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

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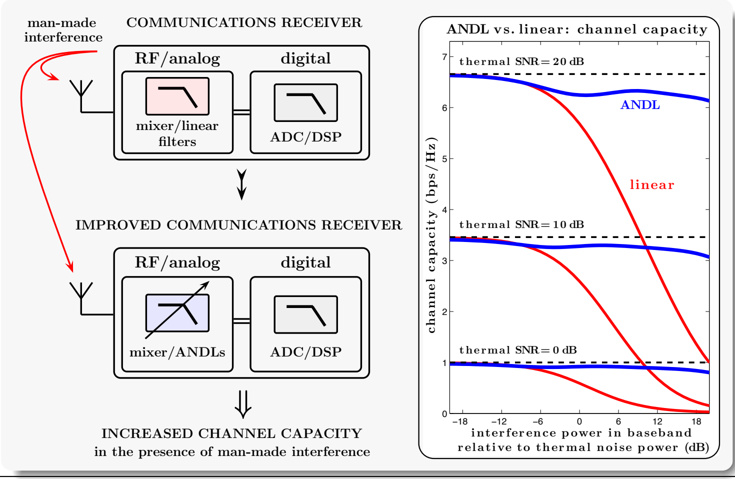
1. Motivation
   - Communications receivers resistant to man-made interference
2. Impulsive nature of interchannel interference
   - Effects of symbol rates and pulse shaping
3. Nonlinear Differential Limiters (NDLs)
4. NDL-based mitigation of out-of-band interference
   - Adaptive NDLs (ANDLs)
5. Concluding remarks
   - Digital NDLs

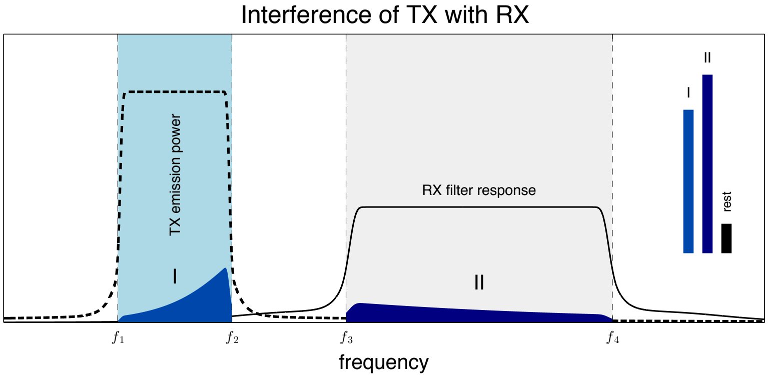
Motivation:
Communications receivers resistant to man-made interference



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

▸ ANDLs vs. linear: baseband SNR (14/18)

Impulsive nature of interchannel interference

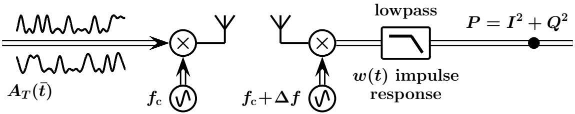


Qualitative illustration of different contributions into the interference which a receiver (RX) experiences from a transmitter (TX)

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

▸ Impulsive interference (8/18)   ▸ Increasing peakedness (10/18)

Impulsive nature of interchannel interference: TX OOB interference in the RX channel (part II of the total interference)



For example, it can appear as an impulsive pulse train

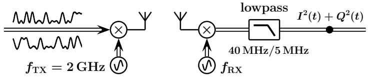
$$P(t, \Delta f) = \frac{1}{(T\,\Delta f)^{2n}} \sum_i |\alpha_i|^2\, h^2\left(\bar{t} - \bar{t}_i\right)$$

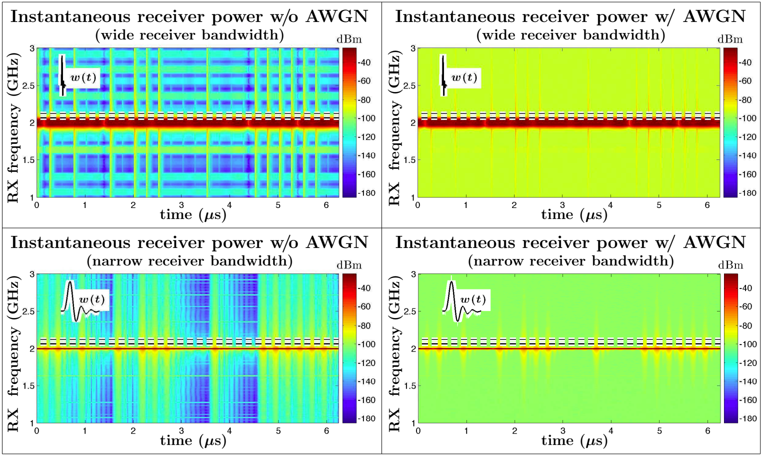
- for sufficiently large T and/or Δf
- T is symbol duration (unit interval)
- $\bar{t}$ is nondimensionalized time, $\bar{t} = \frac{2\pi}{T} t$
- $h(\bar{t}) = \frac{T}{2\pi} w(t)$, $w(t)$ is impulse response of lowpass filter
- $A_T(\bar{t})$ is modulating signal
- $|\alpha_i|$ is magnitude of discontinuity of $A_T^{(n-1)}(\bar{t})$ at $\bar{t}_i$

EURASIP J Adv Signal Process 2011, 2011:137
Proc. IEEE Radio and Wireless Symposium, Phoenix, AZ 2011:118-121
Experimental evidence: *EURASIP J Adv Signal Process* 2012, 2012:79

▸ Effects of symbol rates and pulse shaping (9/18)

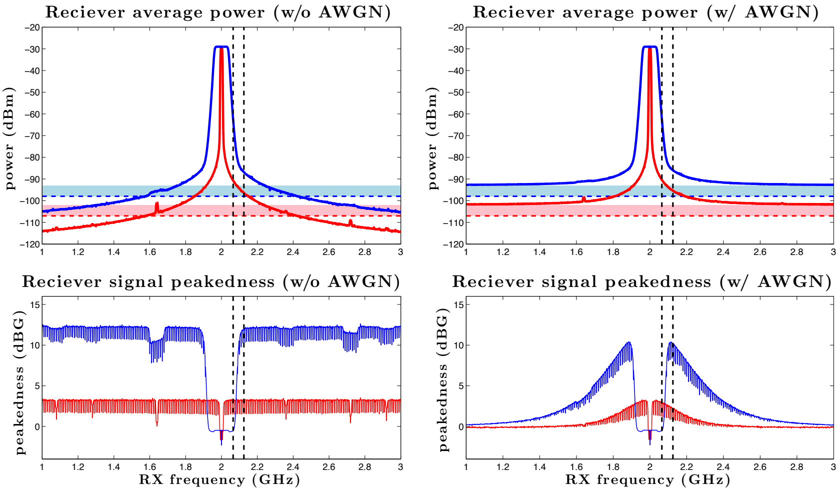
Impulsive nature of interchannel interference:
Instantaneous power response of a quadrature receiver





▸ Simulation parameters (19/18)

Impulsive nature of interchannel interference:
Average power and peakedness

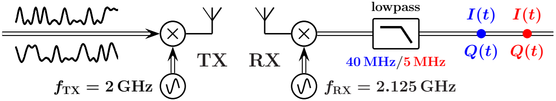


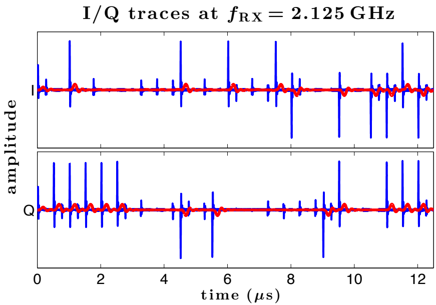
Red lines: 5 MHz lowpass	**Blue lines:** 40MHz lowpass

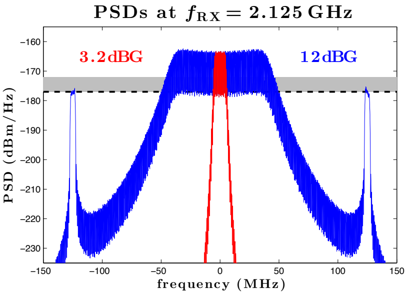
Measure of peakedness (20/18)
Simulation parameters (19/18)

Impulsive nature of interchannel interference

Impulsive interference: Part II dominates





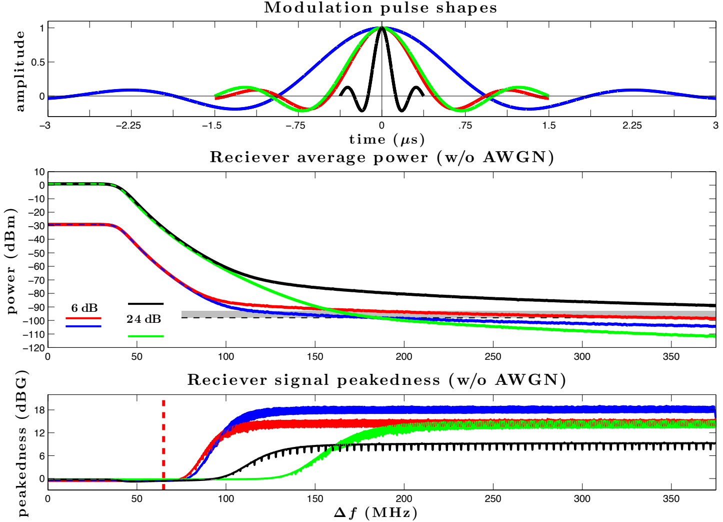


Blue lines and text: 40 MHz bandwidth	**Red lines and text:** 5 MHz bandwidth

For a sufficiently large $|\Delta f|$ (e.g. 125 MHz), impulsive component (part II) dominates

▸ TX RX interference (4/18)

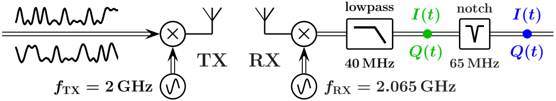
Impulsive nature of interchannel interference:
Effects of symbol rates and pulse shaping

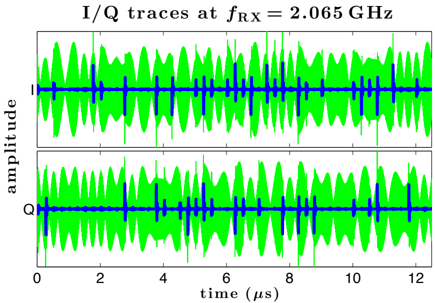


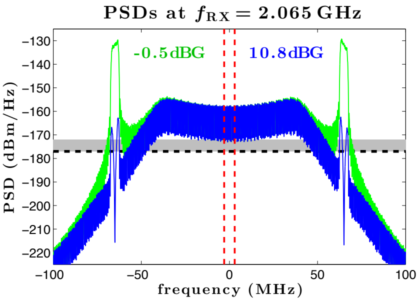
▸ OOB interference (5/18)

▸ Simulation parameters (19/18)

Impulsive nature of interchannel interference:
Increasing peakedness





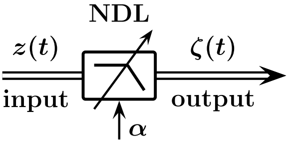


Green lines and text: before notch	**Blue lines and text:** after notch

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

TX RX interference (4/18)

Nonlinear Differential Limiters (NDLs)



For example, for a second order linear lowpass filter:

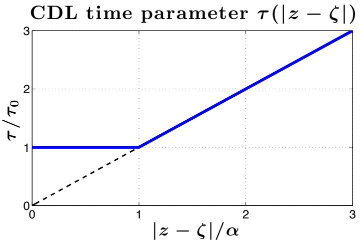
$$\zeta(t) = z(t) - \tau\,\dot{\zeta}(t) - (\tau Q)^2\,\ddot{\zeta}(t)$$

- τ is time parameter, Q is quality factor

A particular NDL example:

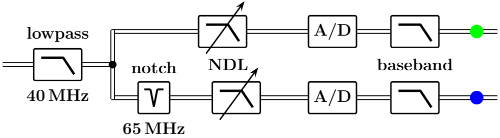
$$\tau(|z-\zeta|) = \tau_0 \times \begin{cases} 1 & \text{for } |z-\zeta| \le \alpha \\ \left(\frac{|z-\zeta|}{\alpha}\right)^{\beta} & \text{otherwise} \end{cases}$$

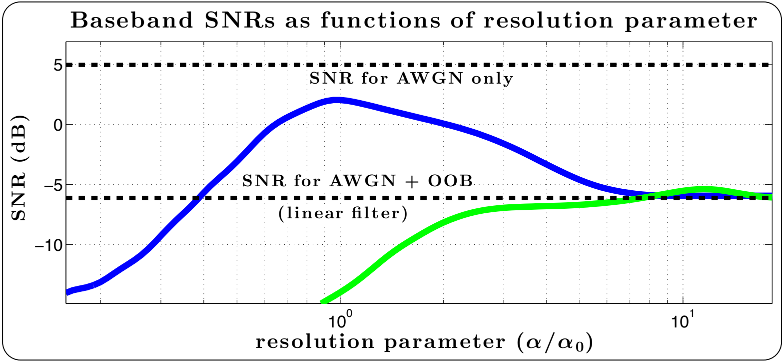
- $\beta > 0$
- Canonical Differential Limiter (CDL) for $\beta = 1$
- Differential over-Limiter (DoL) for $\beta > 1$



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

NDL-based mitigation of out-of-band interference:
SNRs in the receiver as functions of the NDL resolution parameter





Green: w/o notch	**Blue:** with notch

NDL-based mitigation of out-of-band interference:
Adaptive NDLs (ANDLs)

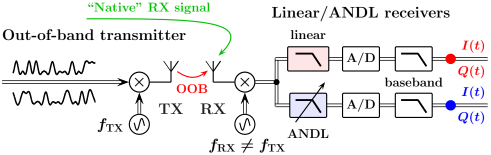
Adaptive NDL (ANDL) configurations
contain a sub-circuit (characterized by a gain parameter)
that monitors a chosen measure of the signal+noise mixture
and provides a time-dependent resolution parameter $\alpha = \alpha(t)$
to the main NDL circuit,
making it suitable for improving quality of non-stationary signals
under time-varying noise conditions

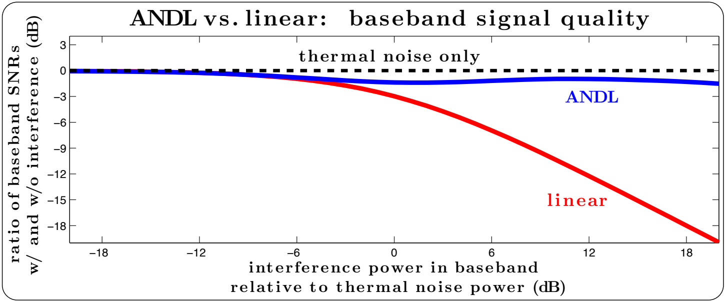
More on NDLs/ANDLs:

- Nikitin AV, Davidchack RL, Sobering TJ: **Adaptive analog nonlinear algorithms and circuits for improving signal quality in the presence of technogenic interference.** To be presented at the *2013 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.** WO 2013/151591 (10 October 2013)
- http://www.avatekh.com

NDL-based mitigation of out-of-band interference

ANDLs: Baseband signal quality of an ANDL-based receiver



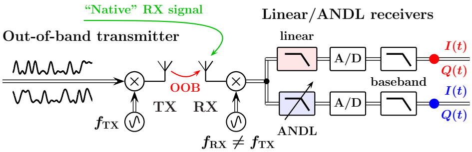


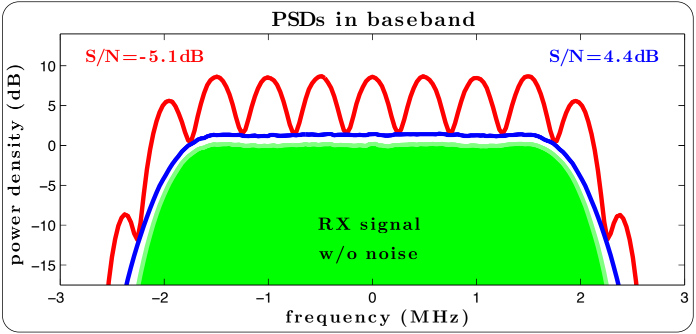
Baseband signal quality of an ANDL-based receiver is largely independent of the strength of the out-of-band interference from a nearby transmitter

Communications receivers resistant to man-made interference (3/18)

NDL-based mitigation of out-of-band interference

ANDLs: PSDs in signal passband

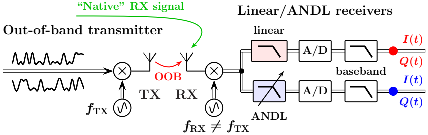


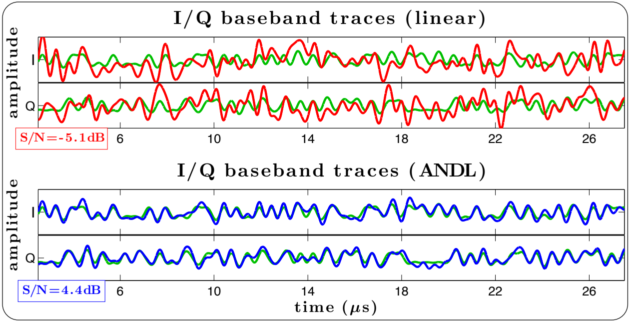


ANDLs can reduce the spectral density of a man-made interference in the signal passband without affecting the signal of interest

NDL-based mitigation of out-of-band interference

ANDLs: Time domain I/Q traces in baseband





Time domain I/Q traces of the signals measured at the test points indicated by the fat colored dots on the signal path diagram at the top. The green lines show the I/Q traces of the baseband "native" receiver signal without noise

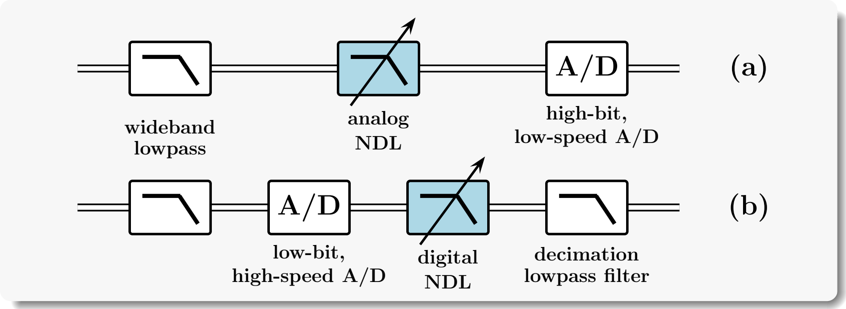
Concluding remarks

- Interference induced in a communications receiver by external transmitters can be viewed as a wide-band non-Gaussian noise affecting a narrower-band baseband signal of interest
- At any given frequency, a linear filter affects both the noise and the signal of interest proportionally, and cannot improve the baseband SNR
- A linear filter can be converted into an NDL by introducing an appropriately chosen feedback-based nonlinearity into the response of the filter
- NDLs may reduce the spectral density of a non-Gaussian interference in the signal passband without significantly affecting the signal of interest, thus increasing the capacity of a communications channel
- NDLs are designed to be fully compatible with existing linear devices and systems, and to be used as an enhancement, or as a low-cost alternative, to the state-of-art interference mitigation methods

Concluding remarks:
Digital NDLs

Increasing sampling rate of high-resolution converters in order to enable use of digital NDLs would be impractical

Instead, low-bit high-rate A/D converters should be used to provide input to digital NDLs. Then NDL outputs can be downsampled to provide desired high-resolution signals at lower sampling rates



Analog (a) and digital (b) NDL deployments

Appendix I

Simulation parameters

The TX signal used in the simulations on pages 6, 7, 9, 10, and 12 was a random QPSK signal. In all simulations except those shown on page 9 the symbol rate was 4 Mbit/s (unit interval $T = 250$ ns), and an FIR RRC filter with the roll-off factor 1/4 and the group delay $3T$ was used for pulse shaping. The average TX signal power was 125 mW (21 dBm), and the path/coupling loss at any RX frequency was 50 dB, except for the TX signals shaped with the filters shown by the black and green lines on page 9, where it was 20 dB

The RX lowpass filters were 8th order Butterworth filters. A 5 dB noise figure of the receiver was assumed at all receiver frequencies f_{RX} ($\Rightarrow -172$ dBm/Hz for the total AWGN level at room temperature). The incoming RX signal used on page 12 was a random QPSK signal with the rate 4.8 Mbit/s. An FIR RRC filter with the roll-off factor 1/4 and the group delay $3T$ was used for the RX incoming signal pulse shaping, and the same FRI filter was used for the matched filtering in the baseband. The PSD of the RX signal without noise was approximately -167 dBm/Hz in the baseband, leading to the S/N ratio without interference of approximately 5 dB

▸ Instantaneous power response of a quadrature receiver (6/18)
▸ Average power and peakedness (7/18)
▸ Effects of symbol rates and pulse shaping (9/18)

Peakedness of a complex-valued signal $z(t) = I(t) + \mathrm{i}Q(t)$ can be expressed in terms of the measure

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

where the angular brackets denote time averaging. This measure is based on an extension of the classical definition of *kurtosis* to complex variables

- "decibels relative to Gaussian" (dBG) - i.e. in relation to the kurtosis of the Gaussian (aka normal) distribution
- K_{dBG} vanishes for a Gaussian distribution
- sub-Gaussian and super-Gaussian distributions have negative and positive dBG peakedness, respectively

Average power and peakedness (7/18)