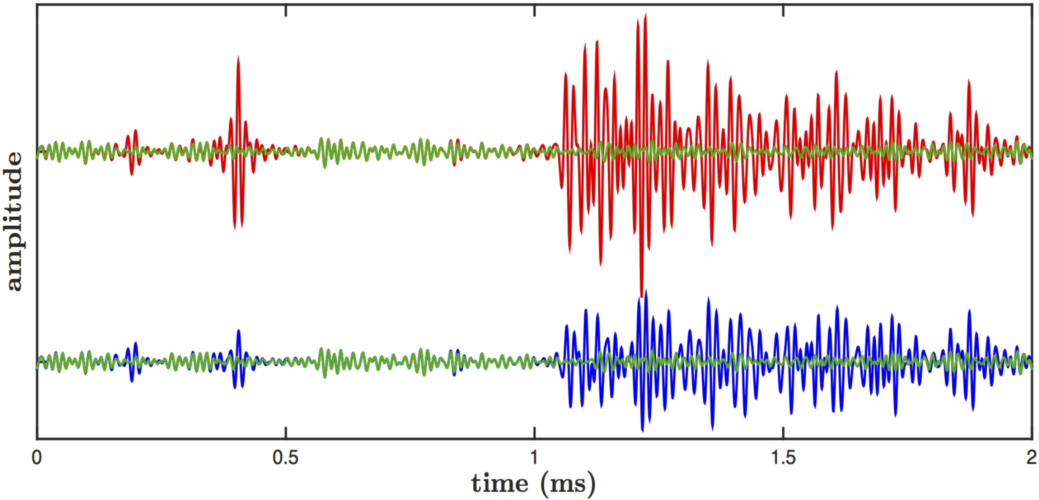


RED – "wide" ($\sim$2.5 ms), BLUE – "mid-range" ($\sim$500 μs), and GREEN – "narrow" ($\sim$100 μs) cyclostationary noise bursts

▸ PLC receivers resistant to powerline noise (20/30)

Nonlinear Differential Limiters

ANDLs at work: Powerline noise mitigation – Example of signal traces

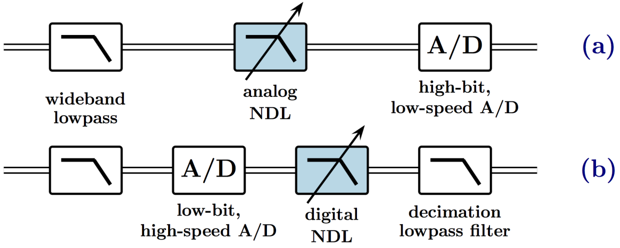


GREEN: Without/with NDL for background noise only RED: Without NDL BLUE: With NDL

Digital NDLs/ANDLs

Digital implementations of conceptually analog filters

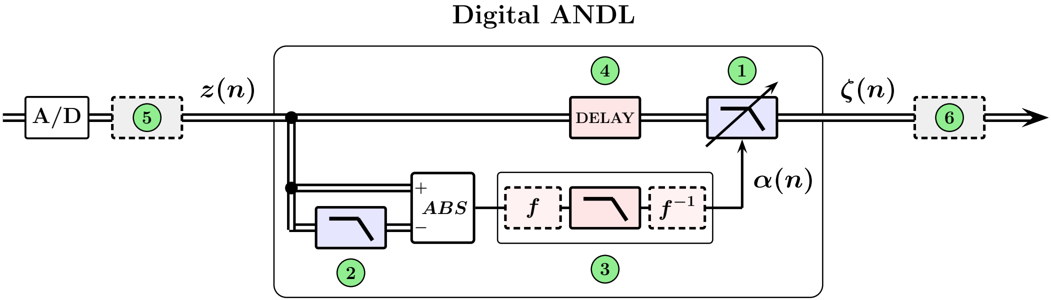
- NDLs/ANDLs are conceptually *analog* filters
  - combine bandwidth reduction with mitigation of interference
- Also allow for near-real-time finite-difference (digital) implementations
  - relatively simple
  - computationally inexpensive
  - low memory requirements
- Digital NDLs/ANDLs require high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



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

Digital NDLs/ANDLs

Digital ANDL example

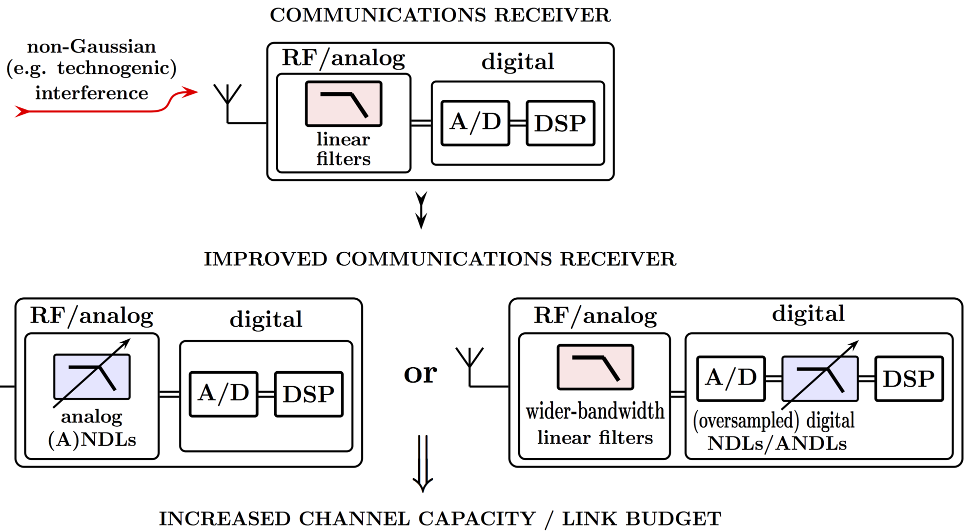


1. Digital NDL
2. Linear lowpass filter equivalent to NDL with $\alpha \to \infty$
3. WMT module
4. Digital delay line (to compensate for WMT delay)
5. Optional linear filter to increase peakedness (e.g. notch)
6. Equalization / decimation

Analog ANDL (15/30)

Digital NDLs/ANDLs

Communications receivers resistant to technogenic interference: Analog and/or digital implementations



Summary

NDLs/ANDLs' ability to preferentially reduce PSD of man-made noise in signal passband provides opportunity for noise mitigation in various communication systems that deserves further development

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

Summary: Impacts

- **Technology for real-time mitigation of ambient and intentional interference to increase capacity and link budget of communication channels**
  - when non-Gaussian (e.g. technogenic) interference is present
  - with impacts ranging from "no harm" for purely thermal noise to orders of magnitude increase in throughput/link budget when man-made noise dominates
  - does not impact usage of other techniques for maximizing channel throughput (e.g. turbo codes)
  - does not noticeably affect SWaP-C and/or other requirements
- **Impacts communications systems by improving capacity/link budget in channels that are concerned with performance constraints in the presence of competing signals (ambient or intentional interference)**
  - including co-channel, co-site and out-of-band wideband interference in various wireless and wireline environments
  - can leverage various programs concerned with capacity constraints of communications systems affected by interfering signals
  - can improve quality of other communications (e.g. audio)

Summary: References to NDL-related work

Nikitin AV, Davidchack RL, Smith JE
Out-of-band and adjacent-channel interference reduction by analog nonlinear filters
EURASIP J Adv. Signal Process., 2015, 2015:12

Nikitin AV, Scutti D, Natarajan B, Davidchack RL
Blind adaptive analog nonlinear filters for noise mitigation in powerline communication systems
In *Proc. IEEE International Symposium on Power Line Communications and Its Applications* (ISPLC 2015), Austin, TX, March 29-31, 2015

Nikitin AV, Davidchack RL, Sobering TJ
Adaptive analog nonlinear algorithms and circuits for improving signal quality in the presence of technogenic interference
In *Proc. IEEE Military Communications Conference* (MILCOM 2013), San Diego, CA, 18-20 November 2013

Nikitin AV
Method and apparatus for signal filtering and for improving properties of electronic devices
US Patents 8,489,666 and 8,990,284 US Patent Application Publications 2013/0339418 and 2014/0195577

Nikitin AV, Epard M, Lancaster JB, Lutes RL, Shumaker EA
Impulsive interference in communication channels and its mitigation by SPART and other nonlinear filters
EURASIP J Adv. Signal Process., 2012, 2012:79

Nikitin AV
On the interchannel interference in digital communication systems, its impulsive nature, and its mitigation
EURASIP J Adv. Signal Process., 2011, 2011:137

Nikitin AV, Davidchack RL
Signal analysis through analog representation
Proc. R. Soc. Lond. A, 2003, 459(2033):1171-1192

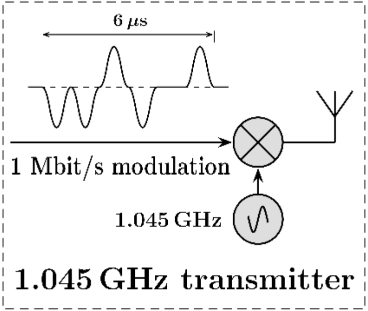
Appendices

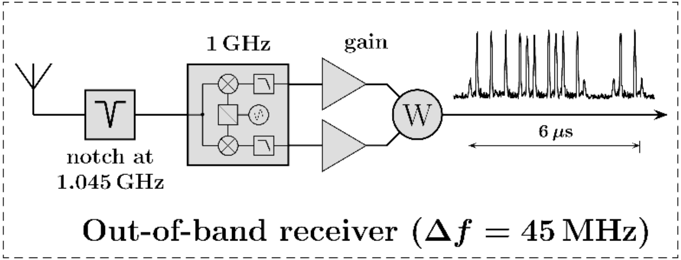
Experimental examples from prior work

- Peakedness of interchannel EMI
- Throughput of 1.95 GHz HSDPA with 2.4 GHz WiFi interference
- Mitigating impulsive EMI in GPS

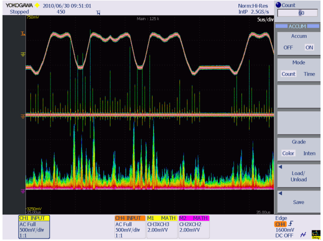
Experimental examples from prior work

Appendix I: Illustrative measurement for impulsive nature of OOB interference (at IEEE RWS 2011)



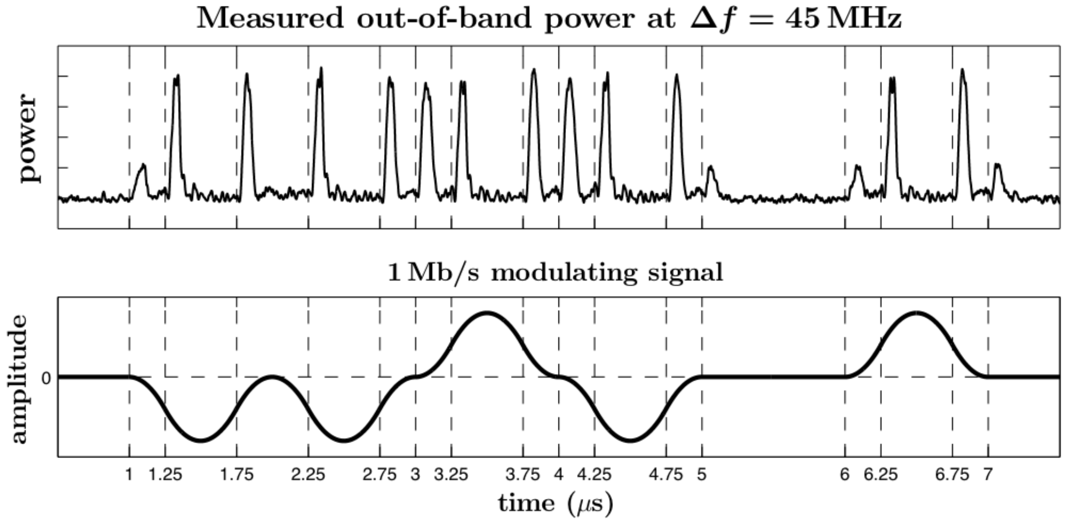


- Transmit a tone modulated by a ‘smooth’-looking message
- Observe instantaneous power in an out-of-band receiver
  - impulsive pulse train



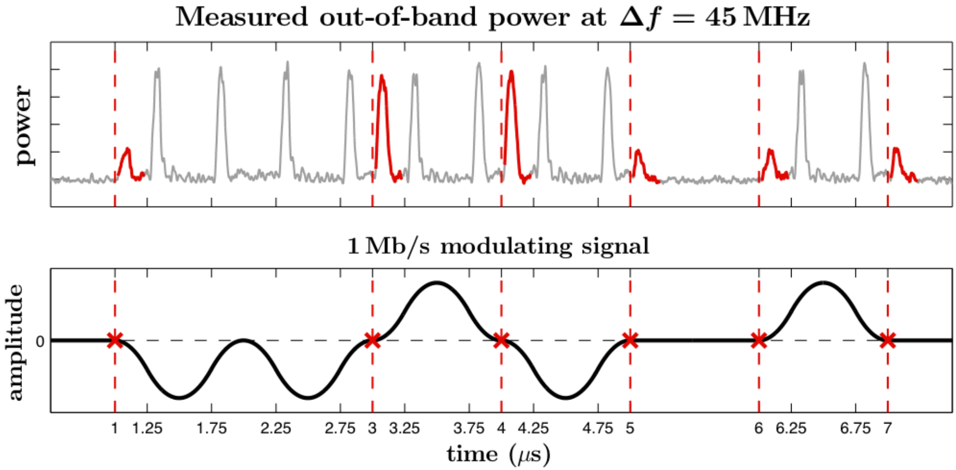
Experimental examples from prior work

Appendix I: Illustrative measurement: Signal traces



Experimental examples from prior work

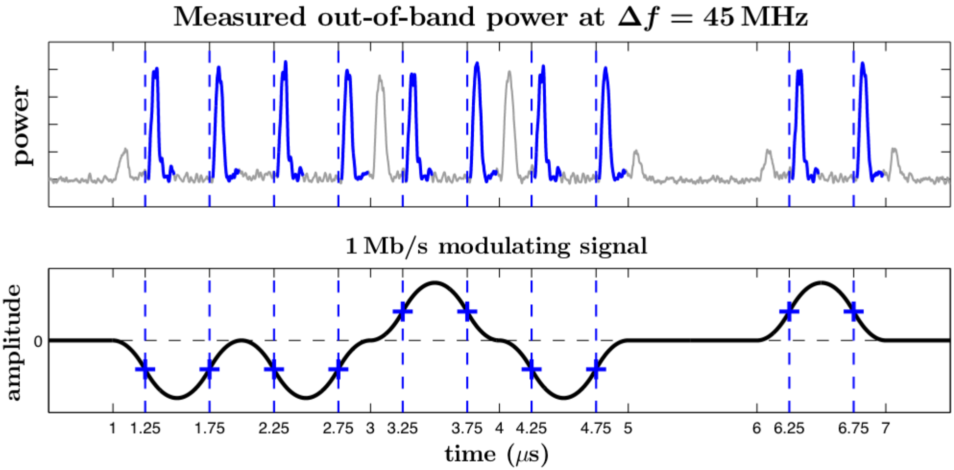
Appendix I: Illustrative measurement: Signal traces



- Some peaks originate at zero modulation amplitude
  - at onsets and ends of modulating pulses

Experimental examples from prior work

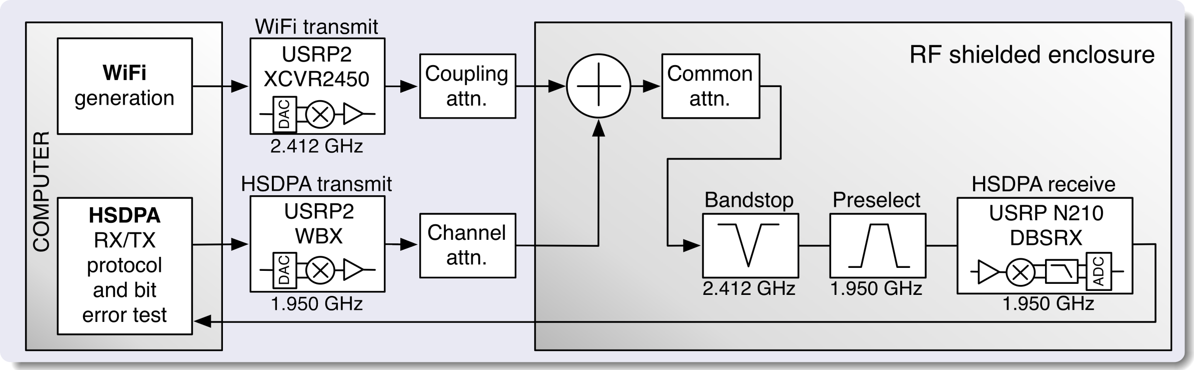
Appendix I: Illustrative measurement: Signal traces



- Others originate at 'smoothest', most linear parts of modulating pulses

Experimental examples from prior work

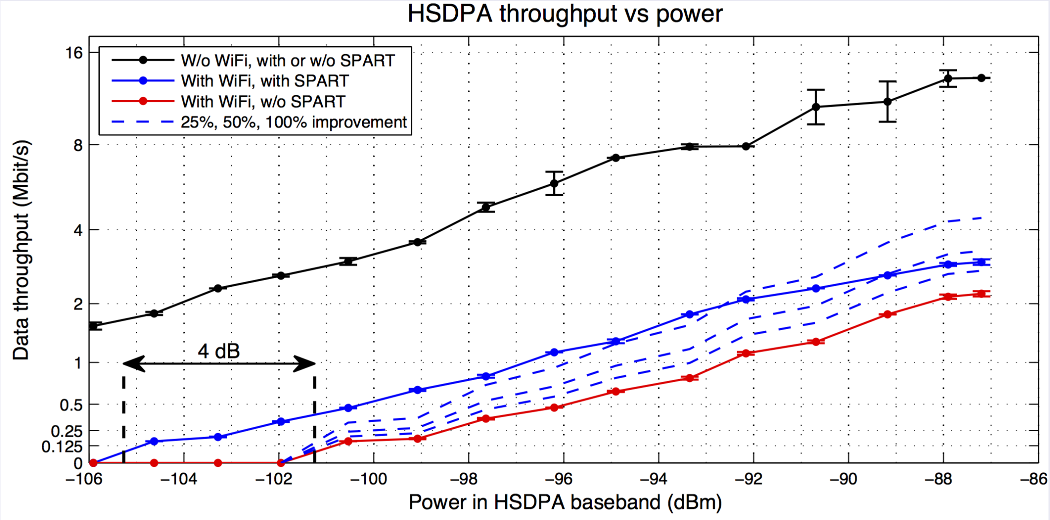
Appendix II: Throughput of 1.95 GHz HSDPA with 2.4 GHz WiFi interference



Setup from AV Nikitin et al: Impulsive interference in communication channels and its mitigation by SPART and other nonlinear filters. *EURASIP J Adv Signal Process* 2012, 2012:79

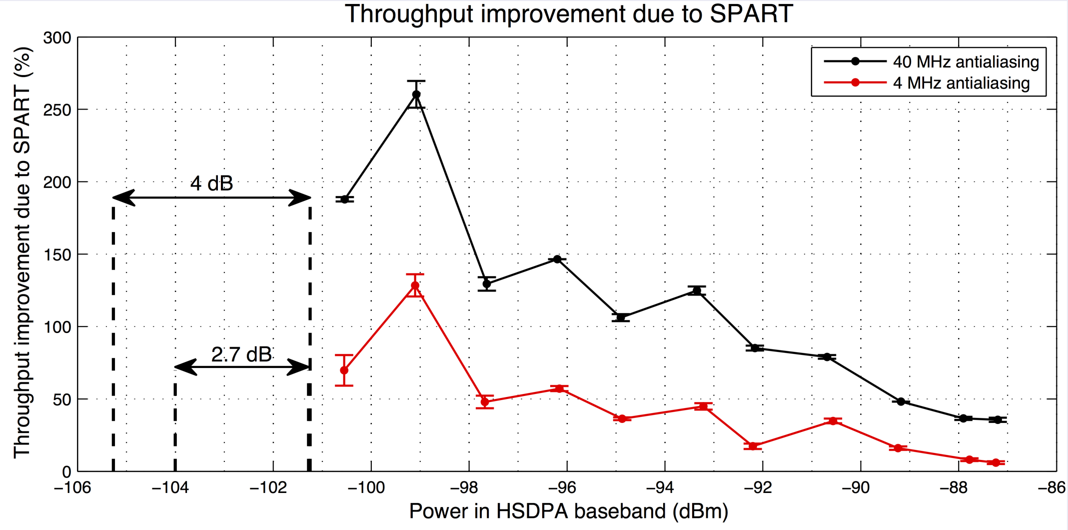
Experimental examples from prior work

Appendix II: Throughput of 1.95 GHz HSDPA with 2.4 GHz WiFi interference



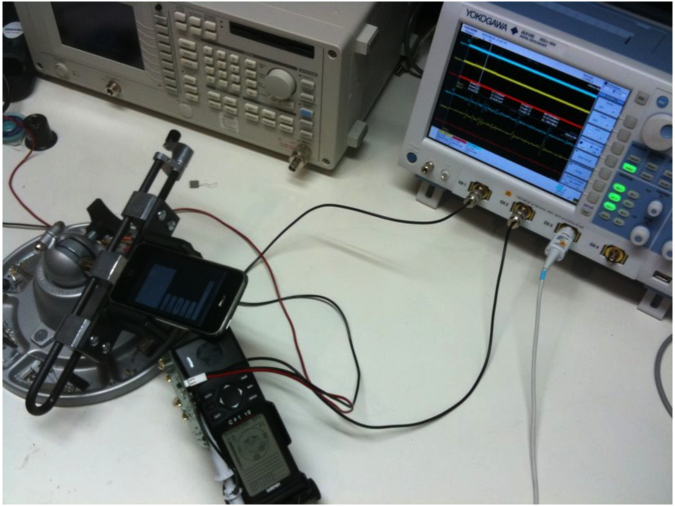
Experimental examples from prior work

Appendix II: Throughput of 1.95 GHz HSDPA with 2.4 GHz WiFi interference



Experimental examples from prior work

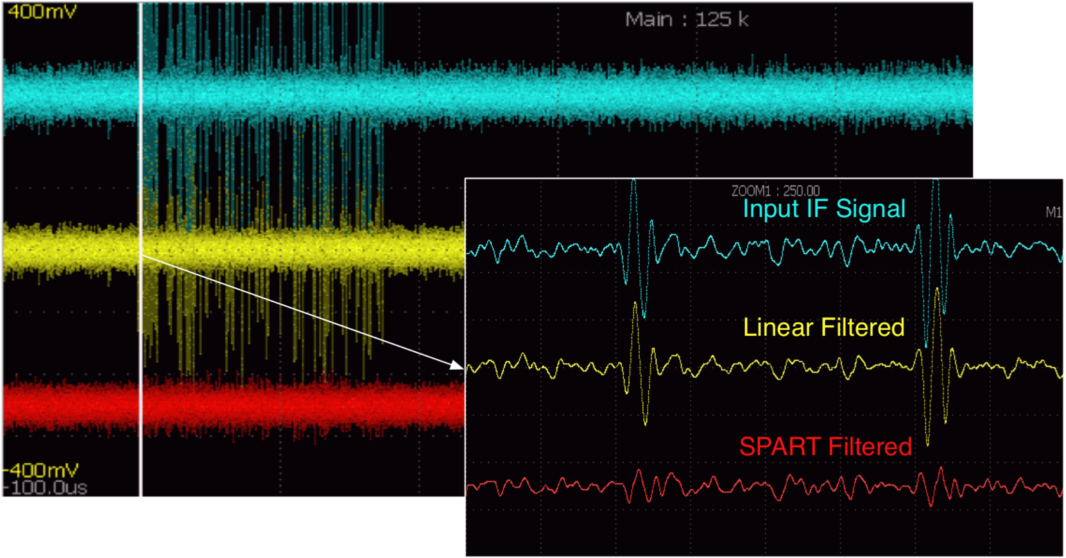
Appendix III: Impulsive EMI in GPS: Bench setup for WiFi/Bluetooth interference



iPhone's WiFi/Bluetooth interfering with GPS12

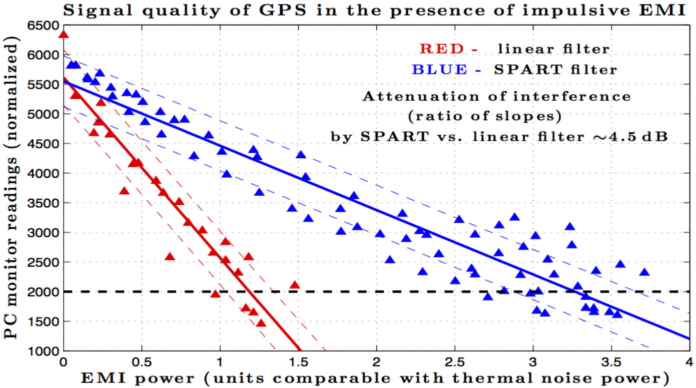
Experimental examples from prior work

Appendix III: Impulsive EMI in GPS: Scope traces



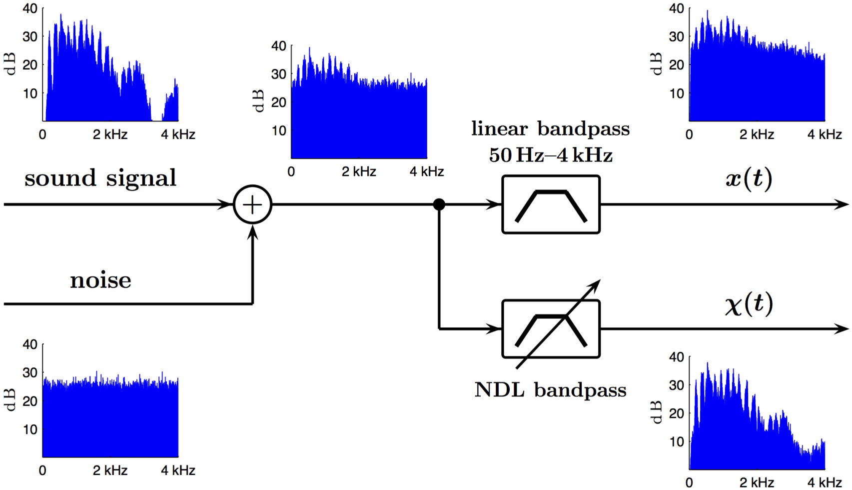
Experimental examples from prior work

Appendix III: Impulsive EMI in GPS: RF anechoic chamber test



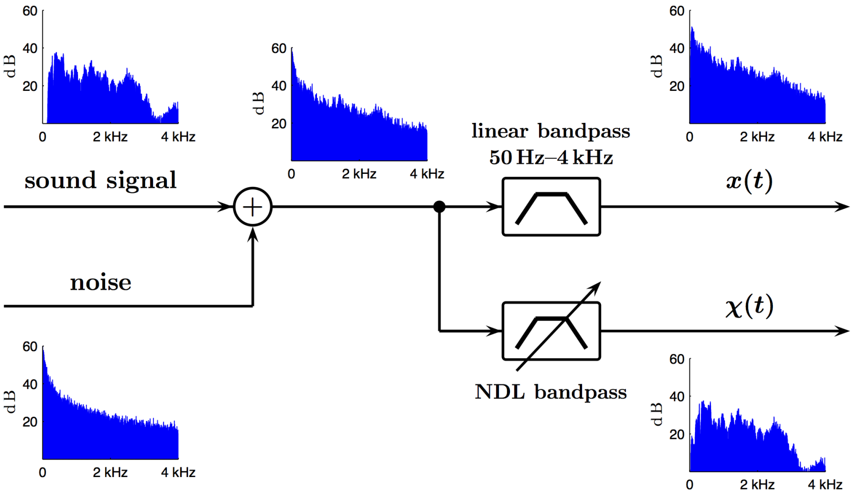
As the EMI power increases, the signal quality (PC monitor readings) deteriorates much slower in the GPS unit with a SPART filter than in the unit with a linear filter. Also, as the interference power is increased to GPS signal lock failure (the PC readings below the horizontal dashed line), the SPART-modified unit loses lock at significantly higher EMI power

Audio demo I: White impulsive noise (super-Gaussian)



I II III IV V

Audio demo II: Red (f^{-2}) sub-Gaussian noise



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