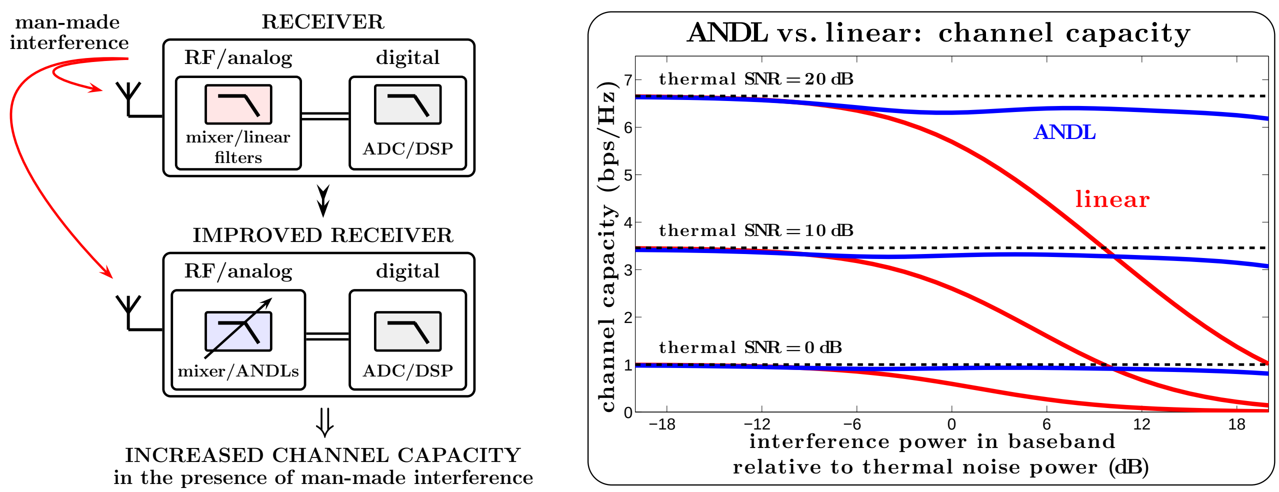
Adaptive analog nonlinear circuits for improving properties of electronic devices

Communications receivers resistant to man-made interference

In a perfect-world communication technology we would have “brick wall" filters, no-distortion amplifiers and mixers, and well-coordinated spectrum operations. The real world, however, is prone to various types of unintentional and intentional interference of technogenic (man-made) origin that can disrupt communication systems, with impacts ranging from a slight reduction in the channel capacity to the channel failure. Such interference can be effectively mitigated by the Adaptive Nonlinear Differential Limiters (ANDLs) being developed by AvaTekh. ANDLs simply replace certain existing linear filters in the receiver (for example, the anti-aliasing filters preceding the analog-to-digital converters), providing resistance to the technogenic interference independent of the modulations schemes and communication protocols, as illustrated in the figure below.

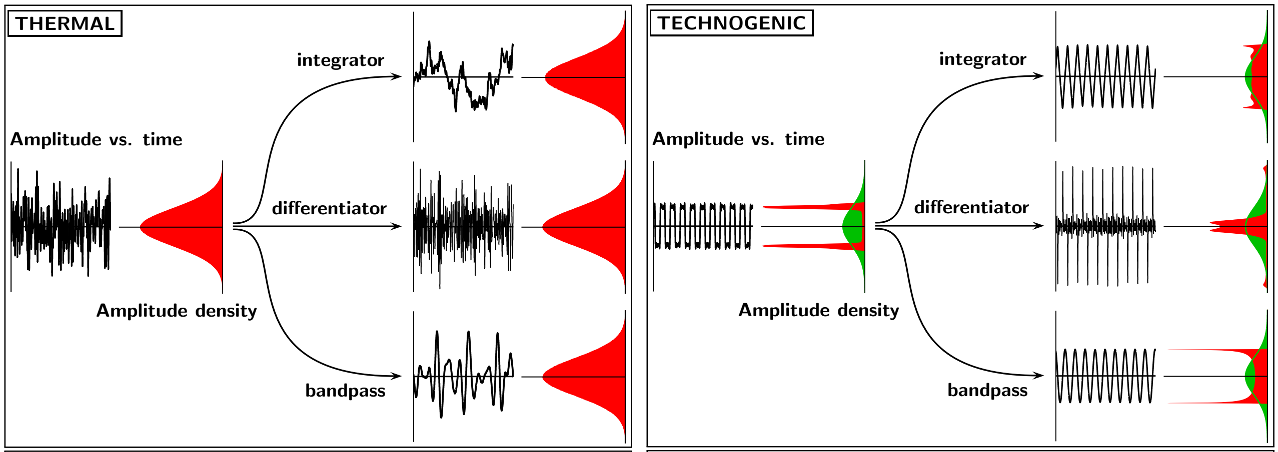


Replacing certain analog filters in the receiver by ANDLs provides resistance to man-made interference

ANDLs 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 other state-of-art interference mitigation methods.

Nonlinear vs. linear: The rationale

Technogenic (man-made) signals are typically distinguishable from purely random signals (e.g. thermal), specifically, in terms of amplitude distributions/densities (non-Gaussian), as they have some type of temporal and/or amplitude structure. This is illustrated in the figure below.

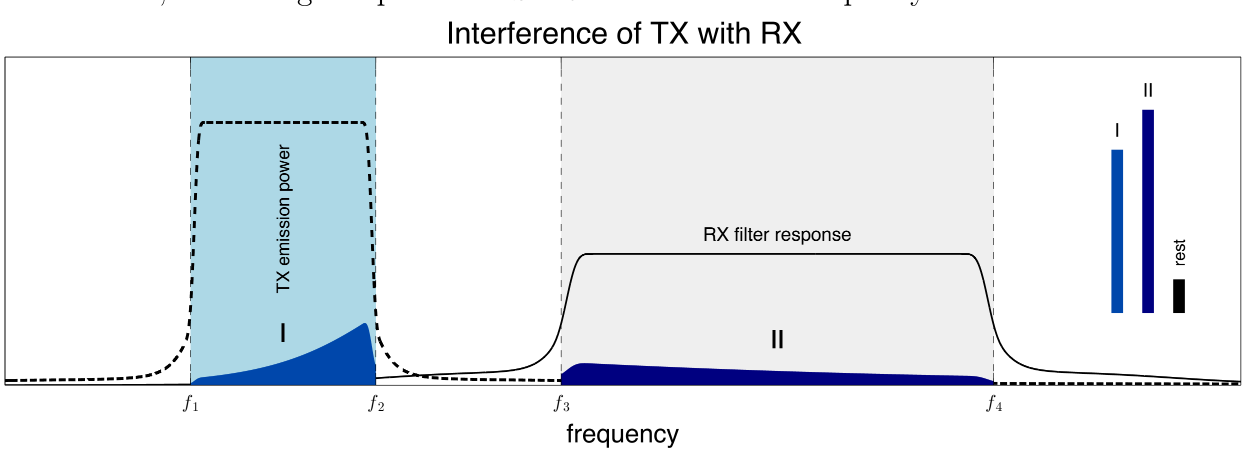


For Gaussian (e.g. thermal) signals, amplitude distribution remains Gaussian regardless of linear filtering

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

At any given frequency, linear filters affect the power of both the noise and the signal of interest proportionally, and cannot improve the SNR in passband. Nonlinear filters, however, can reduce the PSD of non-Gaussian interference in passband without significantly affecting signals of interest, and thus can increase the passband SNR and the channel capacity.

For example, it can be shown that out-of-band (OOB) interference from a digital transmitter (TX) in the receiver (RX) channel (part II of the total interference in the figure below) would be non-Gaussian, and can appear impulsive under a wide range of conditions. This interference can degrade the RX communication signal as it raises the noise floor in the RX band. Nonlinear Differential Limiters (NDLs) and Adaptive NDLs (ANDLs) can mitigate this interference, increasing the passband SNR and the channel capacity.



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

Distributional differences between thermal noise and technogenic signals

A convenient statistic quantifying distributional differences between complex-valued thermal noise and technogenic signals can be defined as

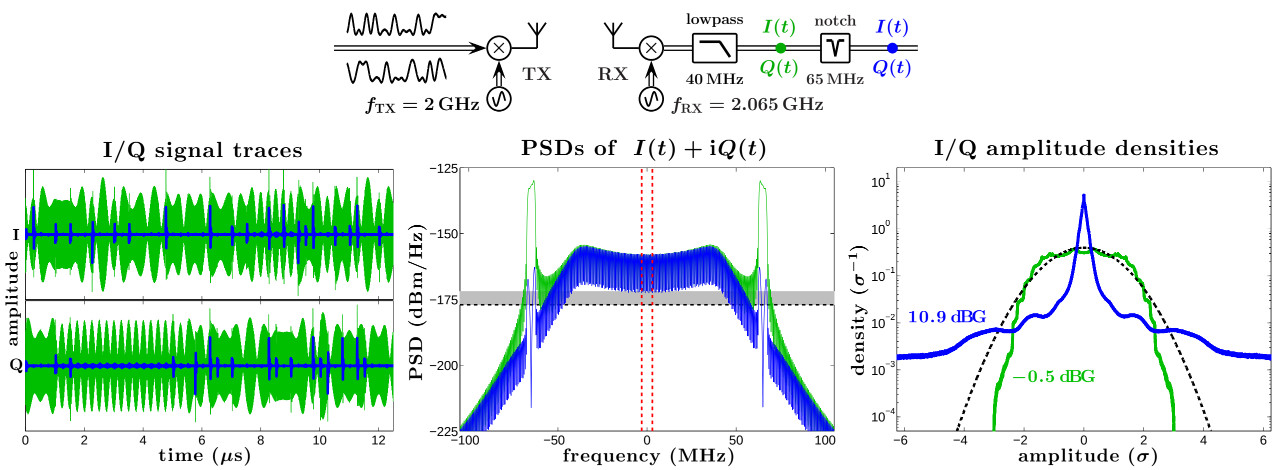
$$K_{\mathrm{dBG}}(z) = 10\lg\left(\frac{\langle |z|^4\rangle - |\langle zz\rangle|^2}{2\langle |z|^2\rangle^2}\right),$$

where $z(t) = I(t) + \mathrm{i}Q(t)$, and the angular brackets denote time averaging. This can be interpreted as a measure of *peakedness* and is based on a definition of *kurtosis* for complex variables. This measure expresses signal peakedness in units "decibels relative to Gaussian" (dBG), that is, in relation to a Gaussian distribution. K_{dBG} vanishes for a Gaussian distribution, and takes negative ($K_{\mathrm{dBG}} < 0$) and positive ($K_{\mathrm{dBG}} > 0$) values for sub-Gaussian and super-Gaussian distributions, respectively. A high value of peakedness typically implies frequent occurrence of outliers, that is, an *impulsive* signal.

Since amplitude distributions of non-Gaussian signals, in general, are modifiable by linear filtering, even a sub-Gaussian signal can typically be made to appear impulsive (super-Gaussian) by applying an appropriately chosen linear filter.

Practical example of increasing peakedness

In a communications receiver, such filtering can often be performed without affecting the baseband signal of interest, as illustrated in the figure below.

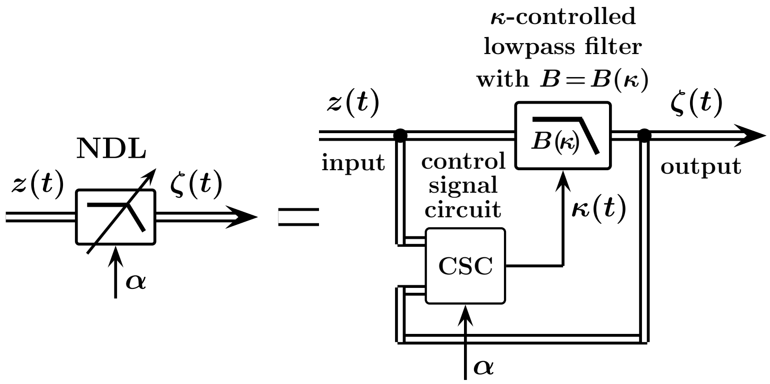


Green lines and text: before notch	**Blue lines and text:** after notch

Note that the notch filter reduces the sub-Gaussian part of the interference without affecting the signal of interest and/or the PSD of the impulsive interference around baseband, enabling its effective mitigation by nonlinear filters such as Nonlinear Differential Limiters (NDLs). Linear filters are converted into NDLs by introducing feedback-based nonlinearities into filter responses as illustrated further.

Nonlinear Differential Limiters (NDLs)

NDLs are designed for mitigation of *impulsive* interference (i.e. characterized by relatively high occurrence of outliers). A simplified block diagram of and NDL is shown in the figure below.



Block diagram of Nonlinear Differential Limiter

In an NDL, the filter bandwidth B is dynamically modified based on a magnitude of the *difference signal* $z(t) - \zeta(t)$. It should be understood, however, that, since an NDL is a nonlinear filter and does not have a well-defined bandwidth, this “bandwidth" is just a convenient computational proxy equal to the bandwidth of a respective linear filter with the same (time-invariant) filter coefficients as the instantaneous values of the NDL coefficients. In an NDL, B is non-increasing function of $|z-\zeta|$, monotonically decreasing for $|z-\zeta| > \alpha$, where α is a *resolution parameter*. Note that an NDL becomes a linear filter in the limit $\alpha \to \infty$. This is an important property of an NDL that enables its compatibility with linear systems.

As an example, let us consider a second order lowpass filter given by the following differential equation:

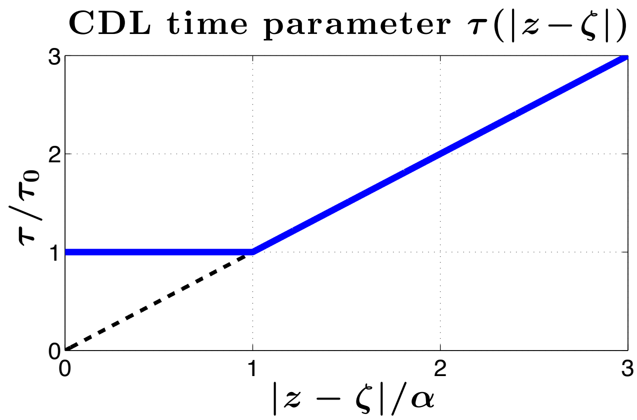
$$\zeta(t) = z(t) - \tau\,\dot{\zeta}(t) - (\tau Q)^2\,\ddot{\zeta}(t)\,,$$

where τ is the filter *time parameter*, and Q is its *quality factor*. Note that the bandwidth of this filter is a *decreasing* function of τ, and an *increasing* function of Q. We can choose, for example, to keep Q constant and vary τ in the following manner:

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

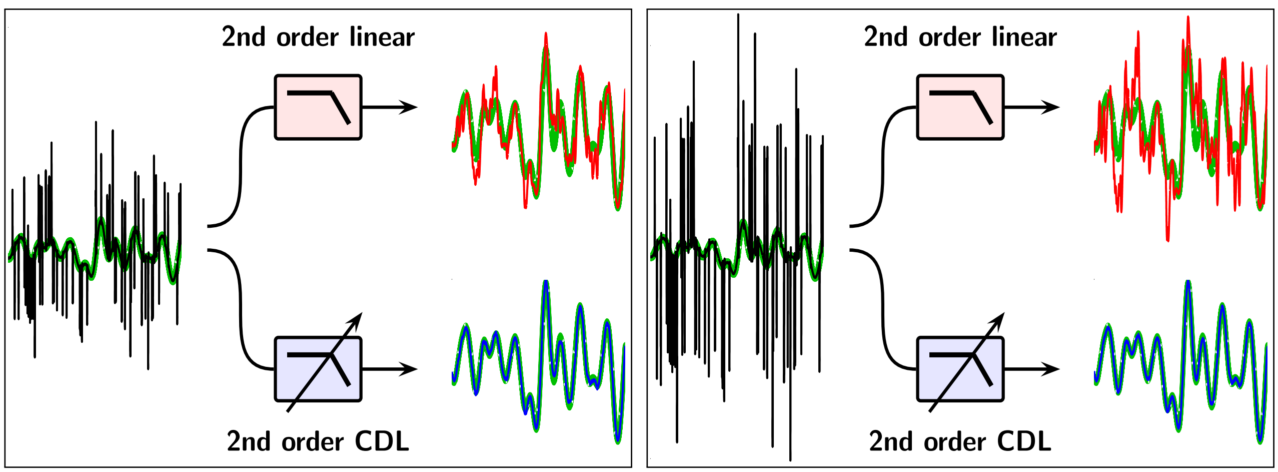
where $\beta > 0$, and τ_0 is the initial time parameter. Then the bandwidth of such a filter will remain constant for $|z-\zeta| \le \alpha$, and will be a monotonically decreasing function of $|z-\zeta|$ otherwise. When $\beta = 1$, such a filter can be called a *Canonical Differential Limiter* (CDL). When $\beta > 1$, it can be called a *Differential over-Limiter* (DoL).

The figure below provides an example of a CDL time parameter τ as a function of a magnitude of the difference signal $z(t)-\zeta(t)$.



CDL time parameter τ as a function of a magnitude of the difference signal $z(t)-\zeta(t)$

The figure below provides an example of “disproportional" (nonlinear) suppression of impulsive noise by such 2nd order CDL.

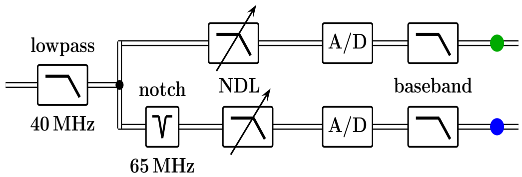


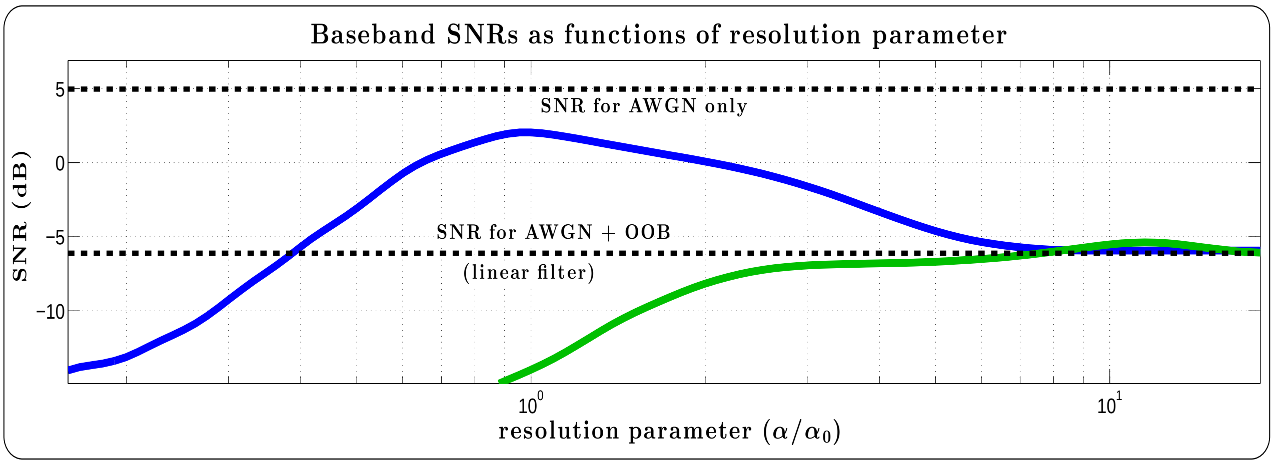
Linear filter: Output noise is proportional to input noise NDL: Output is insensitive to impulsive noise

More information on the NDLs/ANDLs can be found in US patent 8,489,666 (16 July 2013).

NDL-based mitigation of out-of-band interference

The figure below provides an illustrative example of NDL-based mitigation of out-of-band interference for the interference scenario outlined in the figure on page 3. The figure compares the SNRs in the receiver (measured in the baseband) as functions of the NDL resolution parameter α for two filtering configurations, without and with a notch filter in the signal chain.



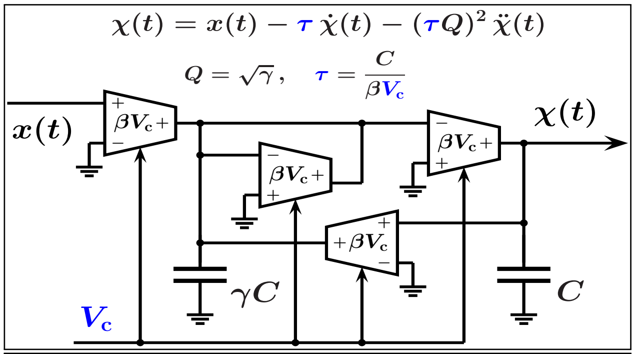


Green: w/o notch **Blue:** with notch

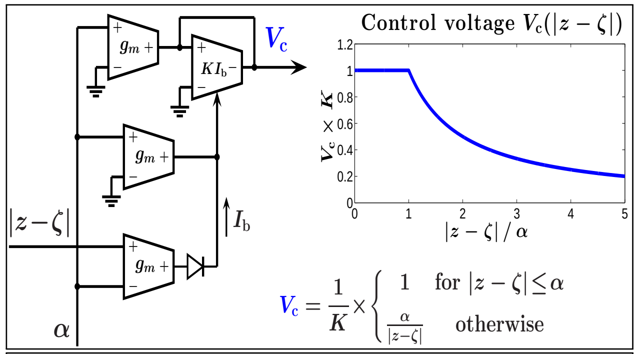
In the limit $\alpha \to \infty$, the SNRs in both configurations converge to the SNR achieved by deploying a respective linear filter in place of an NDL. However, a notch filter preceding the NDL makes the interference impulsive (see the discussion on page 3), and the SNR exhibits a maximum at some value of the resolution parameter $\alpha = \alpha_0$. This increase in the SNR would translate into an increase in the channel capacity. A detailed discussion of experimental evidence of effectiveness of such mitigation of out-of-band interference by nonlinear filters can be found in: 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.

Example of NDL sub-circuit topologies

The figure below provides an example of implementation of a 2nd order CDL based on Operational Transconductance Amplifiers (OTAs).



Voltage-controlled 2nd order lowpass filter with Tow-Thomas topology



CDL control voltage circuit

The sub-circuit in the left-hand panel corresponds to the κ-controlled lowpass filter shown in the figure on page 4, and the sub-circuit in the right-hand panel corresponds to the control signal circuit (CSC) shown in the figure on page 4.

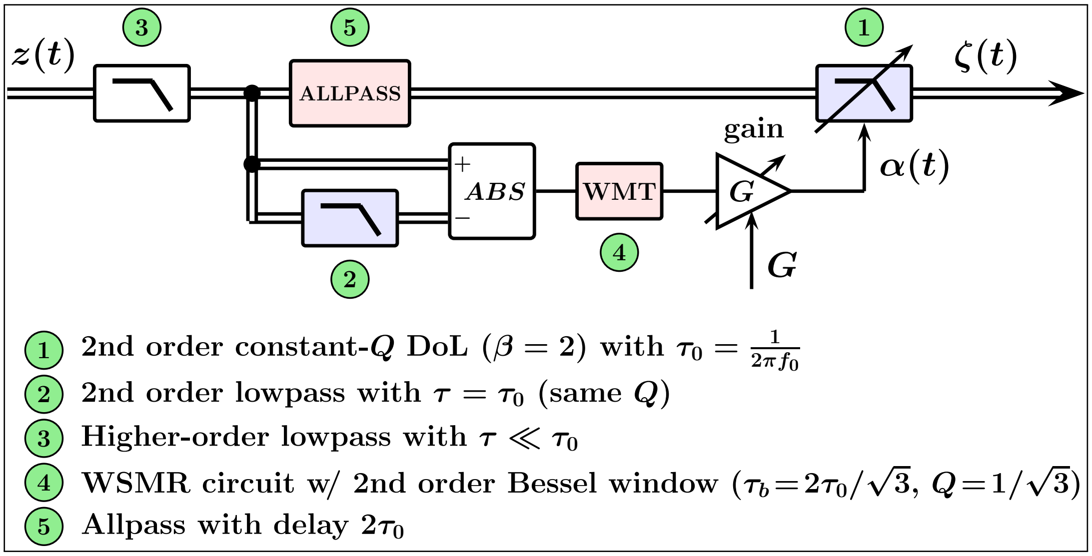
Adaptive NDLs (ANDLs)

An important consideration of technogenic noise is its dynamic nature, which makes it extremely challenging to quantify and address the multitude of complicated interference scenarios in non-stationary communication systems such as, for example, cognitive networks comprising mobile transmitters and receivers, each acting as a local router communicating with a mobile *ad hoc* network (MANET) access point. In such situations interference mitigation tools must adapt to the dynamically changing interference. The Adaptive NDLs (ANDLs) have been developed to address this challenge. ANDL configurations contain a sub-circuit 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 information on ANDLs can be found in: (i) Method and apparatus for signal filtering and for improving properties of electronic devices. WO 2013/151591 (10 October 2013), and in: (ii) AV Nikitin et al: 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.

ANDL example

A simplified block-diagram of an analog circuit exemplifying an adaptive NDL is shown in the figure below.



ANDL example

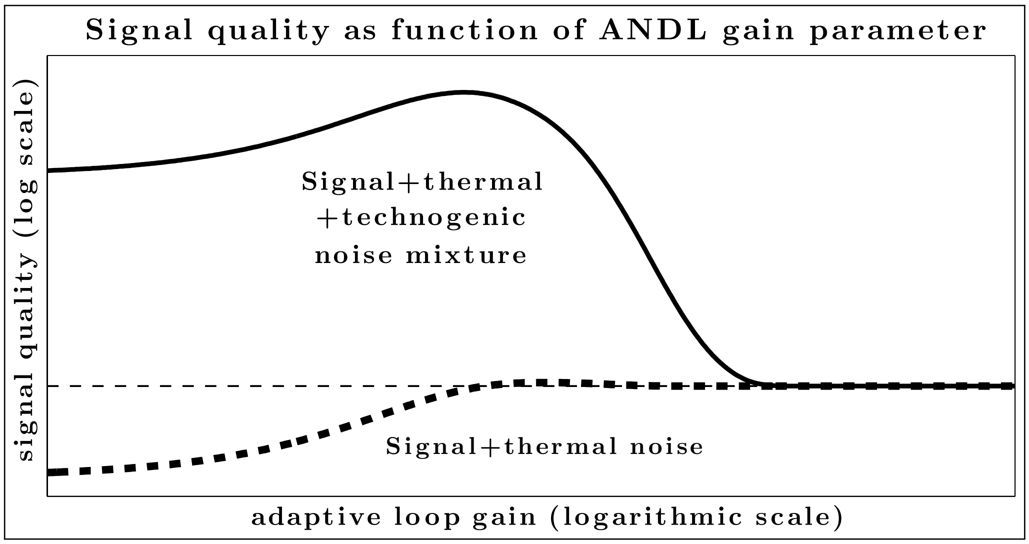
In this example, the NDL ① is of the same type and order as the linear lowpass filter ②, and the time parameter τ of the NDL is a function of the difference signal, $\tau = \tau(|z - \zeta|)$, while $Q = \text{const}$. In the limit $\alpha \to \infty$, the NDL ① and the linear filter ② are equivalent.

The Windowed Measure of Tendency (WMT) circuit ④ is applied to the absolute value of the difference signal of the linear filter, providing a measure of a magnitude of this difference signal in a moving time window. In this particular example, the WMT circuit is a Windowed Squared Mean Root (WSMR) circuit with a Bessel window, and with a bandwidth similar to the bandwidth of the linear lowpass filter.

If the effective width of the moving window of the WMT circuit is larger than the outliers duration, then the attenuation of the outliers in the magnitude of the difference signal of the linear filter by the WMT circuit will be greater in comparison with the attenuation of the portions of the difference signal not containing such outliers. By applying an appropriately chosen gain $G > 1$ to the output of the WMT circuit, the gained WMT output can be made larger than the magnitude of the difference signal of the linear filter when the latter does not contain outliers, and smaller than the magnitude of the difference signal otherwise. As a result, if the gained WMT output is used as the NDL's resolution parameter $\alpha(t)$, the NDL's response will become nonlinear only when an outlier is encountered.

Since the WMT circuit ④ employs a causal moving window with non-zero group delay, the input to the NDL circuit ① needs to be delayed to compensate for the delay introduced by the WMT circuit. In the above example, such compensation is accomplished by an appropriately chosen all-pass filter ⑤. When an all-pass filter is used for the delay compensation, as indicated in the figure on page 8, a high-bandwidth lowpass filter ③ may need to be used as a front end of an ANDL to improve the signal shape preservation by the all-pass filter.

It should be easily seen that in the limit of a large gain, $G \to \infty$, an ANDL becomes equivalent to the respective linear filter with $\tau = \tau_0 = \text{const}$. When the noise affecting the signal of interest contains impulsive outliers, however, the signal quality will exhibit a global maximum at a certain finite value of the gain parameter $G = G_{\max}$, providing the qualitative behavior of an ANDL illustrated in the figure below.

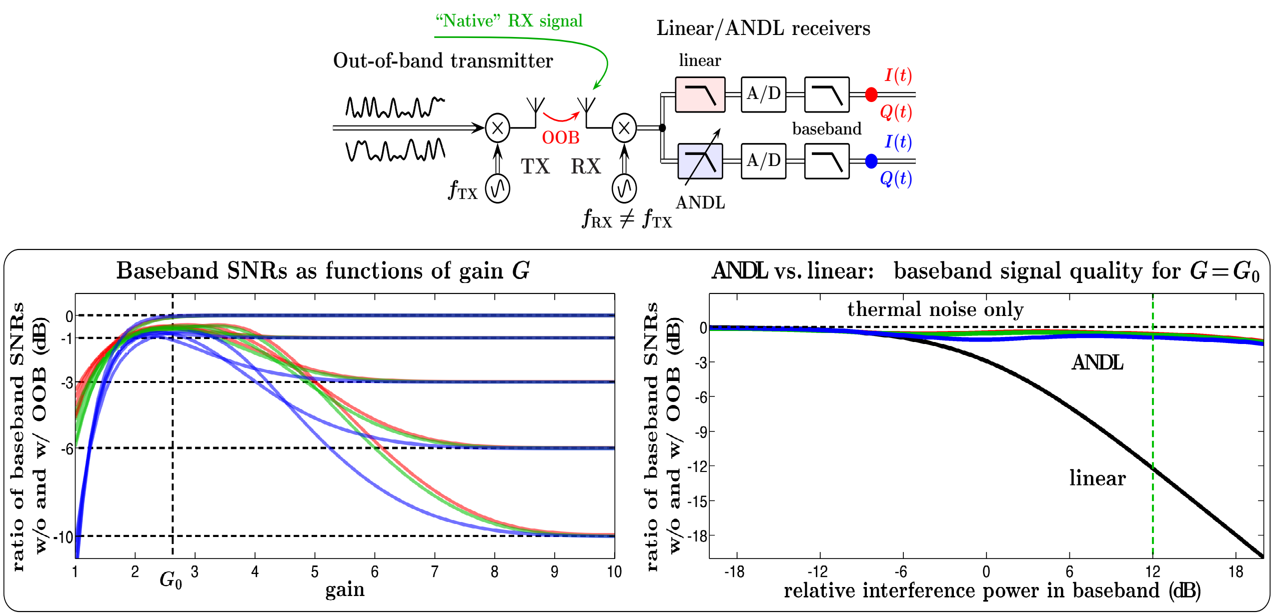


Improving signal quality by ANDL

As indicated by the horizontal dashed line in the figure, as long as the noise retains the same power and spectral composition, the signal quality of the output of a linear filter remains unchanged regardless the proportion of the thermal and the technogenic (e.g. impulsive) components in the noise mixture. In the limit of a large gain parameter, an ANDL is equivalent to the respective linear filter with $\tau = \tau_0 = \text{const}$, resulting in the same signal quality of the filtered output as provided by the linear filter, whether the noise contains an impulsive component (solid curve) or it is purely thermal (dashed curve). If viewed as a function of the gain, however, when the noise contains an impulsive component the signal quality of the ANDL output exhibits a global maximum, and the larger the fraction of the impulsive noise in the mixture, the more pronounced is the maximum in the signal quality. This property of an ANDL enables its use for improving the signal quality in excess of that achievable by the respective linear filter, effectively reducing the in-band impulsive interference.

ANDLs at work

It can be demonstrated that, for an appropriately chosen width of the WMT sub-circuit's window, the optimal gain can be relatively insensitive to at least some parameters of the signal+noise mixtures. This is clarified in the figure below, which provides an illustrative example of reducing technogenic interference by an ANDL shown on page 8.



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

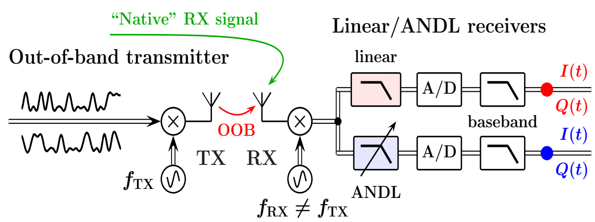
The technogenic out-of-band (OOB) interference affecting the "native" receiver signal is produced by the OOB transmitter, and the baseband signal quality (baseband SNR) is compared for the linear and the ANDL-based receivers for 3 initial ("pre-interference", or purely thermal) SNRs (0, 10, and 20 dB), and 5 relative OOB interference powers (no interference, and 1, 3, 6, and 10 dB interference relative to the thermal noise power).

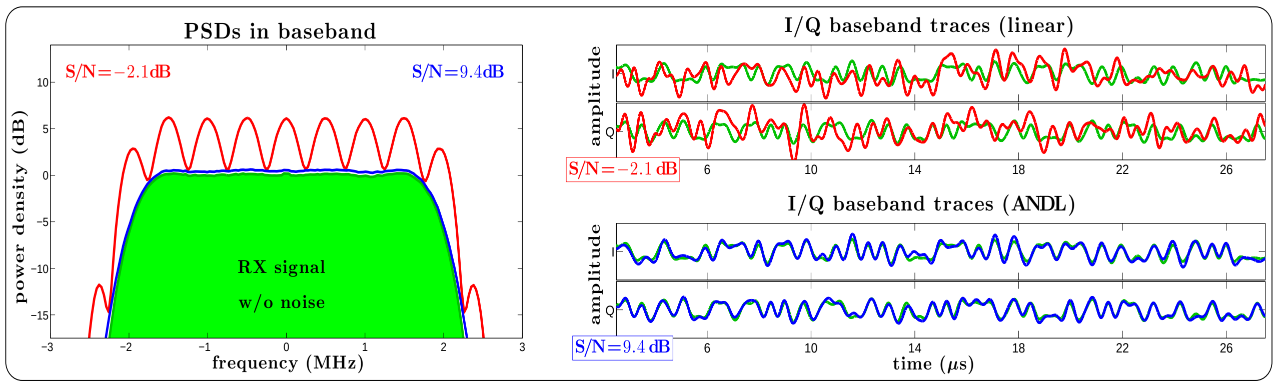
The left panel shows the baseband SNRs in the presence of the OOB interference relative to the respective thermal SNRs, for the linear receiver (horizontal dashed lines), and for the ANDL-based receiver as functions of the ANDL gain (curves). As can be seen in this panel, the signal quality (as characterized by the baseband SNR) of the ANDL-based receiver reaches a maximum value for the gain values in the neighborhood of G_0 (indicated by the vertical dashed line), for various initial (thermal) SNRs and interference powers.

The right panel shows the relative baseband SNRs for the linear (black curve) and the ANDL-based receiver with gain G_0 (same line colors as the curves in the left panel) as functions of the interference power in baseband (relative to the thermal noise power). As one can see, in the linear receiver the signal quality decreases with the increase of interference, while the ANDL-based receiver mainly maintains the initial (thermal) signal quality and is insensitive to the OOB interference.

Reducing interference in the signal passband

A linear filter affects both the noise and the signal of interest proportionally, and when a linear filter is used to suppress the interference outside of the passband of interest, the resulting signal quality is invariant to the type of the amplitude distribution of the interfering signal, as long as the total power and the spectral composition of the interference remain unchanged. ANDLs, however, can reduce the spectral density of a man-made interference in the signal passband without significantly affecting the signal of interest. This is illustrated in the figure below for the 12 dB relative OOB interference power in baseband (indicated by the vertical green dashed line in the right panel of the figure on page 10).





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

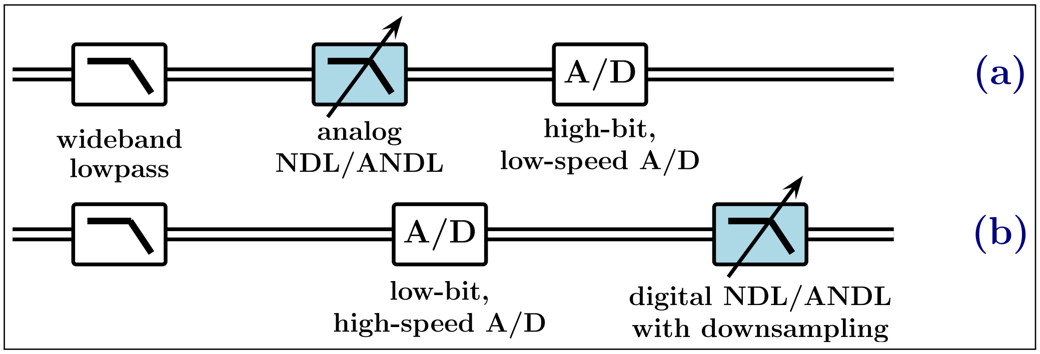
The left panel shows that ANDLs can reduce the spectral density of a man-made interference in the signal passband without affecting the signal of interest. This can be deduced and gauged from observing how the quasiperiodic structure of the PSD is affected by the ANDL in comparison with the linear filter. As a result, the baseband signal quality is improved.

The right panel shows the time domain baseband 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.

One can see from the figure above that the 12 dB relative OOB interference (that would result in 12 dB decrease in the SNR when a linear filter is used) results only in 0.5 dB SNR decrease when an ANDL replaces the linear filter. If the Shannon formula is used to calculate the capacity of a communication channel, the baseband SNR increase from -2.1 dB to 9.4 dB provided by the ANDLs in the two examples above results in a 373% (factor of 4.73) increase in the channel capacity.

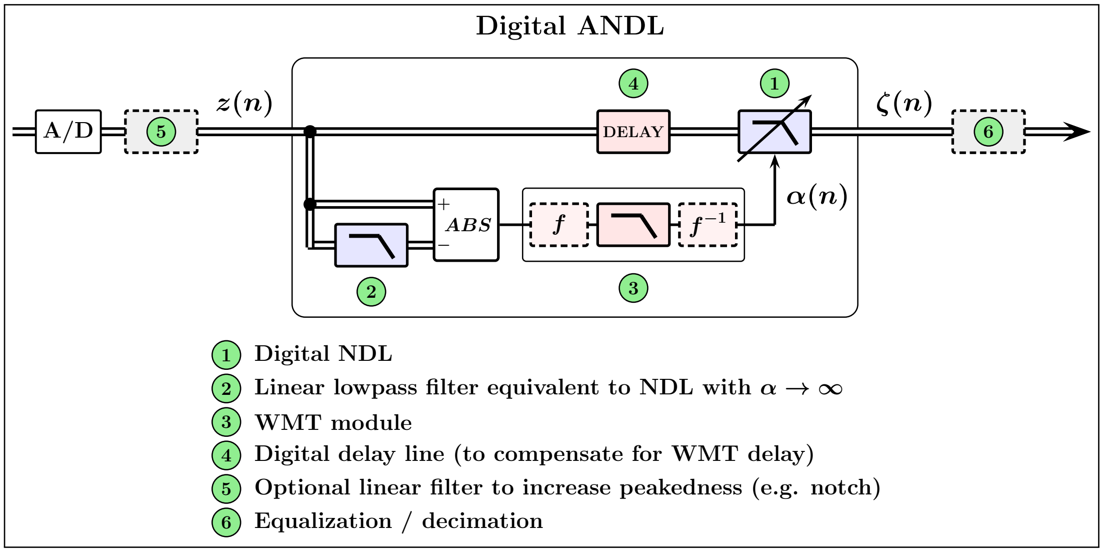
Digital NDLs/ANDLs

While NDLs/ANDLs are conceptually *analog* filters that combine bandwidth reduction with mitigation of interference, they also allow for near-real-time finite-difference (digital) implementations. Such digital implementations can be relatively simple, computationally inexpensive, and would have low memory requirements. However, since the bandwidth of the incoming signal should be much larger (for example, by an order of magnitude) than the bandwidth of the output, digital NDLs/ANDLs implementations would require high sampling rates and should use multi-rate processing, as indicated in the figure below.



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

The figure below provides an example of a digital ANDL.



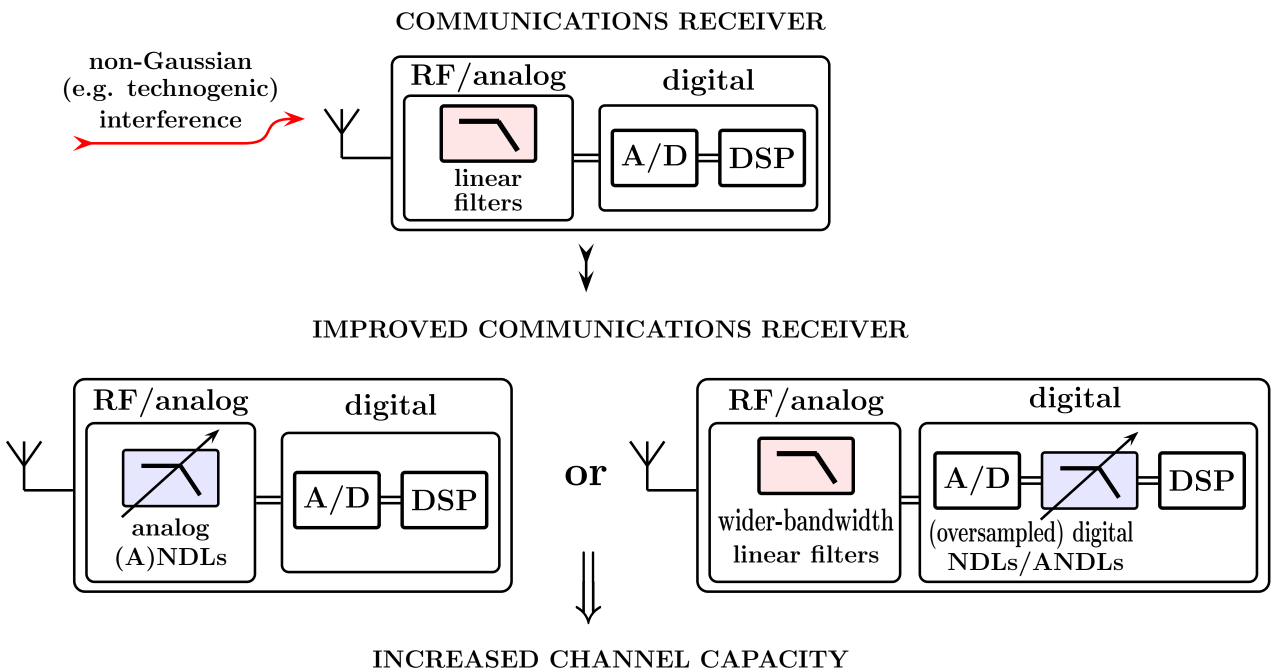
Digital ANDL example

In the figure, ① is a digital NDL of a given type and order (e.g., 1st or 2nd), and ② is a linear lowpass filter equivalent to the NDL in the limit of a large resolution parameter α (e.g., $\alpha \to \infty$). The WMT module ③ outputs a gained windowed measure of tendency of the absolute value of the difference signal of the linear filter ②, and this output is used as a variable resolution parameter $\alpha = \alpha(n)$ supplied to the NDL. In it simplest form, the WMT module is an FIR lowpass filter, or an IIR lowpass filter with a reasonably flat group delay in its passband (e.g., a 2nd order IIR Bessel lowpass filter). To make the WMT module more robust to outliers, one may employ a generalized $\boldsymbol{f}$-mean. For example, if the function $\boldsymbol{f}$ is a square root, then its inverse $\boldsymbol{f}^{-1}$ is a square, and the resulting module would produce a windowed Squared Mean Root (SMR).

The delay line ④ is used to compensate for the delay introduced by the WMT module ③. For example, if the WMT module uses a 2nd order Bessel window (a second order lowpass filter with the time constant $\tau_b = 2\tau_0/\sqrt{3}$ and the quality factor $Q = 1/\sqrt{3}$), then the delay $\Delta n = [2\tau_0 f_s + 1/2]$ may be used, where f_s is the sampling frequency.

An optional Linear Front End (LFE) filter ⑤ may be deployed to suppress the non-impulsive component of the interference and/or to increase the peakedness of the interference in order to enhance the ANDL effectiveness, as discussed earlier. Further, an optional module ⑥ may comprise additional processing/filtering components, such as a decimation filter and/or an equalization filter (e.g., to compensate, if needed, for the effects of the LFE filter).

The figure below provides a schematic illustration of improving wireless and/or wired communications receivers (e.g. through providing resistance to man-made interference) by means of deploying analog or digital NDLs/ANDLs.



Communications receivers resistant to technogenic interference

As discussed earlier, the improvements may be achieved by deploying analog NDLs/ANDLs (e.g. by replacing the respective analog linear filters such as antialiasing filters) in the analog front end of the receiver. Alternatively, wider-bandwidth analog filters may be employed in the analog part of the receiver, and an ADC with a respectively higher sampling rate may be employed in the digital part. Digital NDLs/ANDLs may then be used to reduce the bandwidth of the input digital signal while also reducing non-Gaussian interference affecting a narrower-band signal of interest. Then the output of the NDLs/ANDLs may be (optionally) downsampled, and passed to the subsequent digital signal processing.

Simulation parameters

The TX signal used in all simulations was a random QPSK signal. In all simulations 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.

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 6 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 SNR without interference of approximately 5 dB.

References

[1] Nikitin AV *Method and apparatus for signal filtering and for improving properties of electronic devices* US Patent Application Publication 2013/0339418 (9 December 2013)

[2] 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

[3] Nikitin AV, Davidchack RL, Smith JE Out-of-band and adjacent-channel interference reduction by analog nonlinear filters In *Proc. of the 3rd IMA Conference on Mathematics in Defence*, Malvern, UK, 24 October 2013

[4] Nikitin AV *Method and apparatus for signal filtering and for improving properties of electronic devices* US Patent 8,489,666 (July 16, 2013)

[5] 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 Journal on Advances in Signal Processing*, 2012, 2012:79

[6] Nikitin AV On the interchannel interference in digital communication systems, its impulsive nature, and its mitigation *EURASIP Journal on Advances in Signal Processing*, 2011, 2011:137

[7] Nikitin AV On the impulsive nature of interchannel interference in digital communication systems In *Proc. IEEE Radio and Wireless Symposium*, Phoenix, AZ 2011:118-121

Part of the material contained in this document is based upon work supported by the National Science Foundation under Grant Number 1314790. However, any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation

