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

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***Abstract*— It has been shown that the performance of power line communication (PLC) systems can be severely limited by non-Gaussian and, in particular, impulsive interference from a variety of sources. The non-Gaussian nature of this interference provides an opportunity for its effective mitigation by nonlinear filtering. In this paper, we introduce blind adaptive analog nonlinear filters, referred to as Adaptive Nonlinear Differential Limiters (ANDLs), that are characterized by several methodological distinctions from the existing digital solutions. When ANDLs are incorporated into a communications receiver, these methodological differences can translate into significant practical advantages, improving the receiver performance in the presence of non-Gaussian interference. A Nonlinear Differential Limiter (NDL) is obtained from a linear analog filter by introducing an appropriately chosen feedback-based nonlinearity into the response of the filter, and the degree of nonlinearity is controlled by a single parameter. ANDLs are similarly controlled by a single parameter, and are suitable for improving quality of non-stationary signals under time-varying noise conditions. ANDLs are designed to be fully compatible with existing linear devices and systems (i.e., ANDLs' behavior is linear in the absence of impulsive interference), and to be used as an enhancement, or as a simple low-cost alternative, to the state-of-art interference mitigation methods. We provide an introduction to the NDLs and illustrate their potential use for noise mitigation in PLC systems.**

***Index Terms*— Analog nonlinear filters, cyclostationary noise, impulsive noise, non-Gaussian noise, nonlinear differential limiter (NDL), powerline communications (PLC).**

I. Introduction

Distribution automation, a key feature of the Smart Grid vision, relies on awareness and control of the state of the entire power distribution network down to the home level. The automation capabilities are enabled via reliable communication between smart meters at the customer locations and the local/regional utility. Power line communication (PLC) systems is an attractive choice for this "last mile" problem, as it eliminates the need for new networking infrastructure such as cables and antennas. Recently, there has been significant interest in developing narrowband PLC systems in the 3–500 KHz band, offering data rates up to 800 kbps. The approval of the IEEE P1901.2 standard [1] in 2012, and similar international (ITU-T G.hnem [2]) and industry driven standards (PRIME and PLC G3 [3]), further demonstrate the momentum in advancing PLC systems. While low-cost PLC solutions are attractive, they also provide many challenges for data communication. The medium and low voltage power lines that were designed for power delivery exhibit complex characteristics that vary in time, location and frequency. The transformers and impedance mismatches across branching points cause attenuation and multipath distortion. Powerline noise is a key impairment of PLC systems and its modeling and mitigation has attracted a lot of attention over the past decade [4]–[6]. The power network itself works as an antenna that captures various types of electromagnetic interference, broadband as well as narrowband, and every connected load (e.g., home and industrial appliances) running from the mains injects noise that is typically non-Gaussian and impulsive. Therefore, the noise affecting a PLC system strongly deviates from the standard additive Gaussian noise assumption. Various studies [6]–[8] have shown that, in the 3–500 KHz band of interest, the dominant noise contribution is typically an impulsive noise with strong cyclostationary features, and cyclostationary impulse noise models have been incorporated into the IEEE P1901.2 standard. Mitigation of such noise is of considerable interest and is a focus of this work.

Non-Gaussian nature of impulsive noise provides an opportunity for its effective mitigation by nonlinear means, for example, digital processing based on order statistics, and various approaches to design of nonlinear receivers with improved performance in the presence of impulsive interference have been proposed. Many of these are model-based approaches, which rely on theoretical or empirical assumptions and models of interference distributions. For example, the α-stable [9] and Middleton class A, B and C [10] distributions are commonly used to model the interference in wireline [11] and wireless [12] communications. In the context of PLC, [13] and [14] also pursue a model-based approach to mitigate cyclostationary impulse noise. Such approaches, designed under specific interference model assumptions, are often limited by parameter estimation schemes (e.g. are sensitive to inaccuracies in obtaining derivatives) and may not be robust under a model mismatch.

Alternative methods, that do not explicitly rely on noise distribution models, have also been proposed. Those include receiver designs based on flexible classes of distributions (e.g. myriad filter [15], [16], Normal Inverse Gaussian (NIG) [17]), or directly on the log-likelihood ratio shape (e.g. soft limiter [18], hole puncher [19], p-norm [17], [20]). A straightforward technique to design a receiver that does not assume a specific noise distribution (a *blind* receiver) is to apply a memoryless nonlinearity to the input signal after sampling data, as in [21]. This can be shown to be locally optimal in low-SNR conditions [22], [23]. In [24], samples were either clipped or blanked according to amplitude. The determination of the clipping threshold was based in detection theory and relies only on an approximation of impulse arrival rate. Other methods for applying nonlinearities have been investigated in [25]. In addition to clipping, noise can be estimated and subtracted, as in [26].

A common limitation of state-of-art digital nonlinear techniques is that they are deployed after the analog-to-digital converter (ADC), when the bandwidth is already reduced and it is "too late" to deal with non-Gaussian interference effectively [27], [28]. While this can be overcome by increasing the sampling rate (and thus the acquisition bandwidth), this further exacerbates the memory and DSP intensity of numerical algorithms, making them unsuitable for real-time implementation and treatment of non-stationary noise.

In this paper, we introduce a class of *blind adaptive analog nonlinear filters*, referred to as Adaptive Nonlinear Differential Limiters (ANDLs), that are characterized by several methodological distinctions from the existing digital solutions. The proposed approach is *blind*, as it does not rely on any assumptions for the underlying noise distribution. It is adaptive and can be tuned to operate efficiently in the presence of nonstationary interference. Most importantly, unlike prior approaches, the proposed filters is an analog solution that enables efficient denoising of the received signal before the ADC. ANDLs are nonlinear filters, and they affect the signal of interest and non-Gaussian impulsive noise disproportionally, allowing reduction of the spectral density of such noise in the signal passband without significantly affecting the signal of interest, thus increasing the signal-to-noise ratio (SNR) in the signal passband. When ANDLs are incorporated into a communications receiver, these methodological distinctions can translate into significant practical advantages, improving the receiver performance in the presence of non-Gaussian interference. Specifically, in the context of a PLC system in the presence of impulse noise corresponding to the models specified in IEEE P1901.2, we demonstrate that the use of our ANDL approach can improve the overall signal quality, with the effects ranging from "no harm" for low noise conditions to over 10 dB improvement in the overall passband SNR for high-power noise with strong impulsive component.

II. NDL Basics

In this section, we provide a brief introduction to the NDLs. More comprehensive descriptions of the NDLs, with detailed analysis and examples of various NDL configurations, non-adaptive as well as adaptive, can be found in [27], [29], [30].

A. Theoretical foundation of NDLs

For optimal mitigation of non-Gaussian interference by nonlinear filters, it is imperative that the distributional properties of the interference are known, either *a priori* or through measurements. The "blind" NDL-based approach outlined in this paper arises from the methodology introduced in [31], which relies on the transformation of discrete or continuous signals into normalized continuous scalar fields with the mathematical properties of distribution functions. This methodology enables a variety of nonlinear signal processing techniques that naturally incorporate the consideration of such distributional properties, including those which have no digital counterparts.

For example, the time-dependent amplitude distribution $\Phi(D,t)$ of a continuous signal $x(t)$ obtained in a time window $w(t)$ can be expressed as

$$\Phi(D,t) = w(t) * \mathcal{F}_{\Delta D}\left[D - x(t)\right] \,, \tag{1}$$

where D is a *threshold* value, asterisk denotes convolution, and $\mathcal{F}_{\Delta D}(D)$ is a *discriminator function* that changes monotonically from 0 to 1 in such a way that most of this change occurs over some characteristic range of threshold values ΔD around zero. Since $\Phi(D,t)$ can be viewed as a surface in the three-dimensional space (t, D, Φ), the expression

$$\Phi\left(D_q(t), t\right) = q, \qquad 0 < q < 1\,, \tag{2}$$

defines $D_q(t)$ as a level (or contour) curve obtained from the intersection of the surface $\Phi = \Phi(D,t)$ with the plane $\Phi = q$, as illustrated in Fig. 1.

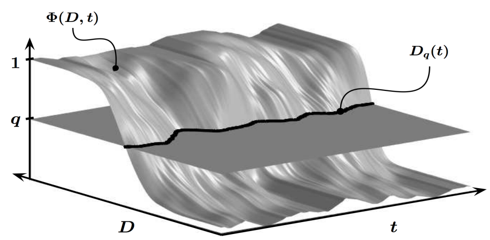

Fig. 1. $\boldsymbol{D_q(t)}$ as a level curve of the distribution function $\boldsymbol{\Phi(D,t)}$.

An explicit (albeit differential) equation of the level curve $D_q(t)$ can be obtained by differentiating equation (2) with respect to time (see, for example, [32], p. 551, eq. (4.29)), leading to

$$\frac{\mathrm{d}D_q}{\mathrm{d}t} = -\frac{\partial\Phi(D_q,t)/\partial t}{\phi(D_q,t)} + \nu\left[q - \Phi(D_q,t)\right], \qquad \nu > 0\,. \tag{3}$$

In (3), $\phi(D,t) = \partial\Phi(D,t)/\partial D$ is the amplitude *density* of $x(t)$ in the time window $w(t)$, and, since $\Phi(D,t)$ is a monotonically increasing function of D for all t, the added term in the right-hand side ensures the convergence of the solution to the chosen *quantile order* q regardless of the initial condition. It can be shown that, depending on the shape of the discriminator function $\mathcal{F}_{\Delta D}(D)$, equation (3) corresponds to a variety of nonlinear filters with desired characteristics. For example, in the limit $\Delta D \to 0$ equation (3) describes an analog *rank* filter (e.g. a *median filter* for $q = 1/2$) in an arbitrary time window $w(t)$, leading, as illustrated below, to the introduction of NDLs.

B. 1st order Canonical Differential Limiter

The digital median filter introduced in the early 1970s [33] is a widely recognized tool for removing outlier (i.e. impulsive) noise. From equation (4.6) in [31], an expression for the output $\chi(t)$ of an "exact" (or "true") analog median filter in an exponential time window with the time constant τ_0 can be written as

$$\dot{\chi}(t) = \lim_{\alpha\to 0} \frac{\frac{1}{2} - \mathcal{F}_{2\alpha}\left[\chi(t) - x(t)\right]}{\int_{-\infty}^{t}\mathrm{d}s\, \exp\left(\frac{s-t}{\tau_0}\right)\, f_{2\alpha}\left[\chi(t) - x(s)\right]}\,, \tag{4}$$

where $x(t)$ is the input signal, $\mathcal{F}_{2\alpha}(x)$ is a discriminator function with a characteristic width 2α, and $f_{2\alpha}(x) = \mathrm{d}\mathcal{F}_{2\alpha}(x)/\mathrm{d}x$ is its respective *probe*. In equation (4), $\mathcal{F}_{2\alpha}(x)$ and $f_{2\alpha}(x)$ are such that $\lim_{\alpha\to 0} \mathcal{F}_{2\alpha}(x) = \theta(x)$ and $\lim_{\alpha\to 0} f_{2\alpha}(x) = \delta(x)$, where $\theta(x)$ is the Heaviside unit step function [34] and $\delta(x)$ is the Dirac δ-function [35]. In equation (4), the parameter α can be called the *resolution parameter*.

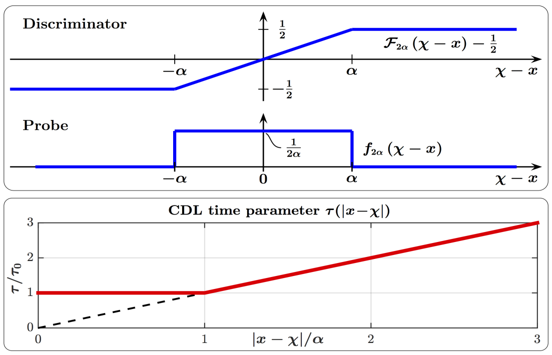

Fig. 2. "Ramp" discriminator and its respective boxcar probe (upper panel), and CDL time parameter $\tau = \tau(|x - \chi|)$ (lower panel).

Let us now choose a particularly simple discriminator function with a "ramp" transition, such that the respective probe will be a boxcar function, as illustrated in the upper panel of Fig. 2. Since the main contribution to the integral in the denominator of equation (4) will come from a relatively close proximity to the point $s = t$, for a finite and sufficiently large α such that $|\chi(t) - x(t)|$ generally remains smaller than the resolution parameter α, except for relatively rare outliers with a typical duration much smaller than τ_0, the denominator in equation (4) can be approximated by a constant value equal to $\tau_0/(2\alpha)$. For a finite α equation (4) becomes

$$\chi = x - \tau(|x - \chi|)\,\dot{\chi}\,, \tag{5}$$

where the time parameter $\tau = \tau(|x - \chi|)$ is given by

$$\tau(|x - \chi|) = \tau_0 \times \begin{cases} 1 & \text{for} \quad |x - \chi| \le \alpha \\ \frac{|x-\chi|}{\alpha} & \text{otherwise} \end{cases}\,, \tag{6}$$

as illustrated in the lower panel of Fig. 2.

We shall call a filter described by equations (5) and (6) a *1st order Canonical Differential Limiter (CDL)*. Note that when the time parameter τ is a constant (e.g., in the limit $\alpha \to \infty$), equation (5) describes a 1st order linear analog filter (RC integrator), wherein the rate of change of the output is proportional to the *difference signal* $x - \chi$. When the magnitude of the difference signal $|x - \chi|$ exceeds the resolution parameter α, however, the rate of change of the output is proportional to the *sign function* of the difference signal and no longer depends on the magnitude of the incoming signal $\chi(t)$, providing an output insensitive to outliers with a characteristic amplitude determined by the resolution parameter.

C. Higher order and adaptive NDLs

A high-order analog linear lowpass filter would be typically constructed as a 1st- (for odd-order filters) or 2nd- (for even-order filters) order stage followed by cascaded 2nd order stages, typically arranged from lowest to highest quality factor. A similar approach can be taken to extend the previous example to higher order NDLs. For example, a 3rd order NDL can be constructed as a 1st order CDL followed by a 2nd order linear filter, and a 4th order NDL – as a 2nd order NDL (introduced below) followed by a 2nd order linear filter. It may be practically unnecessary to cascade NDL stages, since the main burden of removing outliers will be carried out by the first stage, and the subsequent stages would be needed only to provide a desired frequency and phase response for the linear-regime NDL operation.

For even-order NDLs, a 2nd order NDL stage can be introduced as follows. Let us consider a second order lowpass stage that can be described by the differential equation

$$\chi(t) = x(t) - \tau\,\dot{\chi}(t) - (\tau Q)^2\,\ddot{\chi}(t)\,, \tag{7}$$

where $x(t)$ and $\chi(t)$ are the input and the output signals, respectively (which can be real-, complex-, or vector-valued), τ is the *time parameter* of the stage, Q is the quality factor, and the dot and the double dot denote the first and the second time derivatives, respectively.

For a linear time-invariant filter the time parameter τ and the quality factor Q in equation (7) are constants, so that when the input signal $x(t)$ is increased by a factor of K, the output $\chi(t)$ is also increased by the same factor, as is the difference between the input and the output $x(t) - \chi(t)$ (the *difference signal*). A transient outlier in the input signal would result in a transient outlier in the difference signal of a filter, and an increase in the input outlier by a factor of K would result, for a linear filter, in the same factor increase in the respective outlier of the difference signal. If a significant portion of the frequency content of the input outlier is within the passband of the linear filter, the output will typically also contain an outlier corresponding to the input outlier, and the amplitudes of the input and the output outliers will be proportional to each other. A reduction (limiting) of the output outliers, while preserving the relationship between the input and the output for the portions of the signal not containing the outliers, can be achieved by proper dynamic modification of the filter parameters τ and Q in equation (7) based on the magnitude (for example, the absolute value) of the difference signal. A filter comprising such dynamic modification of the filter parameters based on the magnitude of the difference signal will be called an NDL.

Since at least one of the filter parameters depends on the instantaneous magnitude of the difference signal, the differential equation describing such a filter is nonlinear. However, even though in general an NDL is a nonlinear filter, if the parameters remain constant as long as the magnitude of the difference signal remains within a certain range, the behavior of the NDL will be linear during that time. Thus an NDL can be configured to behave linearly as long as the input signal does not contain outliers. By specifying a proper dependence of the NDL filter parameters on the difference signal it can be ensured that, when the outliers are encountered, the nonlinear response of the NDL limits the magnitude of the respective outliers in the output signal.

A comprehensive discussion and illustrative examples of various dependencies of the NDL parameters on the difference signal can be found in [27]–[30]. As a particular example, one can set the quality factor in equation (7) to a constant value, and specify the time parameter τ as

$$\tau(|x-\chi|) = \tau_0 \times \begin{cases} 1 & \text{for} \quad |x-\chi| \le \alpha \\ \left(\frac{|x-\chi|}{\alpha}\right)^{\beta} & \text{otherwise} \end{cases} \tag{8}$$

with $\beta > 0$. Parameter β in equation (8) controls the behavior of the NDL in the presence of outliers – the larger its value, the stronger the suppression of outliers. From practical considerations, the value $\beta = 1$ (as in (6)) is convenient, so we refer to the NDL with $\beta = 1$ as a Canonical Differential Limiter (CDL).

As can be seen from equation (8), in the limit of a large resolution parameter, $\alpha \to \infty$, an NDL becomes equivalent to the respective linear filter with $\tau = \tau_0 = \text{const}$. This property of an NDL enables its full compatibility with linear systems. At the same time, when the noise affecting the signal of interest contains impulsive outliers, the signal quality (e.g. as characterized by a SNR, a throughput capacity of a communication channel, or other measures of signal quality) would exhibit a global maximum at a certain finite value of the resolution parameter $\alpha = \alpha_0$. As illustrated in the next section, this property of an NDL enables its use for improving the signal quality in the presence of impulsive noise, effectively reducing the spectral density of the interference in the signal passband without significantly affecting the signal of interest.

The value of the resolution parameter that maximizes the signal quality may vary widely depending on the composition of the signal+noise mixture, for example, on the SNR and the relative spectral and temporal structures of the signal and the noise. Adaptive NDL (ANDL) configurations (see [27], [29], [30]) contain a sub-circuit (typically 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. While a specific choice of an ANDL adaptation scheme would be driven by the considerations of the respective temporal structures of the noise and of the signal of interest, in the examples of the next section we use an extremely simplified adaptation approach. In particular, the resolution parameter is obtained by applying a gain to the "base" value given by a robust measure of central tendency (the *median*) of the magnitude of the difference signal, obtained on a relatively large time scale (i.e., much larger than the AC line frequency), and the value of the gain is then chosen to maximize the passband SNR.

III. Performance of NDLs

In this section, we provide an overall qualitative illustration of the applicability of NDLs for noise mitigation in powerline communication systems. We do not attempt a direct quantitative comparison between the performance of NDLs and other methods, since for nonlinear filters quantitative results would vary greatly depending on the details of particular compositions of the signal+noise mixtures.

In the examples that follow we use a rather simplistic model that captures the essential features of the PLC noise such as its impulsive and cyclostationary nature. In particular, we use noise mixtures consisting of three basic components: (1) a background Gaussian component (with the power spectrum density decaying at an approximate rate of 30 dB per 1 MHz), (2) cyclostationary exponentially decaying noise "bursts" with the repetition frequency at twice the AC line frequency and a typical duration ranging from hundreds of microseconds to a few milliseconds, and (3) random short (e.g., several microseconds) impulsive bursts with normally distributed amplitudes and typical interarrival times of order of 100 μs. In this simplified model, we intentionally omit the vagaries of a particular noise that may be encountered in practice (such as, for example, presence of narrow-band interferers and a more complicated spectral and temporal structure), since those would not significantly affect the qualitative behavior of NDLs in the context of their overall effect on the passband SNR.

When we vary the total noise power in a particular example, we keep the power of the background Gaussian component at a chosen constant value, and thus the increase in the noise power is entirely due to the increase in the impulsive (cyclostationary+random) noise component. Further, we preserve the composition of the impulsive noise in terms of the relative powers of its cyclostationary and random components.

Since we focus on the passband SNR as a signal quality indicator, a particular modulation protocol is of little relevance, and we assume that the signal of interest is just a band-limited white Gaussian noise. In particular, in the examples that follow, the signal of interest is a white Gaussian noise limited to the 42–89 kHz band, which would correspond to an OFDM signal of PRIME [3].

As an NDL filter, we use a 3rd order NDL constructed as a 1st order CDL with $\tau_0 \approx 0.9\,\mu$s, followed by a 2nd order linear filter with the time parameter $\tau = \tau_0$ and the quality factor $Q = 1$. Thus in the limit $\alpha \to \infty$ this NDL becomes a 3rd order Butterworth filter with the frequency cutoff at approximately 178 kHz, or twice the highest frequency of the signal of interest. As the base resolution parameter for the CDL, we take the *median* of the absolute value of the difference between the input signal+noise mixture and the signal+noise mixture filtered by a 1st order linear lowpass filter with $\tau = \tau_0$ (thus corresponding to the CDL in the limit $\alpha \to \infty$). Then the CDL resolution parameter α is obtained by multiplying this base value by some positive *gain*.

Given a particular signal+noise mixture as the NDL input, let us first consider, as illustrated in Fig. 3, the SNRs obtained in the signal passband for the NDL outputs. In this example, the power of the background noise in the signal passband is one tenth of that of the signal, corresponding to the 10 dB passband SNR. In Fig. 3, the horizontal colored dashed lines indicate the "linear" SNRs, that is, those obtained without NDL filtering. These are shown for various levels of added impulsive noise component, ranging from zero (i.e., purely Gaussian noise equal to the background noise) to 99 times the power of the background noise (resulting in the -10 dB SNR). The solid curves of the respective colors correspond to the SNRs (as functions of the gain applied to the base resolution parameter) obtained for the NDL outputs. As one can see, while asymptotically approaching the linear SNR values in the limits of large resolution parameters, the SNRs for the NDL outputs exhibit global maxima at certain values of the resolution parameter gains, and these maxima are the more pronounced the stronger the impulsive component.

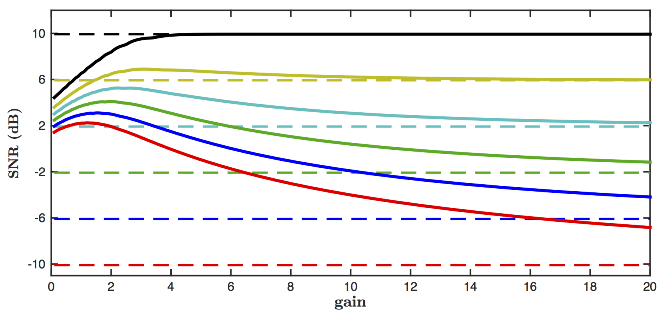

Fig. 3. Passband SNRs as functions of gain applied to the "base" resolution parameter.

If the NDL resolution parameter is set to correspond to the SNR maximum, we can plot such maximum SNRs as a function of the total noise power, as illustrated in the lower panel of Fig. 4. In this panel, the solid black line corresponds to the linear SNR, and the colored lines plot the NDL SNRs for the noise with three different cyclostationary time structures. In particular, the green line corresponds to "narrow" ($\sim 100\,\mu$s) cyclostationary noise bursts, the blue line corresponds to "mid-range" ($\sim 500\,\mu$s), and the red line – to "wide" (~ 2.5 ms) bursts. One may note that narrower cyclostationary noise bursts would result in higher *peakedness* of the noise, that is, in a more impulsive noise. This is illustrated in the upper panel of Fig. 4, which provides time-domain snapshots of the input noise observed for the 0 dB passband SNR (that is, for the passband power of the impulsive component 9 times that of the background noise), and plotted in the colors corresponding to the SNR curves. The noise peakedness is measured in units of "decibels relative to Gaussian" (dBG), in terms of kurtosis in relation to the kurtosis of the Gaussian distribution [28], [30], and is indicated next to the noise traces by the text of the respective color. Thus one may observe from Fig. 4 that NDLs would provide larger SNR improvement for relatively stronger impulsive noise. Likewise, since the signal of interest itself is characterized by low peakedness, it would reduce the overall peakedness of the signal+noise mixture. Thus the potential relative SNR improvement provided by NDLs would be generally more significant at low SNR conditions.

Fig. 5 provides an example of passband noisy signal traces

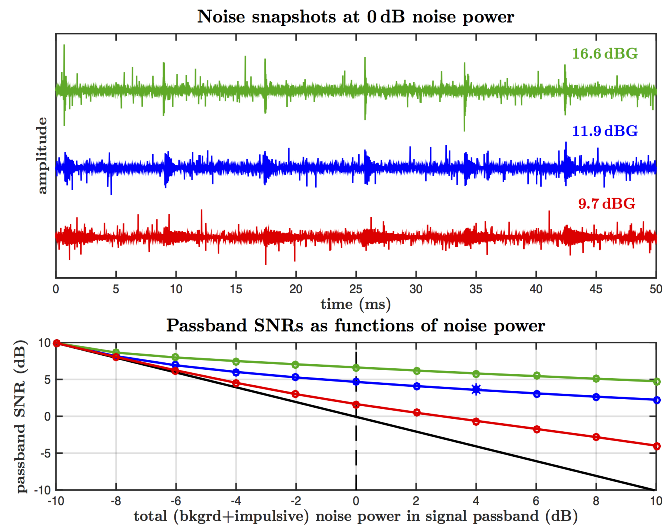

Fig. 4. SNRs as functions of total noise power (lower panel), and snapshots of time-domain input noise traces observed for 0 dB passband SNR (upper panel).

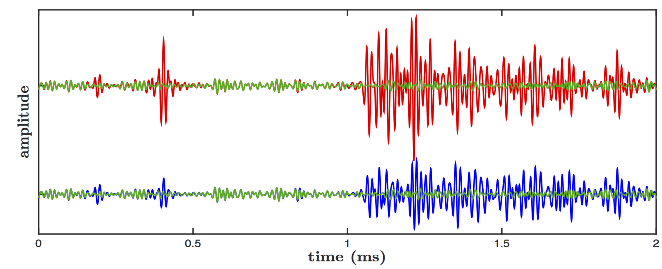

Fig. 5. Example of passband noisy signal traces obtained without (red line) and with NDL (blue line).

obtained without (red line) and with NDL (blue line) for the 4 dB total passband noise power, and for the "mid-range" ($\sim 500\,\mu$s) cyclostationary bursts duration (as indicated by the asterisk on the blue SNR curve in the lower panel of Fig. 4). For comparison, the traces shown by the green lines correspond to the signal affected by the background (Gaussian) noise only. One should be able to see that in the absence of impulsive bursts the NDL behavior corresponds to that of a linear filter. During the impulsive bursts, however, the dynamics of the NDL changes, resulting, for an appropriately chosen resolution parameter, in disproportionally stronger overall suppression of the noise relative to the signal of interest, and thus leading to the increase in the passband SNR.

A. Comment on pre-filtering and NDL use methodology

As discussed in our prior work [27]–[30], the distributions of non-Gaussian signals are generally modifiable by linear filtering, and non-Gaussian interference can often be converted from sub-Gaussian into super-Gaussian, and *vice versa*, by linear filtering (that may or may not affect the signal of interest). Thus employing appropriate linear filtering preceding an NDL in a signal chain can greatly improve effectiveness of NDL-based interference mitigation. While we have previously outlined several approaches to such distribution modification by Linear Front End (LFE) filtering, and to identifying non-Gaussian components in an interfering signal [27], [29], the development of systematic procedures for identification of non-Gaussian interference components and for design of suitable LFE filtering remains a challenging task that is a subject of ongoing research.

IV. Conclusion

In this paper, we introduce blind adaptive analog nonlinear filters, referred to as Adaptive Nonlinear Differential Limiters (ANDLs), and demonstrate their potential use for noise mitigation in PLC systems. ANDL can be used either as a stand-alone simple and inexpensive impulsive noise reduction tool, or in combination with other interference mitigation methods. When used alone, ANDLs can provide improvement in the overall signal quality ranging from "no harm" for low noise conditions to over 10 dB improvement in the overall passband SNR for high-power noise with strong impulsive component. While the quantitative results may vary significantly with the signal+noise compositions encountered in practice, and with a particular choice of an NDL and its linear pre-filtering stage, the NDLs' ability to disproportionally reduce the PSD of impulsive noise in the signal passband provides an opportunity for noise mitigation in PLC systems that deserves further investigation.

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