Bandwidth is not enough

“Hidden” outlier noise and its mitigation

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What's so special? Why all this trouble?

- Tricky to detect
- Hard to track and quantify
- Hides and reappears

- Enables "extra" mitigation

Part I: Many challenges and misconceptions

Outlier noise: Ubiquitous but often elusive

Outlier noise: Why care? What works?

What hides outlier noise?

- #1 – General filtering effects
- #2 – “Outliers” vs “outlier noise” ambiguity
- #3 – Insufficient observation bandwidth
- #4 – Spectral ambiguity
- #5 – Ambiguity of amplitude densities
- #6 – Wide range of powers across spectrum

Outlier noise: Observation vs. mitigation

Complex signal+noise compositions

Part II: Methodology and tools for outlier noise mitigation

ADiC components and their implementation

ADiC as main building block
Basic ADiC structure
QTFs for robust range
Much better way: Feedback-based ADiC

ADiC-based outlier noise filtering

Spectral reshaping by ADiC and *efecto cucaracha*
CAF: Removing outlier noise while preserving signal of interest
CAF vs linear: Effect on channel capacity
"No harm" (default) CAF configurations

Analog vs digital

Digital: Where to get bandwidth?
Addressing complex interference scenarios
Practical configurations: CAF for chirp signals
Practical configurations: CAF for OFDM
CAF for clipping distortions
Designing development & testing platform

Broader picture

Part I

Many challenges and misconceptions

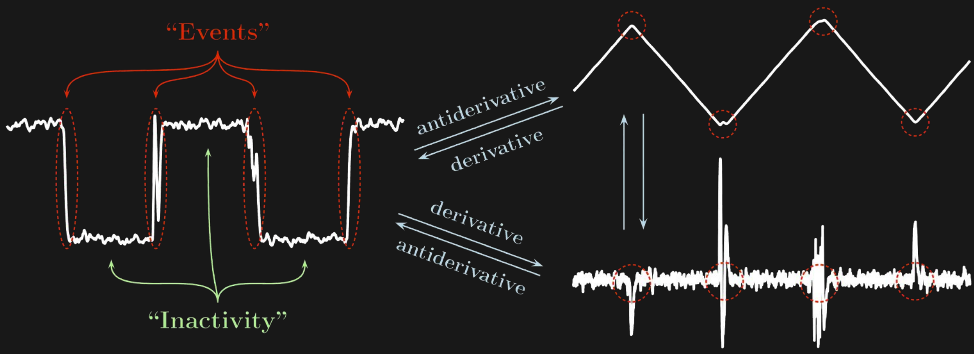
Outlier noise: Ubiquitous but often elusive

"It isn't that they cannot find the solution. It is that they cannot see the problem."

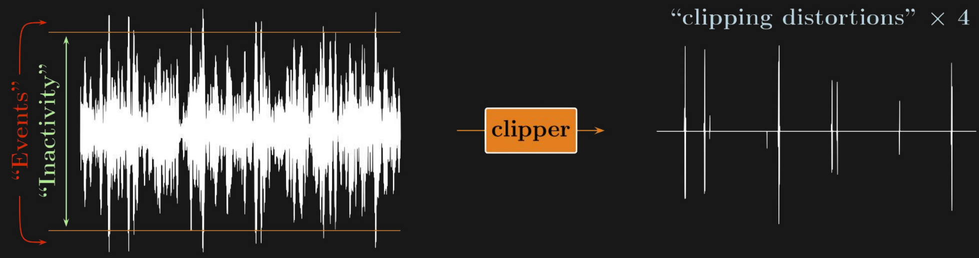
– G.K. Chesterton, *The Scandal of Father Brown* (1933)

Outlier noise's origins: "Events" separated by "inactivity"

E.g. coupled from external sources. . .



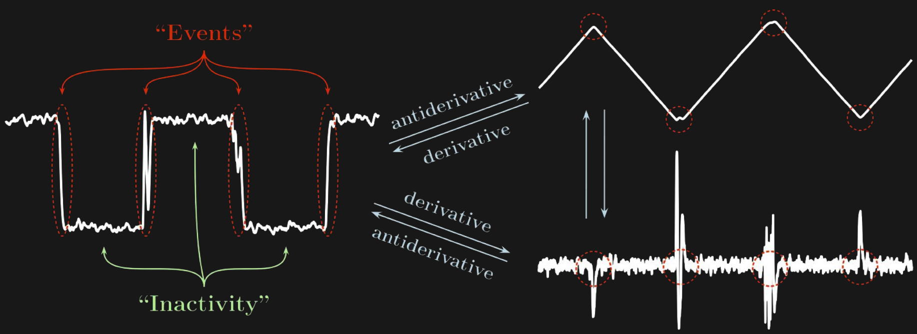
. . . or generated by intermittent nonlinear distortions of signal itself



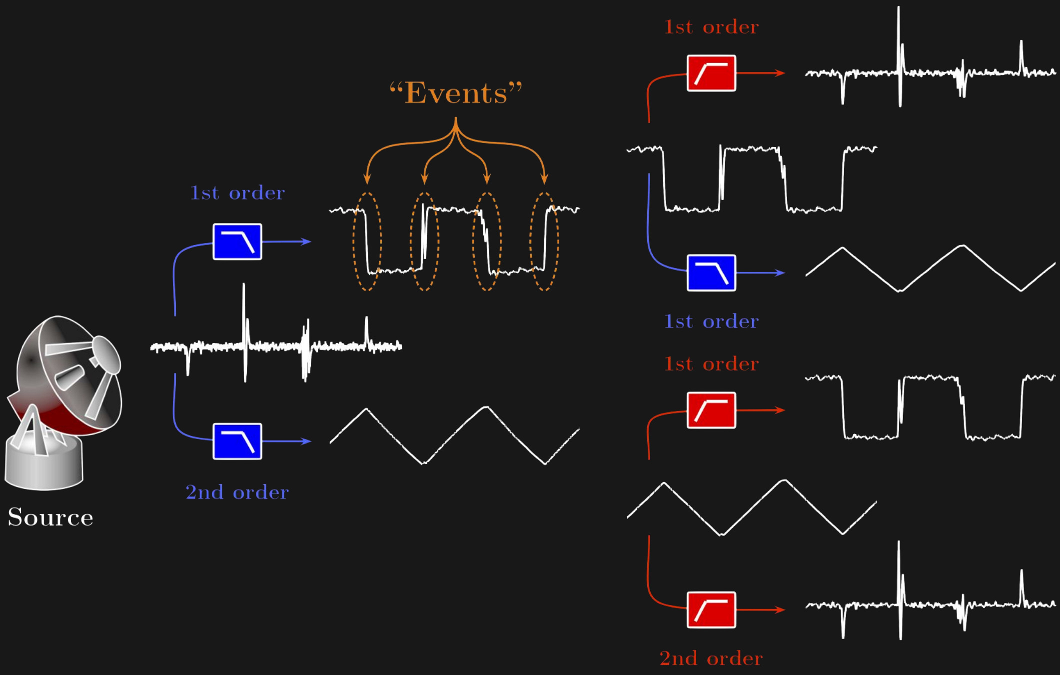
Outlier noise's origins: "Events" separated by "inactivity"

Source of "hidden" outlier noise that disappears and reappears due to various filtering effects (including fading and multipath):

- Analog domain filtering: Combinations of signal and its derivatives and antiderivatives (e.g. convolution) of various orders
- Digital domain filtering: Combination of differencing and summation operations



Outlier noise's origins: "Events" separated by "inactivity"

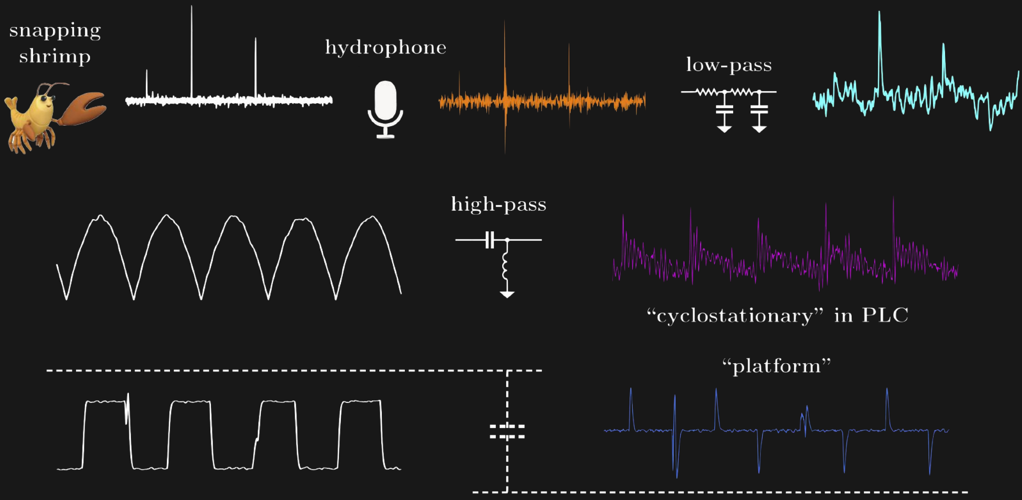


Outlier noise: Ubiquitous but often elusive

Comes from many **natural** and **technogenic** (man-made) sources

E.g. **impulsive** noise, **shot** noise, **transient** noise, **sparse** noise, **platform** noise, **burst** noise, **popcorn** noise, **bi-stable** noise, **crackling** noise, clicks & pops, etc.

It changes "looks" or hides and reappears as it propagates



Technogenic noise is ubiquitous . . .

E.g. close physical proximity of multiple coexisting devices, high-density digital circuits and multiple transmitters and receivers

- E.g. smartphones with Wi-Fi, Bluetooth, GPS; multiple protocols and frequency bands

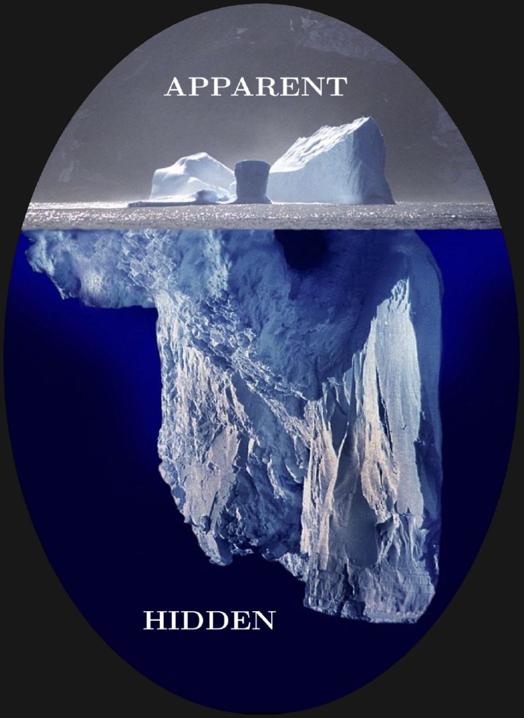
- Cellular voice
- Cellular data
- Bluetooth
- WiFi
- GPS
- Display

- Speaker
- Microphone
- Power supplies
- Digital clocks
- Sensors
- Buses

Also: Electronics equipment in home and office; dense urban and industrial environment; increasingly crowded wireless spectrum

(e.g. radar-communications, radar-radar, narrowband/UWB, etc.)

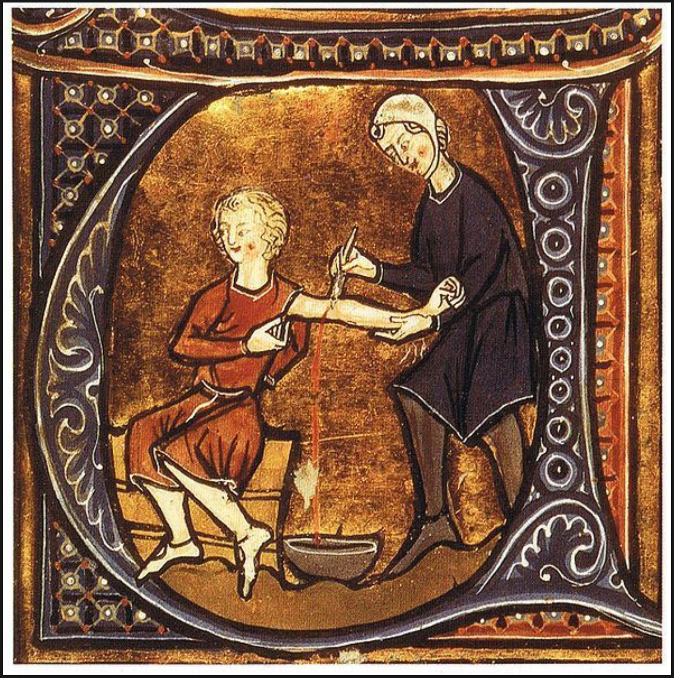
. . . yet its omnipresence and impact remain underappreciated



Outlier noise is omnipresent,

yet only small fraction is apparent . . .

. . . and how we treat problem is still in Dark Ages



Outlier noise: Why care? What works?

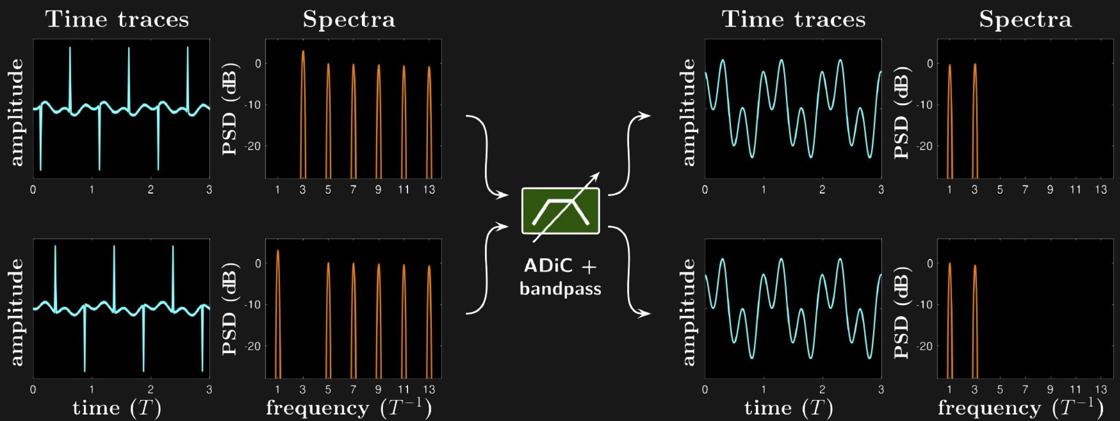
Why care? What works?

In-band outlier noise can be removed in real time

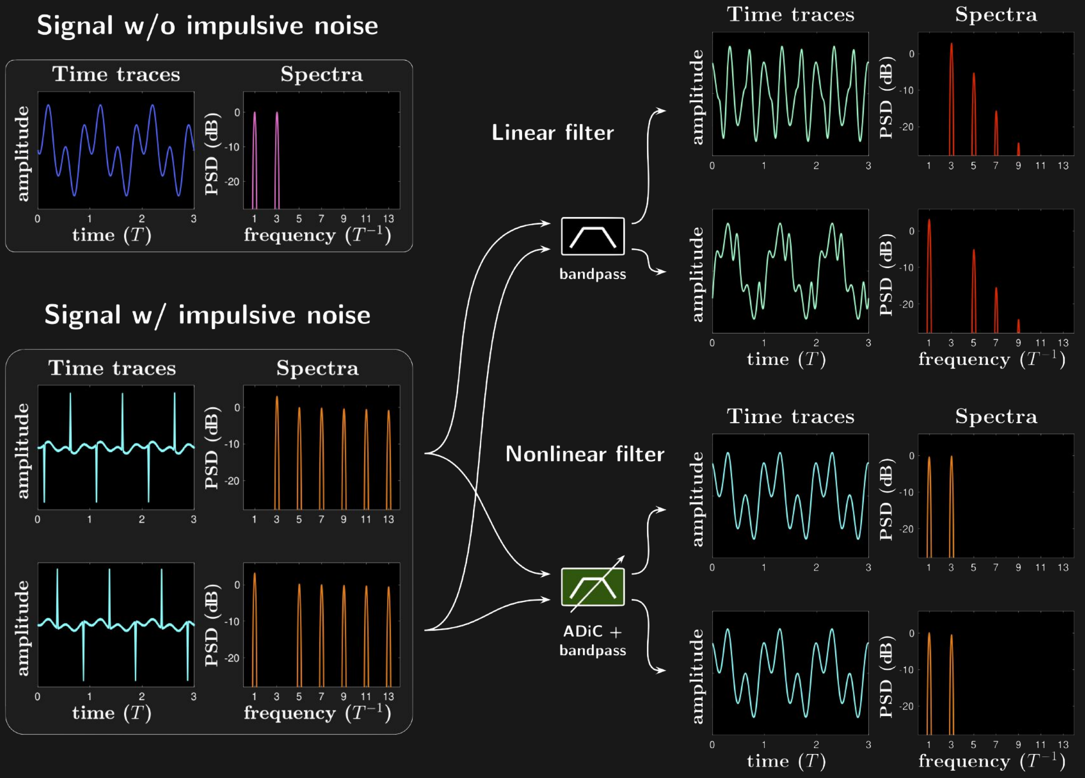
Nonlinear filters:

- Disproportionately affect different temporal and/or amplitude structures
- Enable mitigation levels unattainable by linear filtering (e.g. in signal band)

Toy example: ADiC-based filtering suppresses in-band impulsive interference



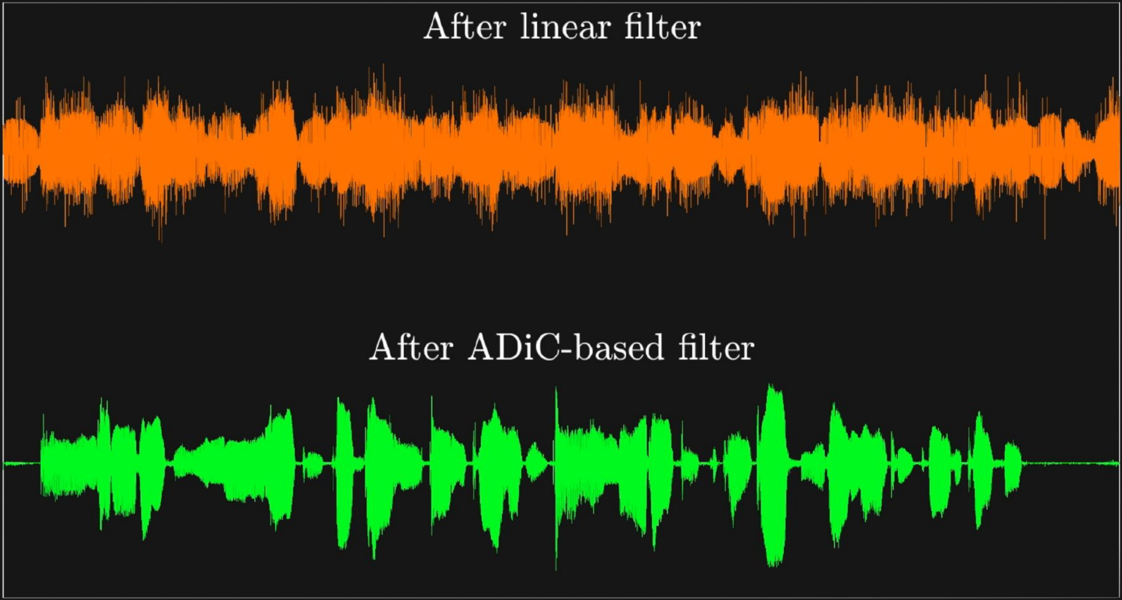
Toy example



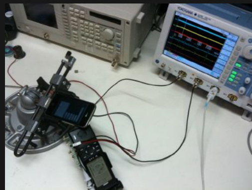
CLICK ON FILTER SYMBOLS FOR AUDIO

Why care? What works?

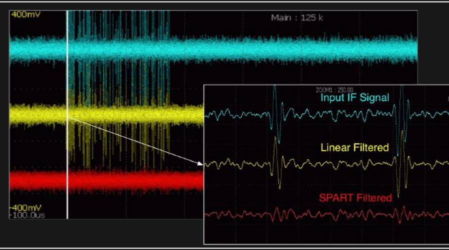
CLICK ON FIGURE BELOW TO PLAY MOVIE



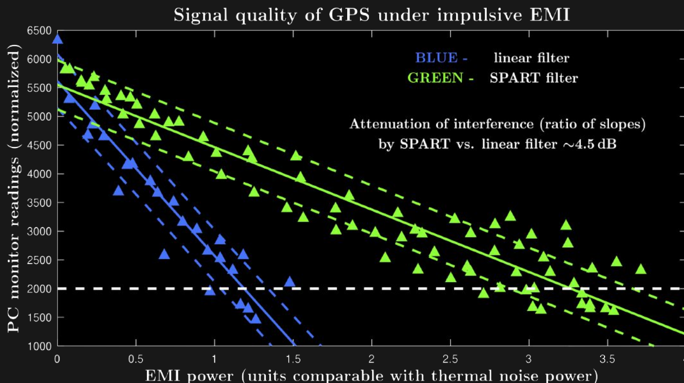
Even crude intermittently nonlinear filters can help



Bench setup



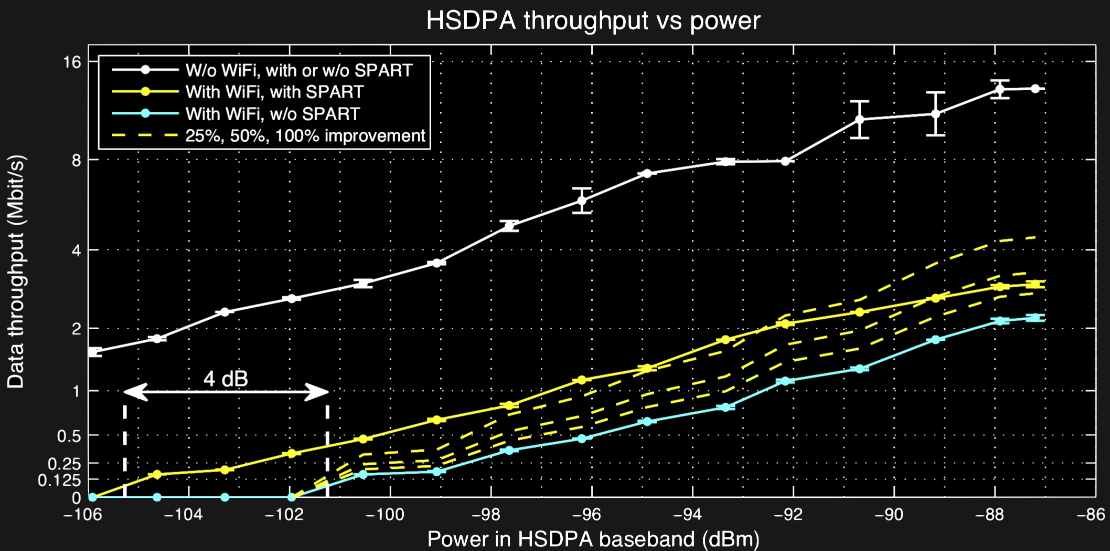
Mitigation of WiFi/Bluetooth interference observed at IF in Garmin GPS-12



Mitigation of EMI from terrestrial communications: Test in RF anechoic chamber of GPS company

Even crude intermittently nonlinear filters can help

Mitigation of 2.4 GHz WiFi interference with 1.95 GHz HSDPA



HSDPA data throughput at various signal levels with and without strong WiFi interference of constant power, and with and without SPART mitigation

Adapted from: "Impulsive interference in communication channels and its mitigation by SPART and other nonlinear filters," EURASIP J. Adv. Signal Process., vol. 2012, no. 79, 2012

Why care? What works? – Fact or fiction?

- ✗ "We can always directly observe outlier noise in time domain"
- ✗ "We can observe outlier noise in power spectra/spectrograms"
- ✗ "We can always deduce presence of outlier noise from amplitude density observations"

✓ **Yet outlier noise can be mitigated even when it's not directly observed!**

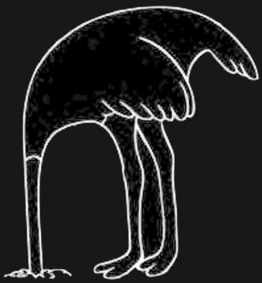
WHY CARE? WHAT WORKS?

TAKE AWAY

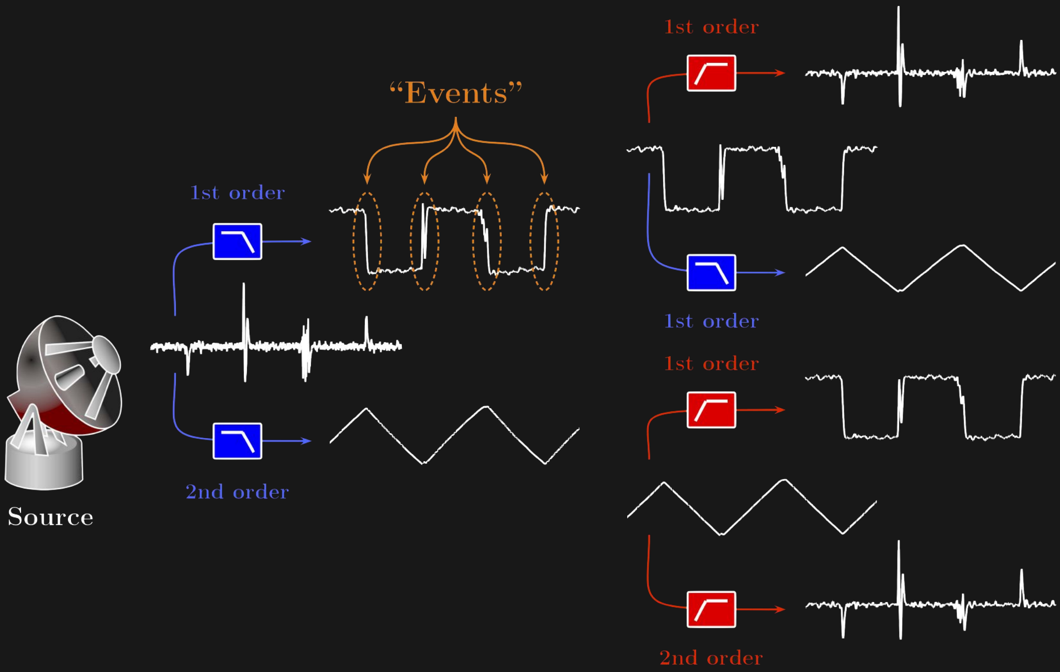
- Enables in-band real-time mitigation
- Utilizing intermittently nonlinear filters

What hides outlier noise?

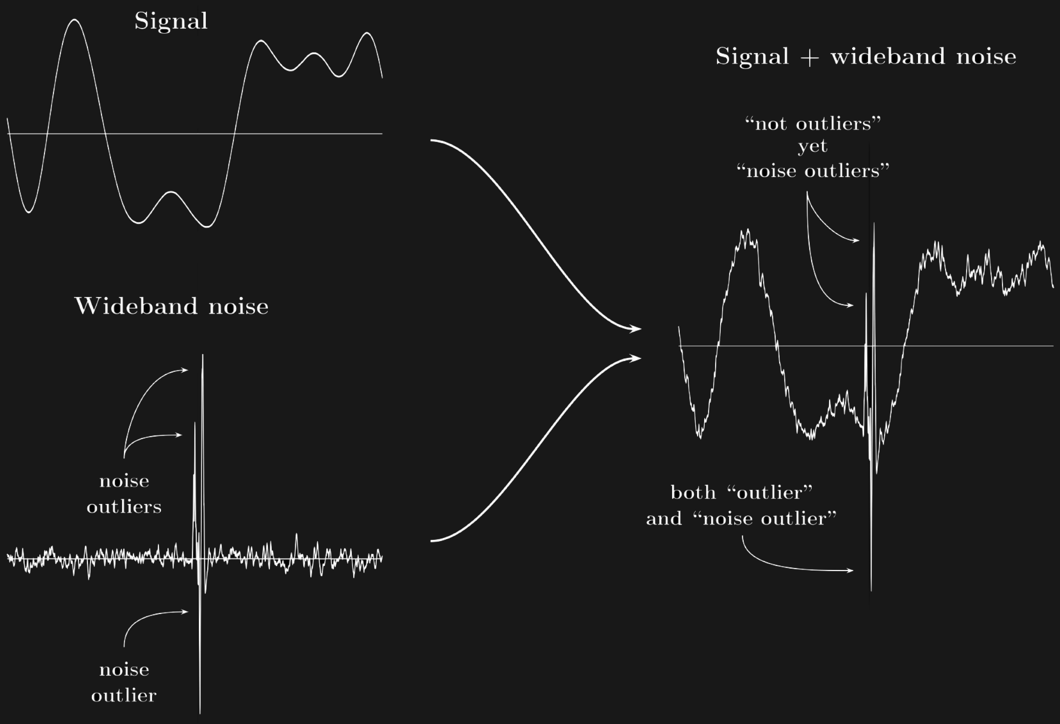
"If I don't see it then I can ignore it!"



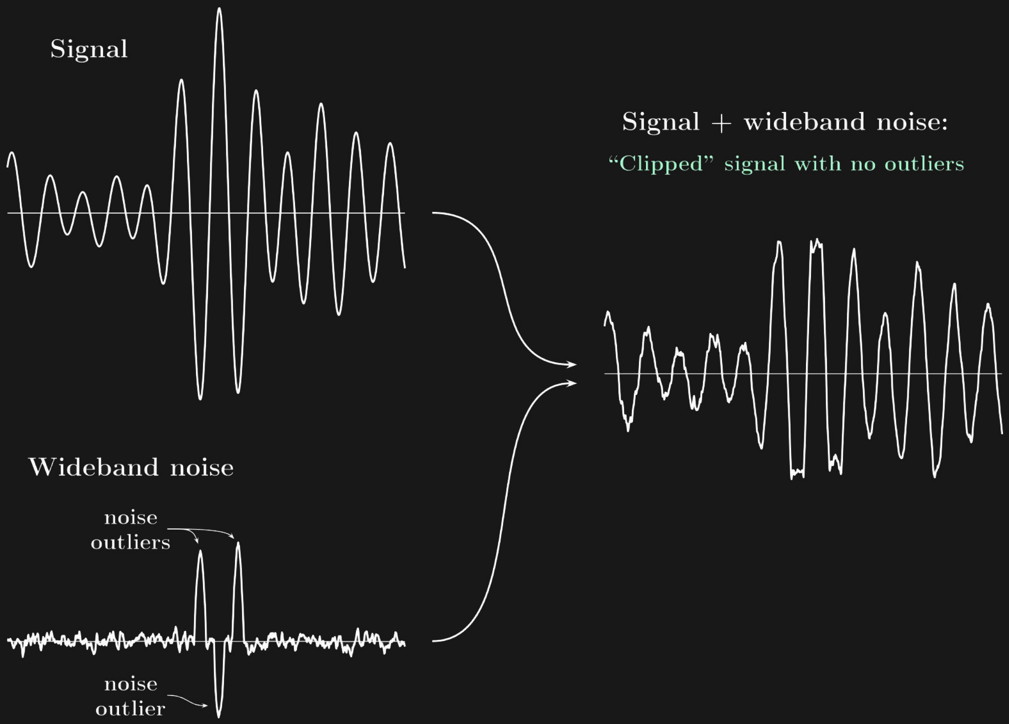
#1 – General filtering effects



#2 – “Outliers” vs “outlier noise” ambiguity



#2 – “Outliers” vs “outlier noise” ambiguity: Clipping



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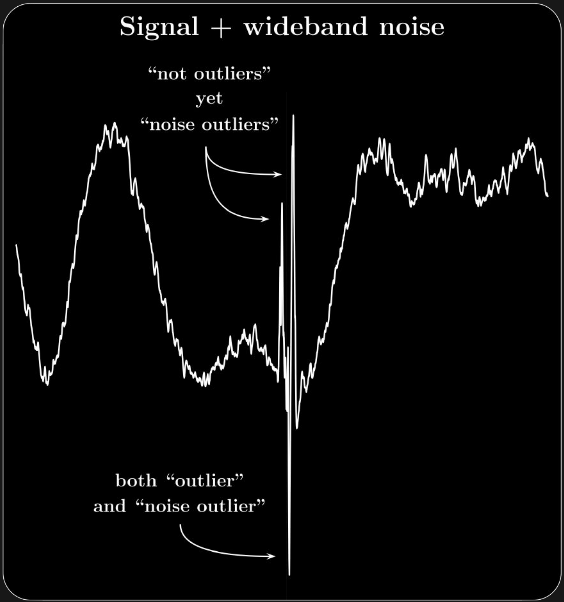
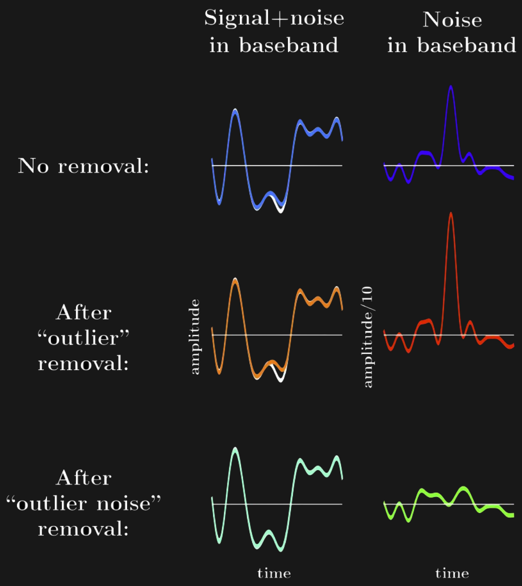


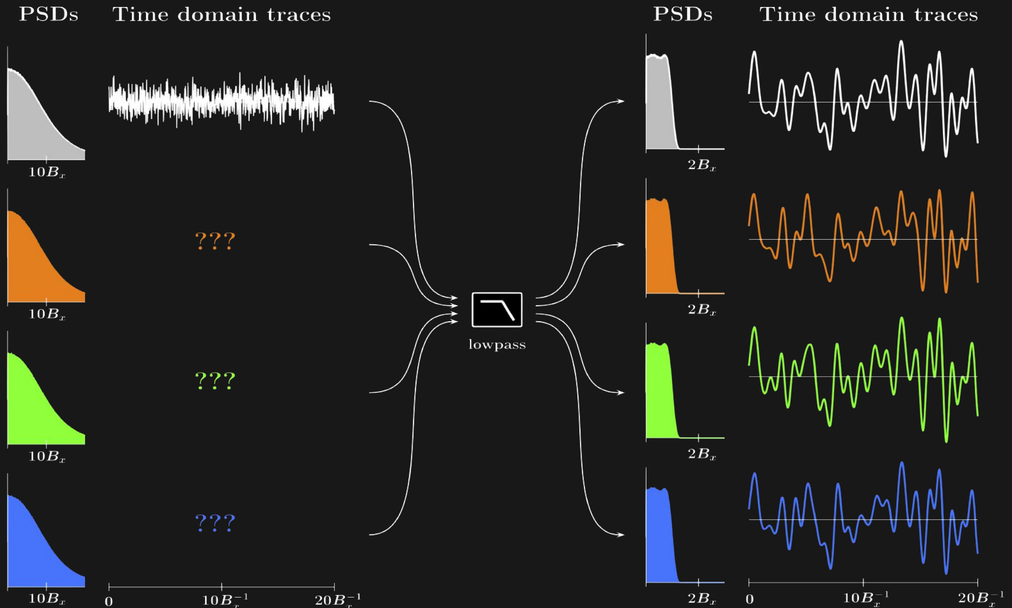


Removing “outliers” degrades baseband signal

We want to remove **outlier noise**!

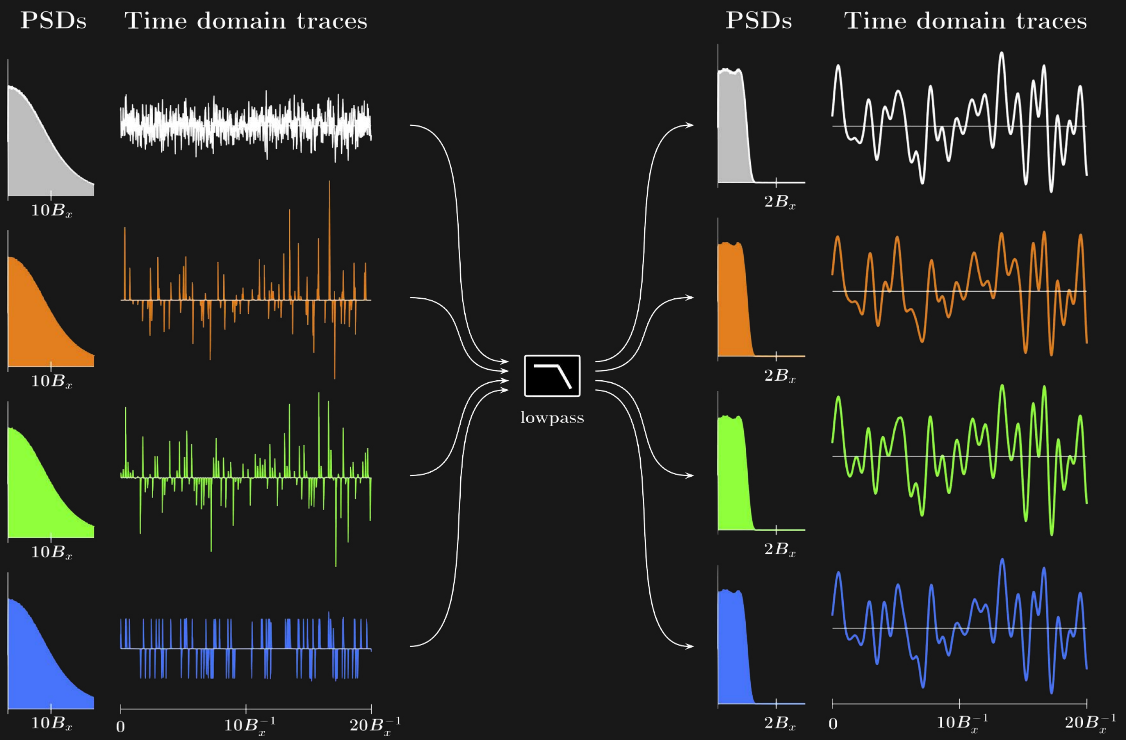
What hides outlier noise?

#3 – Insufficient observation bandwidth
#4 – Spectral ambiguity



Can it be removable outlier noise instead?

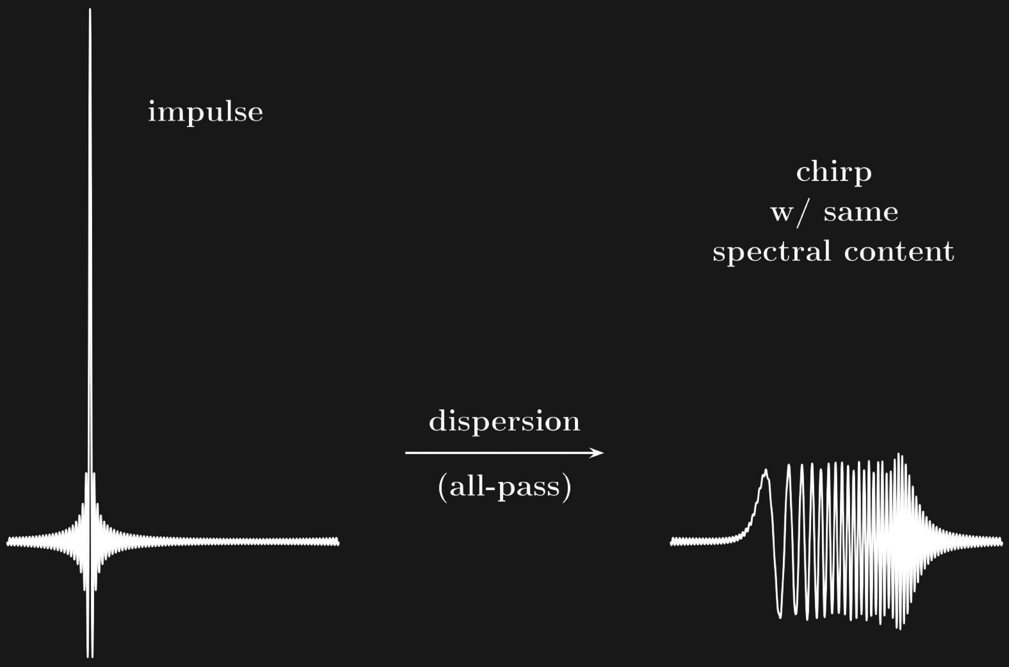
Wide-bandwidth time-domain observations are required!



What hides outlier noise?

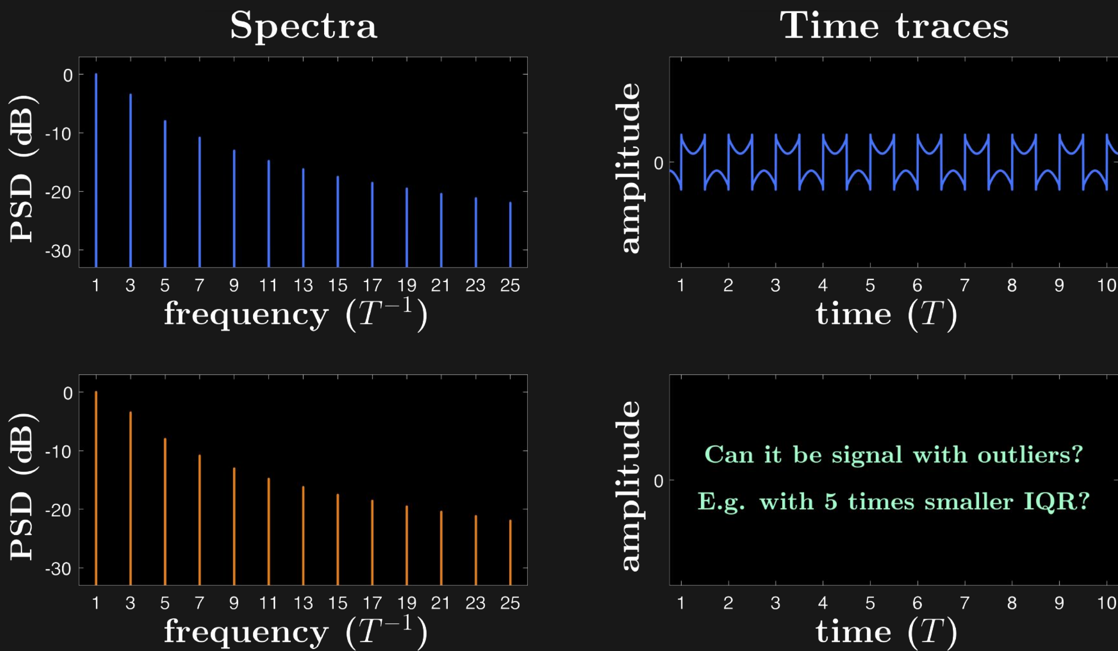
#1 – General filtering effects

#4 – Spectral ambiguity



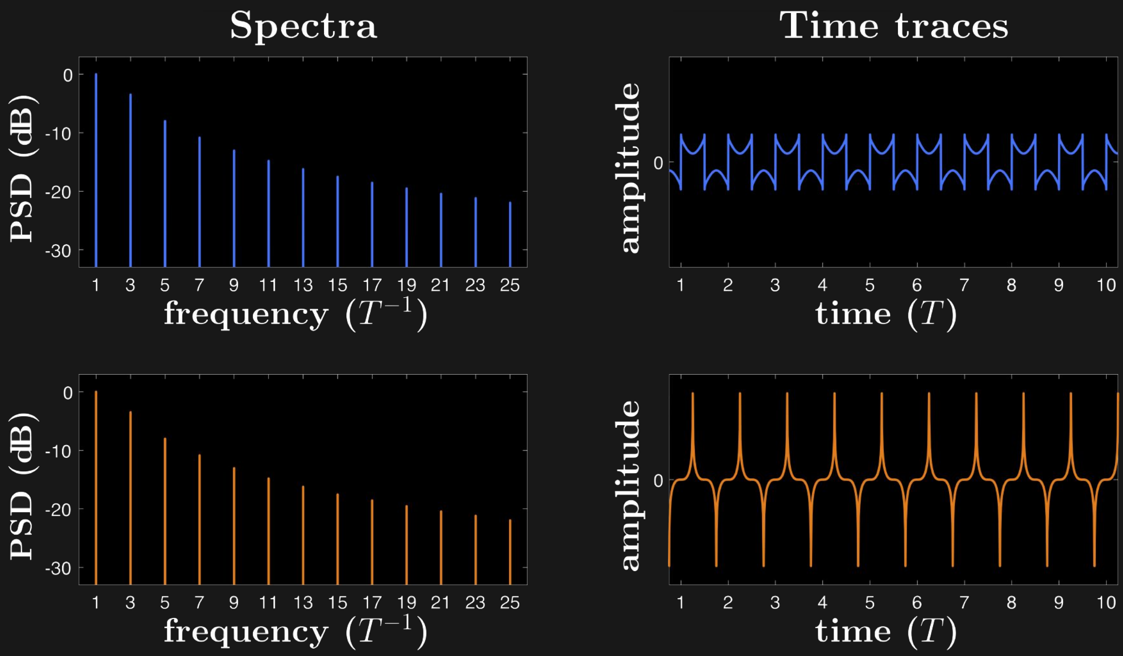
What hides outlier noise?

#4 – Spectral ambiguity



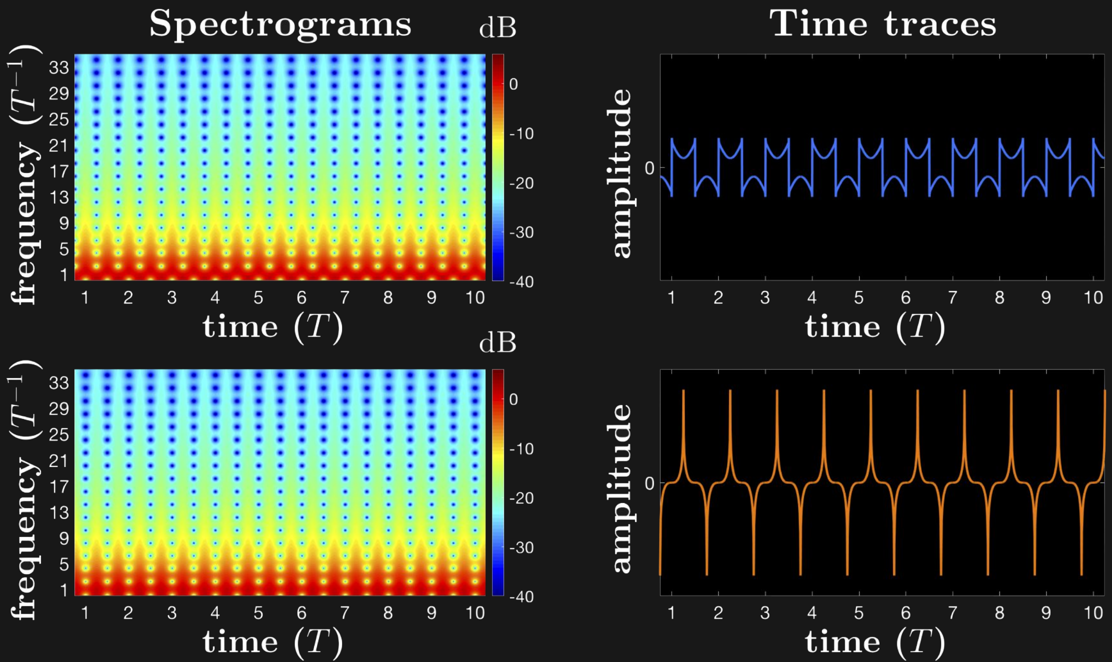
What hides outlier noise?

#4 – Spectral ambiguity



And how about spectrograms?

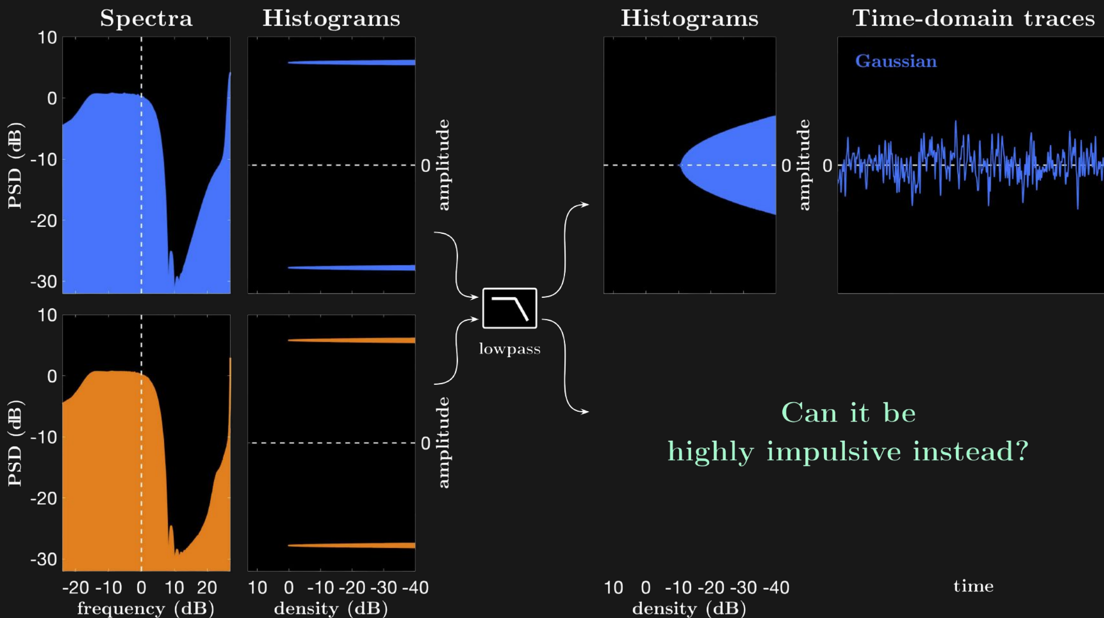
#4 – Spectral ambiguity



What hides outlier noise?

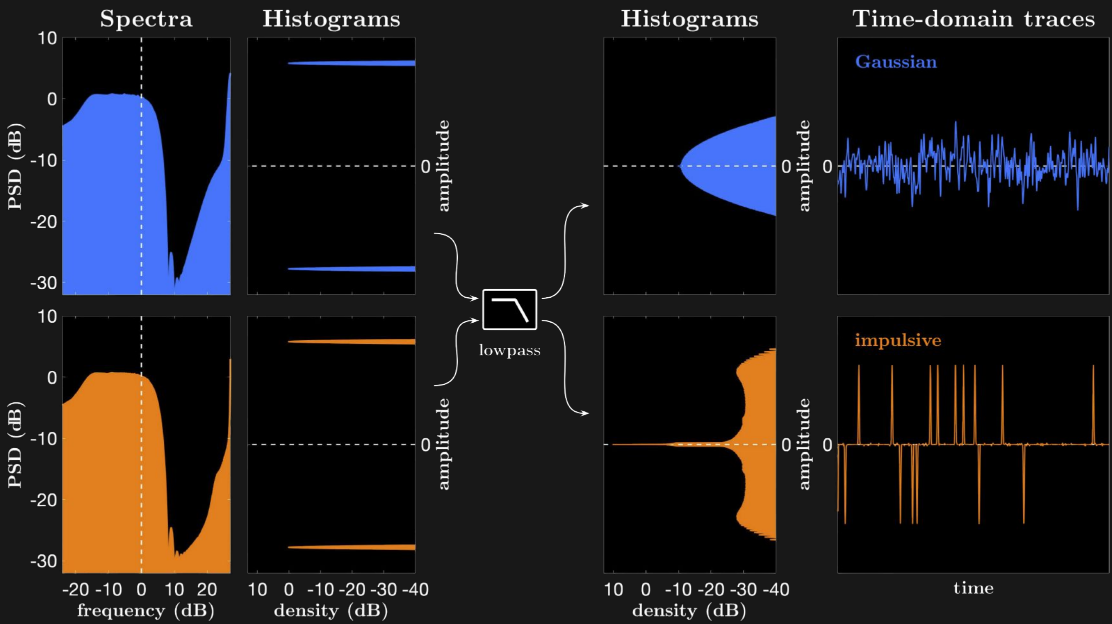
#5 – Ambiguity of amplitude densities
#6 – Wide range of powers across spectrum

E.g. for bi-stable process or two-level PWM:



What hides outlier noise?

#5 – Ambiguity of amplitude densities
#6 – Wide range of powers across spectrum

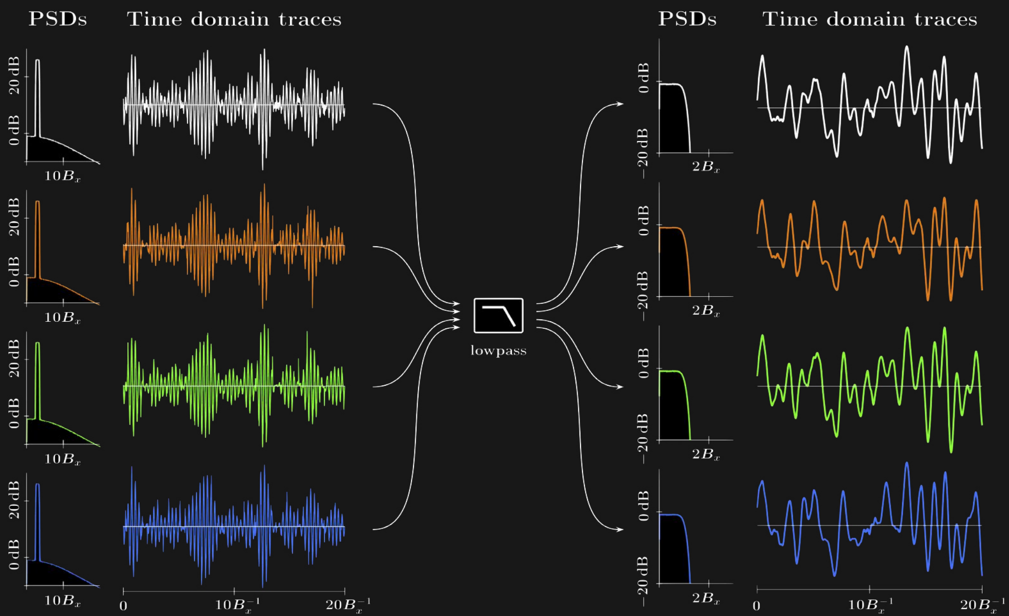


Bandwidth itself is not enough!

What hides outlier noise?

#6 – Wide range of powers across spectrum

E.g. for strong adjacent-channel interference:



Is there removable outlier noise affecting baseband?

WHAT HIDES OUTLIER NOISE?

TAKE AWAY

- Ambiguous and elusive nature
- Inadequacy of tools used for its observation and/or quantification

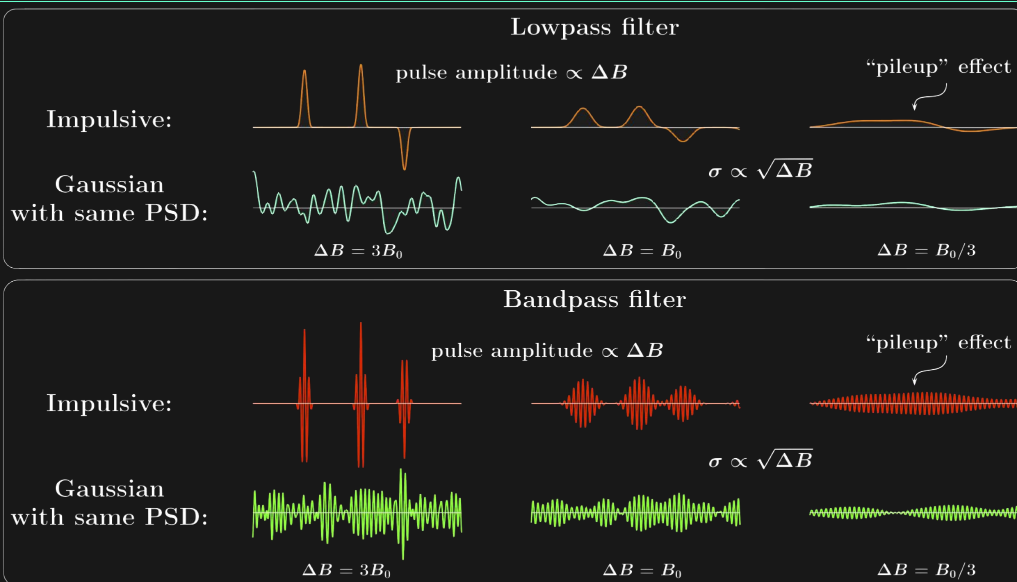
What hides outlier noise?

What hides outlier noise?

#3 – Insufficient observation bandwidth (e.g. below “pileup threshold”)

Time × bandwidth is constant

$\implies$ Definition of “local” depends on bandwidth

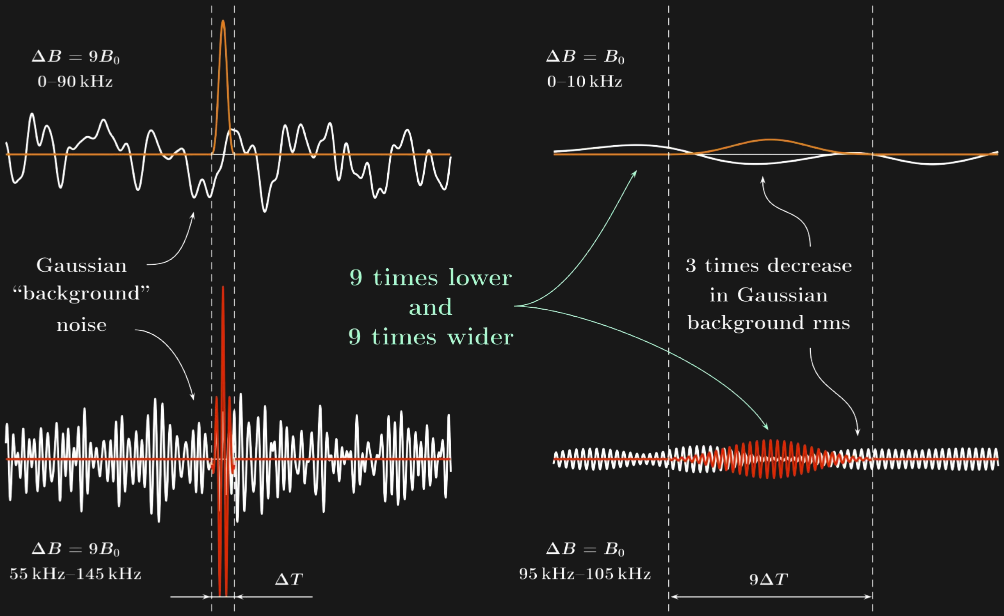


Reduction in bandwidth “hides” outlier noise

What hides outlier noise?

#3 – Insufficient observation bandwidth

Even above pileup threshold:

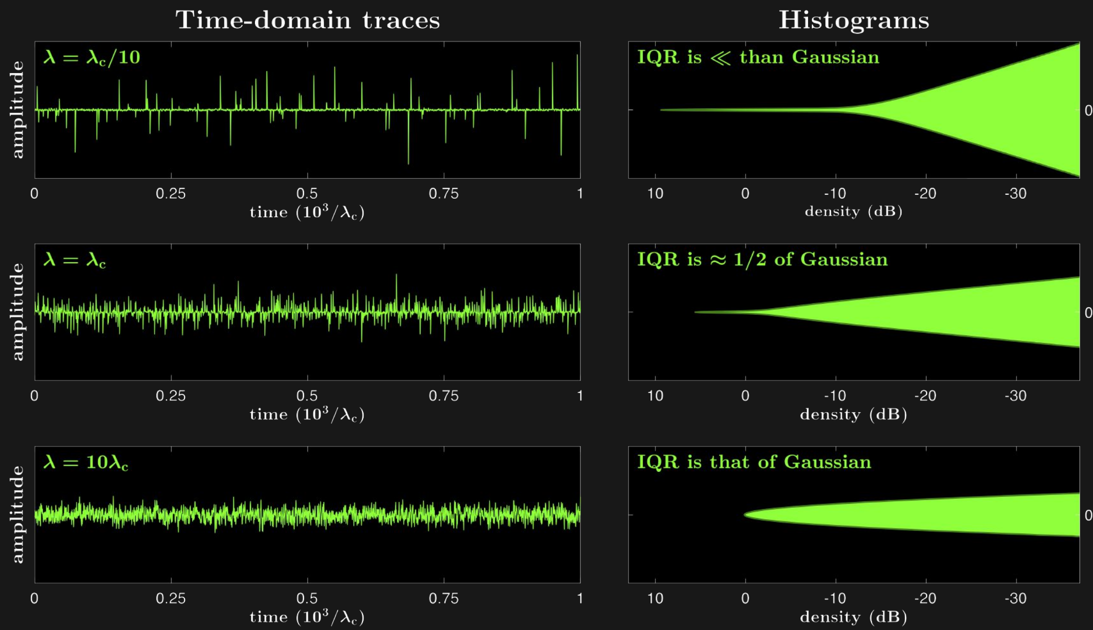


Relative "tails shortening" of noise's amplitude density $\propto \Delta B^{\alpha}$, $0 < \alpha \leq 1$

What hides outlier noise?

#3 – Insufficient observation bandwidth: High rate of outlier-generating events

E.g. filtered (w/ 2nd order Bessel) random noise becomes Gaussian at high rate:

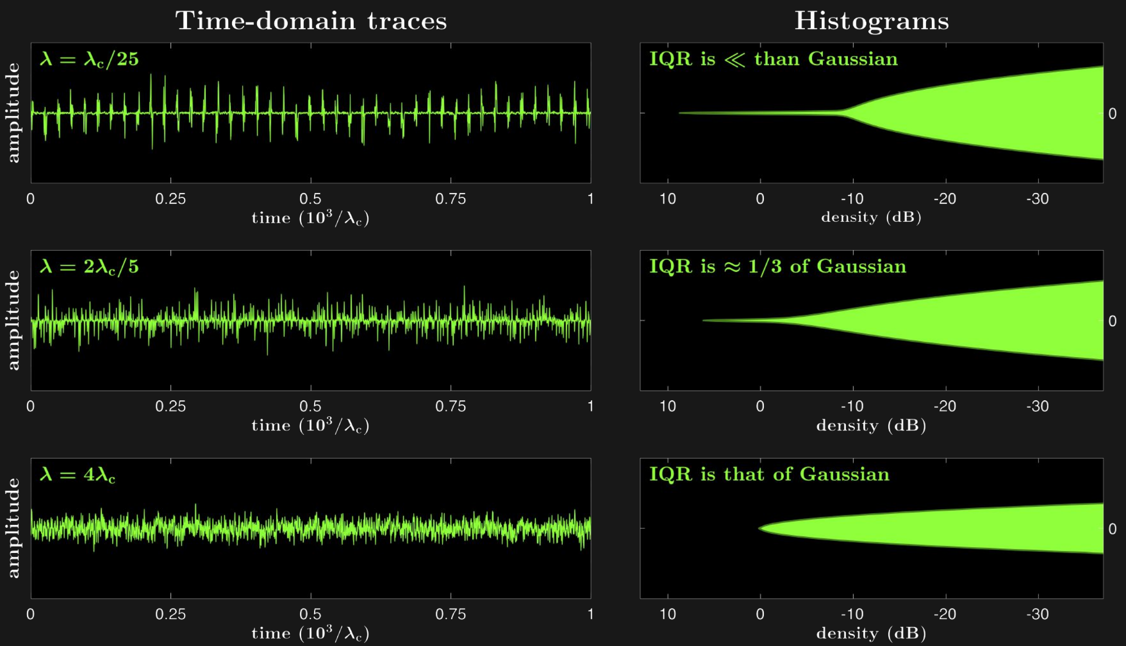


λ_c is bandwidth B_0 of 2nd order Bessel filter divided by Gaussian time-bandwidth product: $\lambda_c \approx 2.27 B_0$

What hides outlier noise?

#3 – Insufficient observation bandwidth: High rate of outlier-generating events

Same for "periodic" Gaussian burst noise with 20% duty cycle:



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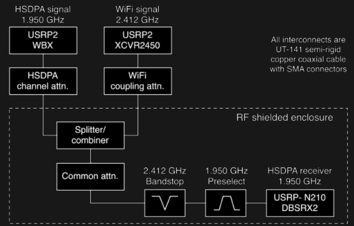
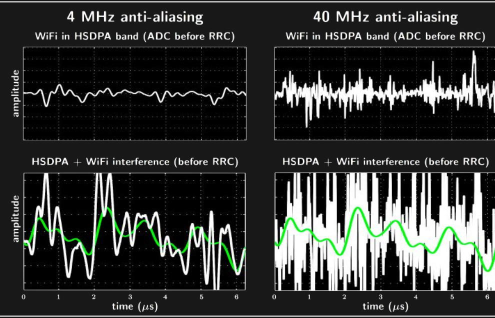
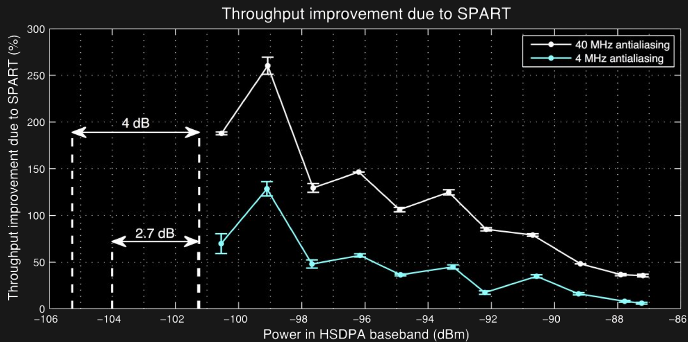
High rate of outlier-generating events – Experimental evidence



Hardware setup

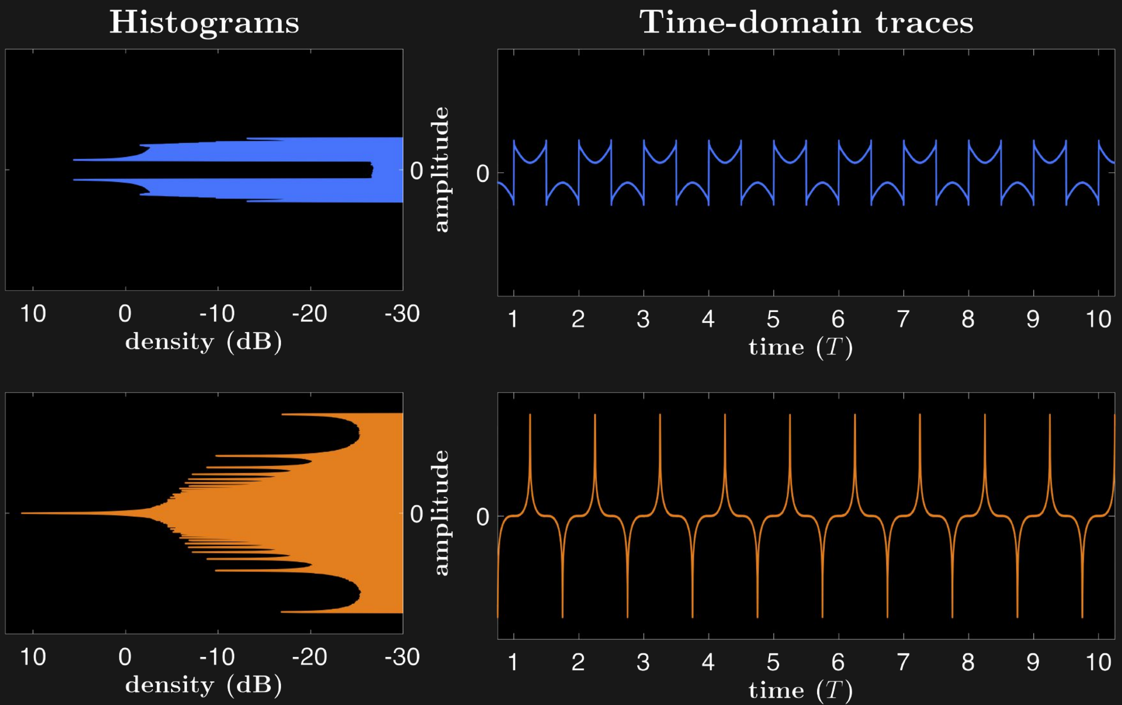




Adapted from: "Impulsive interference in communication channels and its mitigation by SPART and other nonlinear filters," EURASIP J. Adv. Signal Process., vol. 2012, no. 79, 2012

What hides outlier noise?

But what about amplitude densities?



Nonlinear

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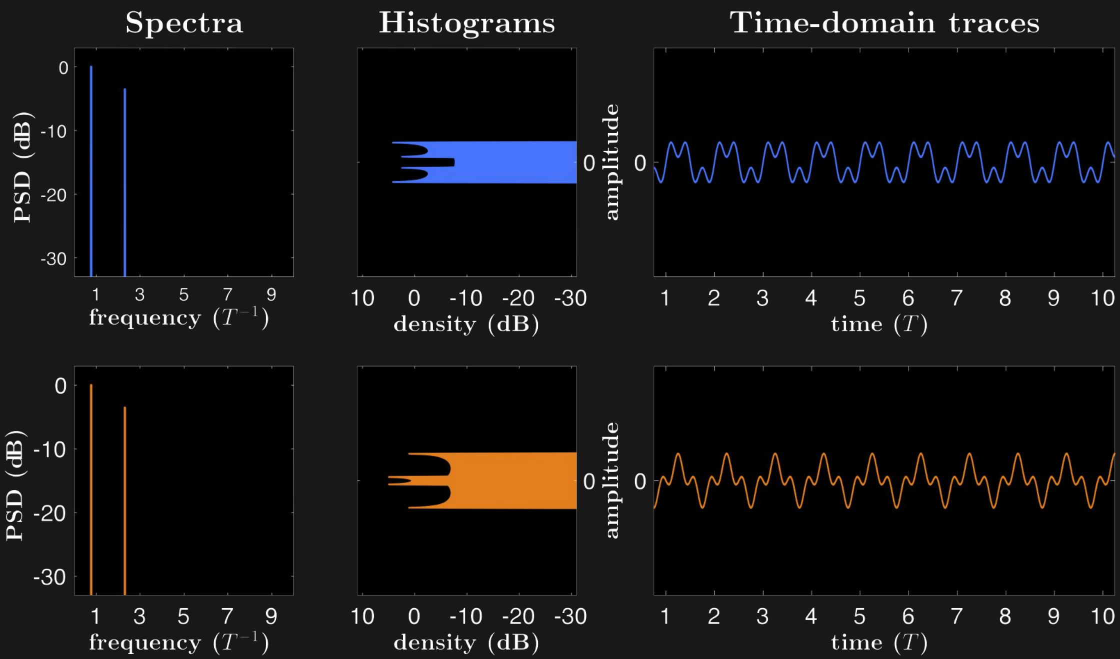
Bandwidth is still important!

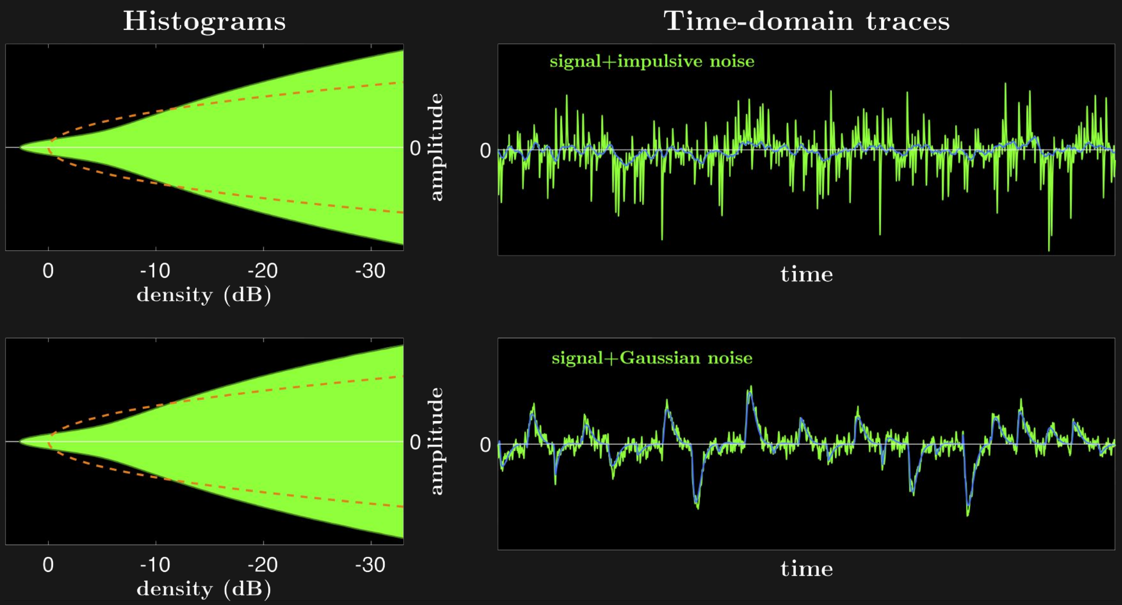
Less wiggle room:



What hides outlier noise?

#5 – Ambiguity of amplitude densities

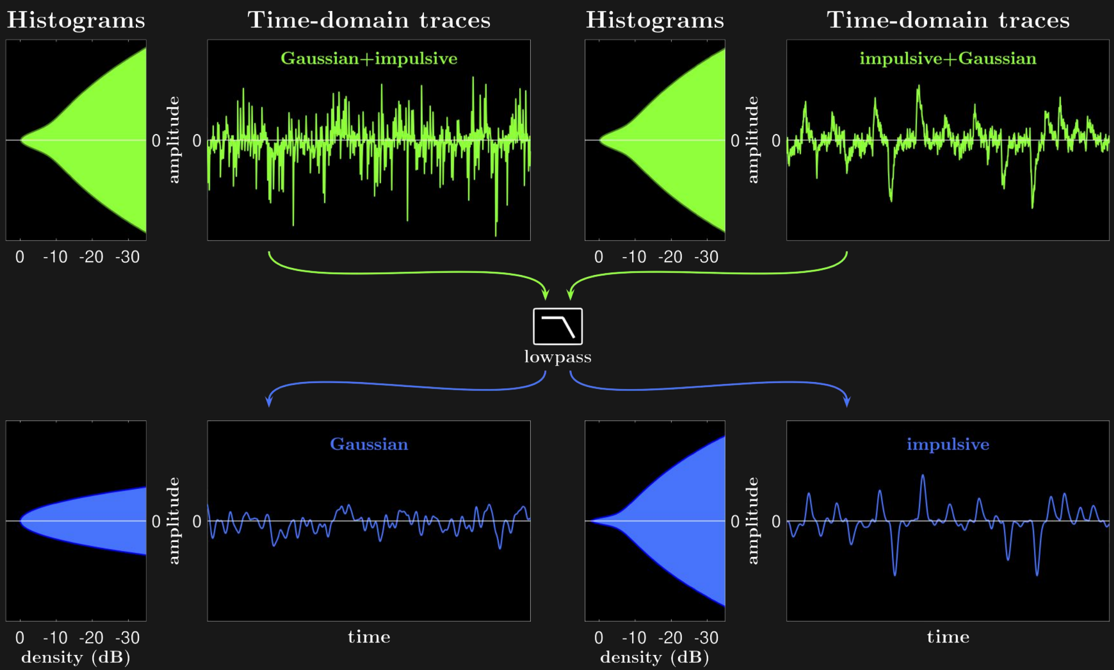
E.g. for two identical Gaussian mixture distributions:



E.g. radar, communications, radiation detection, ToA applications, etc.

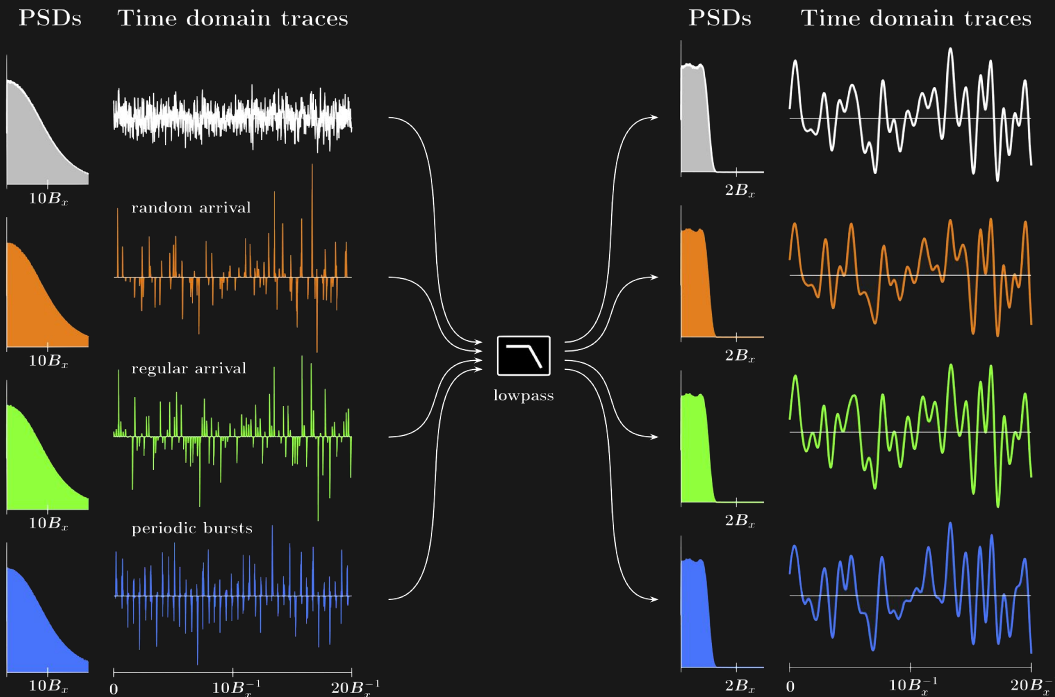
Bandwidth is still important!

#5 – Ambiguity of amplitude densities



What hides outlier noise?

#6 – Wide range of powers across spectrum



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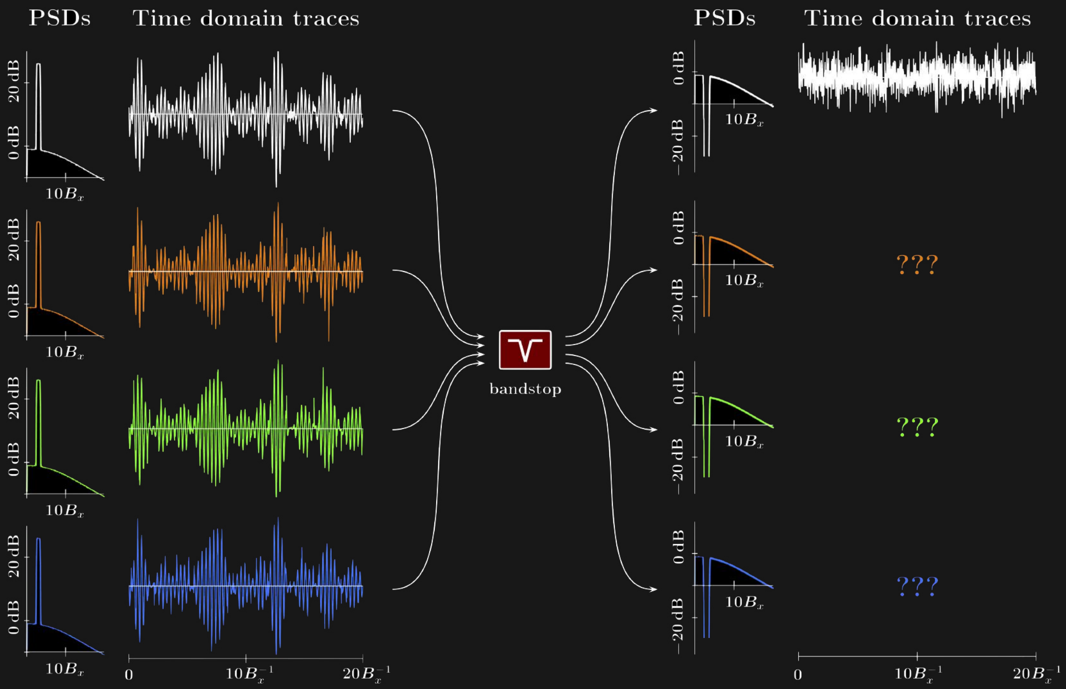
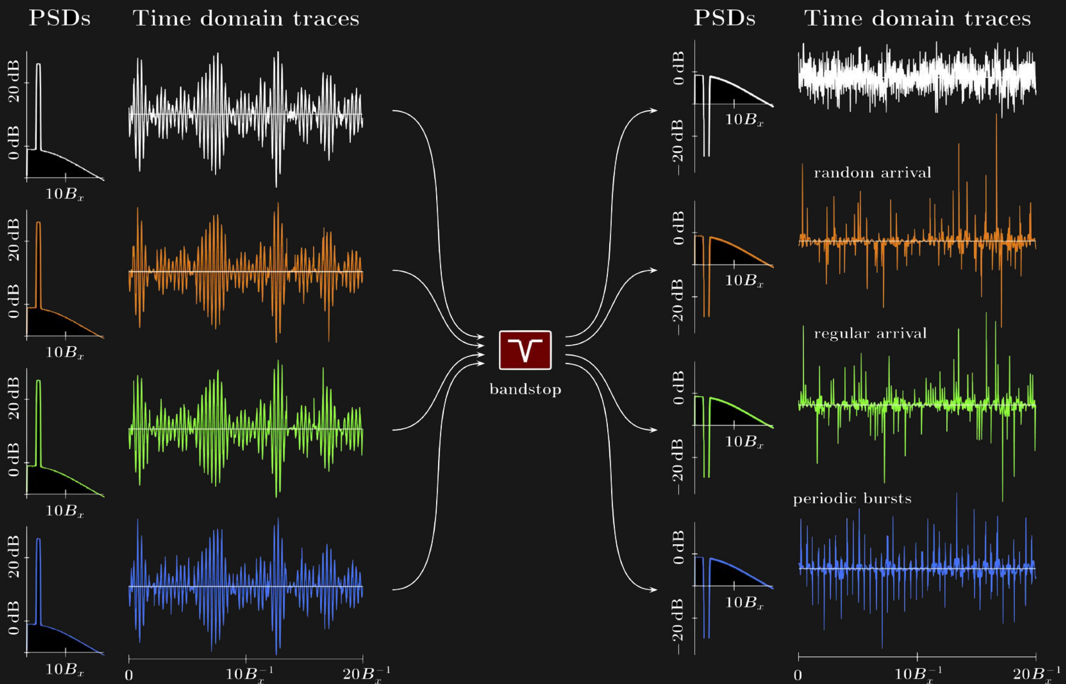
#6 – Wide range of powers across spectrum

Can we still observe outlier noise?



#6 – Wide range of powers across spectrum

Can we still observe outlier noise?



WHAT HIDES OUTLIER NOISE?

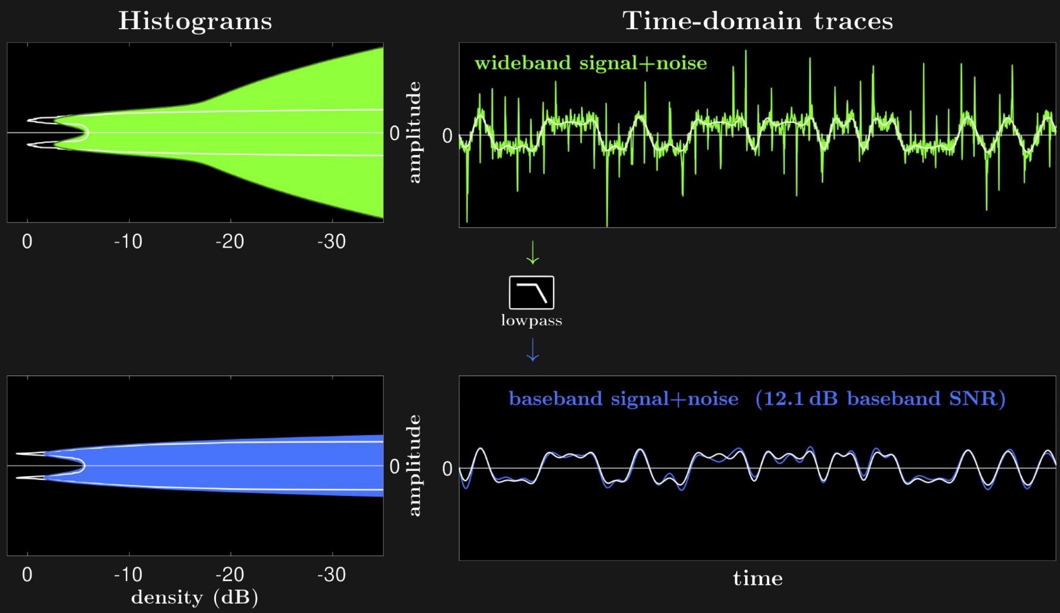
TAKE AWAY

- Insufficient observation bandwidth
- Presence of other signals

Outlier noise: Observation vs. mitigation

Outlier noise: Observation vs. mitigation

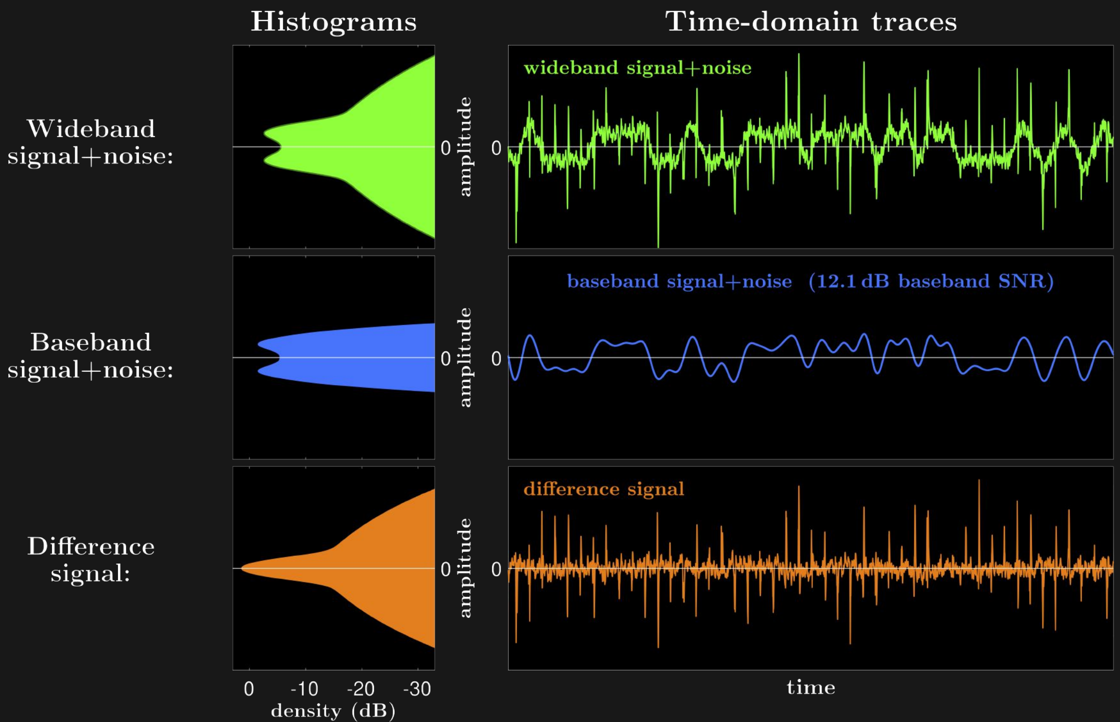
Reducing bandwidth "hides" outlier noise:



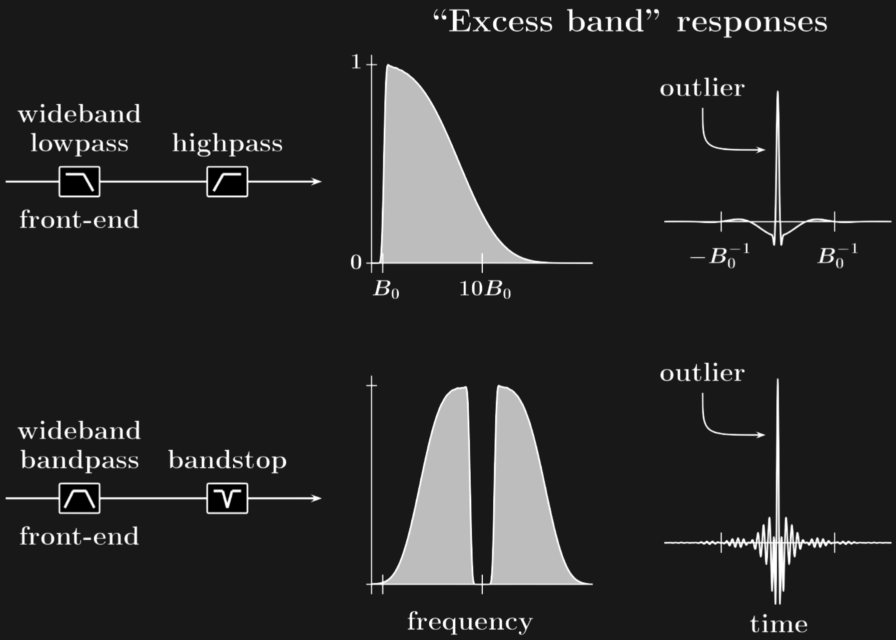
Can we capitalize on pileup effect and/or amplitude-bandwidth proportionality?

Outlier noise: Observation vs. mitigation

Observing outlier noise in "difference signal":

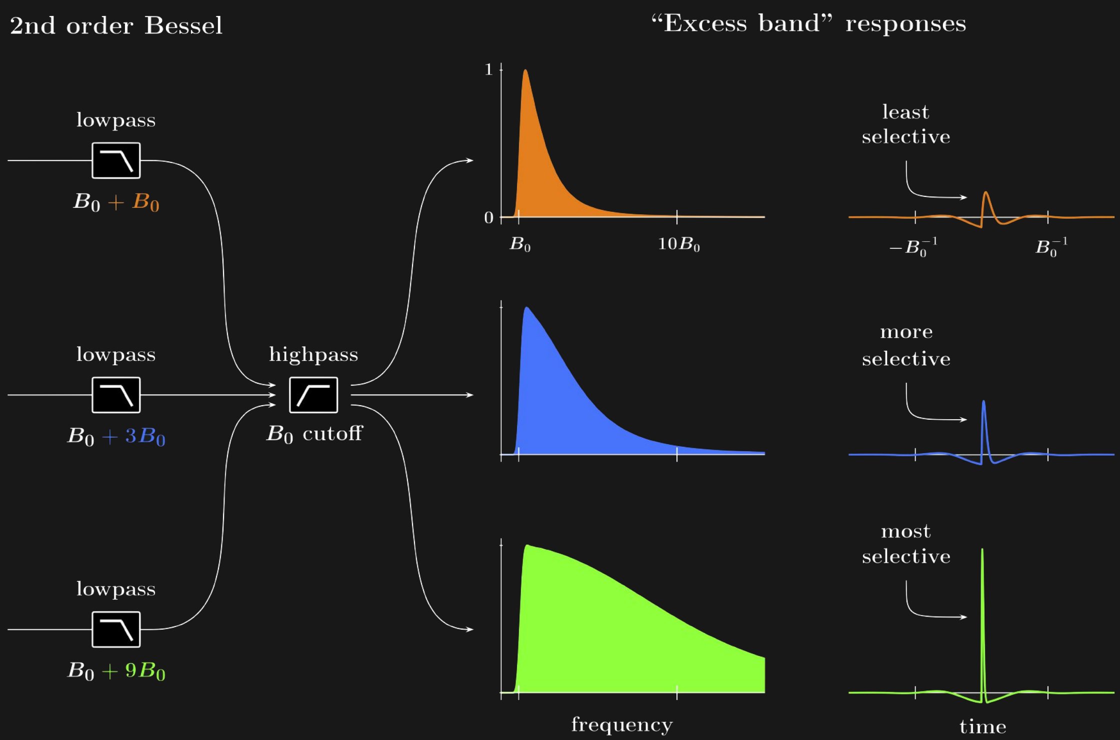


"Excess band" for difference signal



Use front-end filter with small time-bandwidth product for higher selectivity

Effect of "excess bandwidth" on excess band selectivity



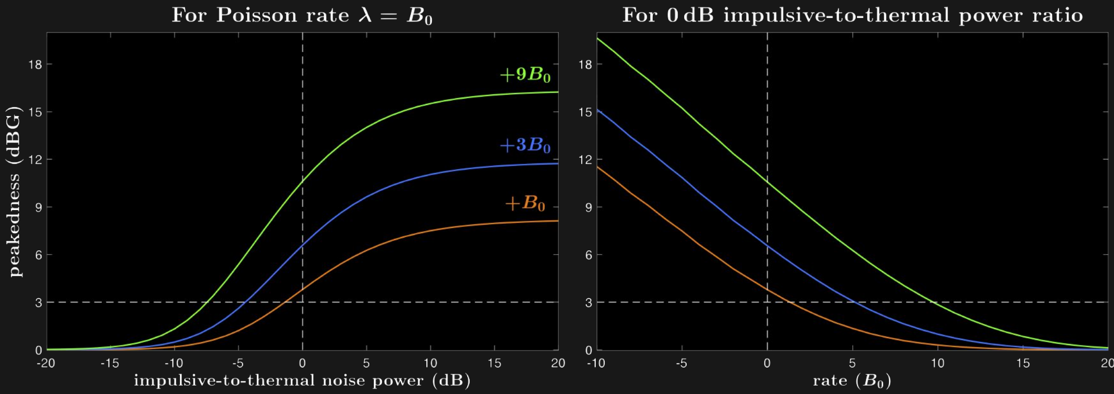
"Peakedness" as indicator of mitigation potential

In units of "decibels relative to Gaussian" (dBG):

$$K_{\mathrm{dBG}}(x) = 10\,\lg\left[\frac{\left\langle (x-\langle x\rangle)^4\right\rangle}{3\left\langle (x-\langle x\rangle)^2\right\rangle^2}\right]$$

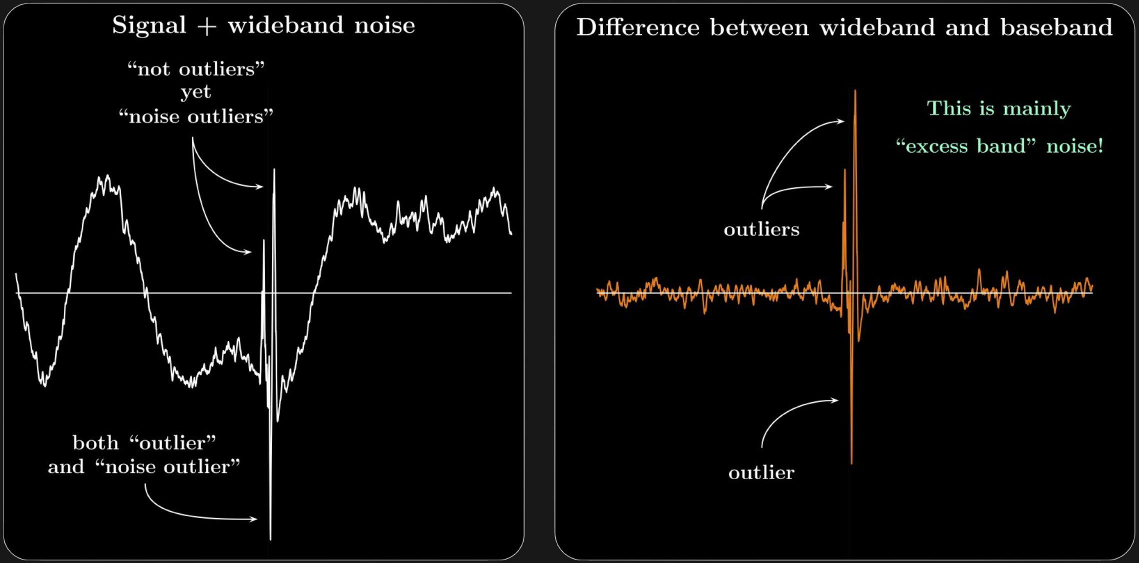
– kurtosis in relation to kurtosis of Gaussian (aka normal) distribution

E.g. for thermal+Poisson noise in different excess bands:



"Pileup rates" and "mitigable SNRs" are lower with less excess bandwidth

Outlier noise: Observation vs. mitigation



But what to do with outlier noise component affecting baseband?

Bandwidth itself is not enough!

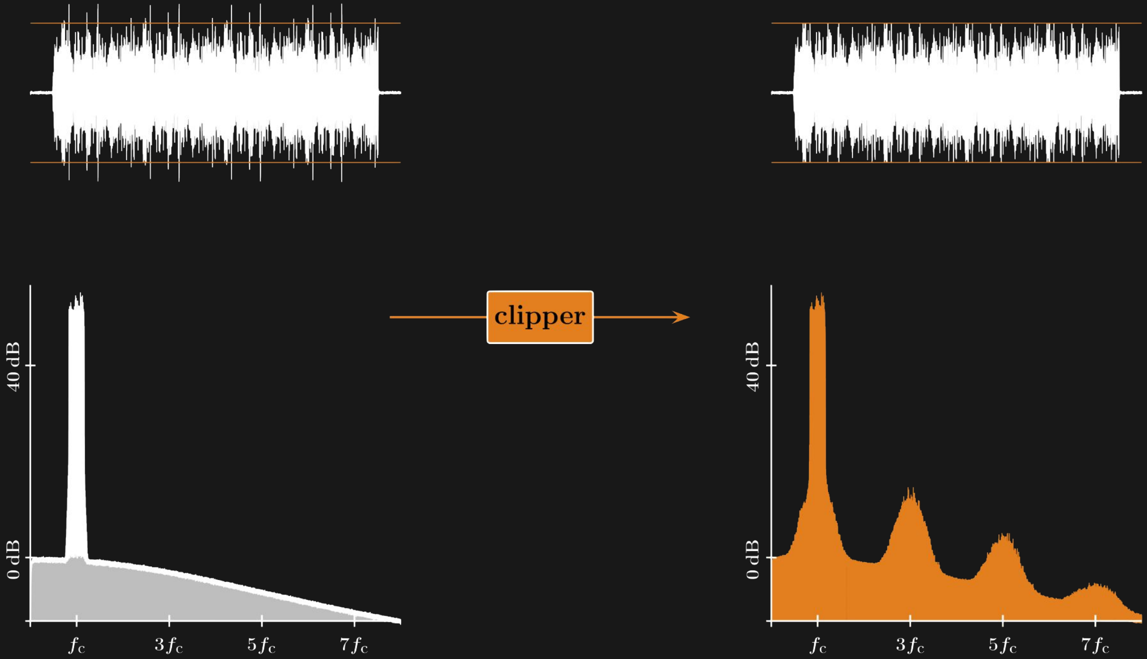
Excess-band observation

yet

in-band mitigation

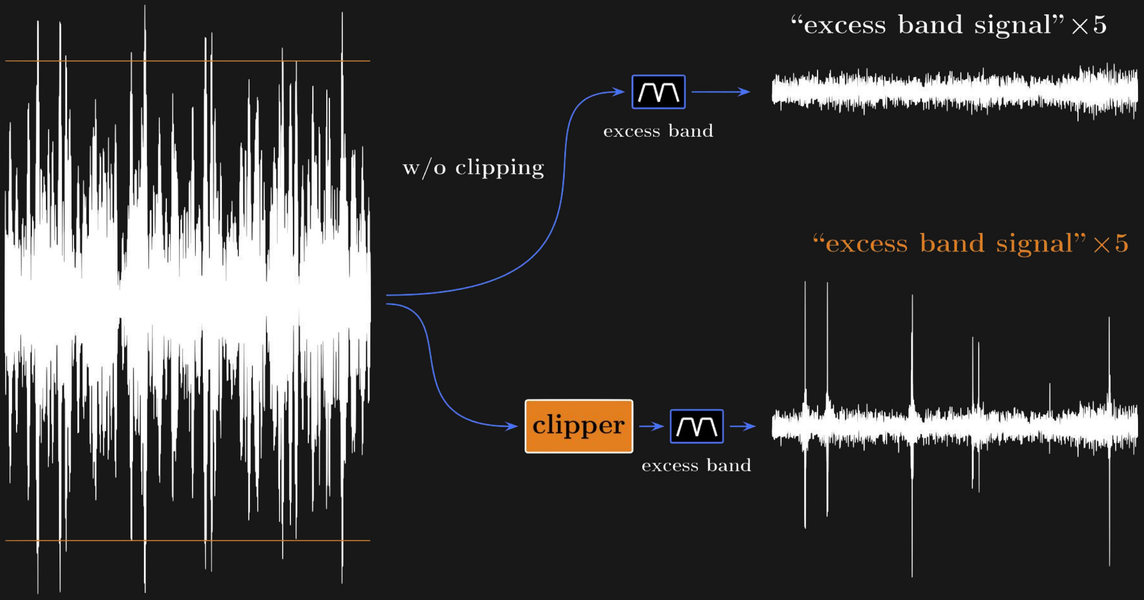
Outlier noise: Observation vs. mitigation

E.g. for intermittent nonlinear distortions ("clipping") of passband signal:



Outlier noise: Observation vs. mitigation

E.g. for clipping distortions:



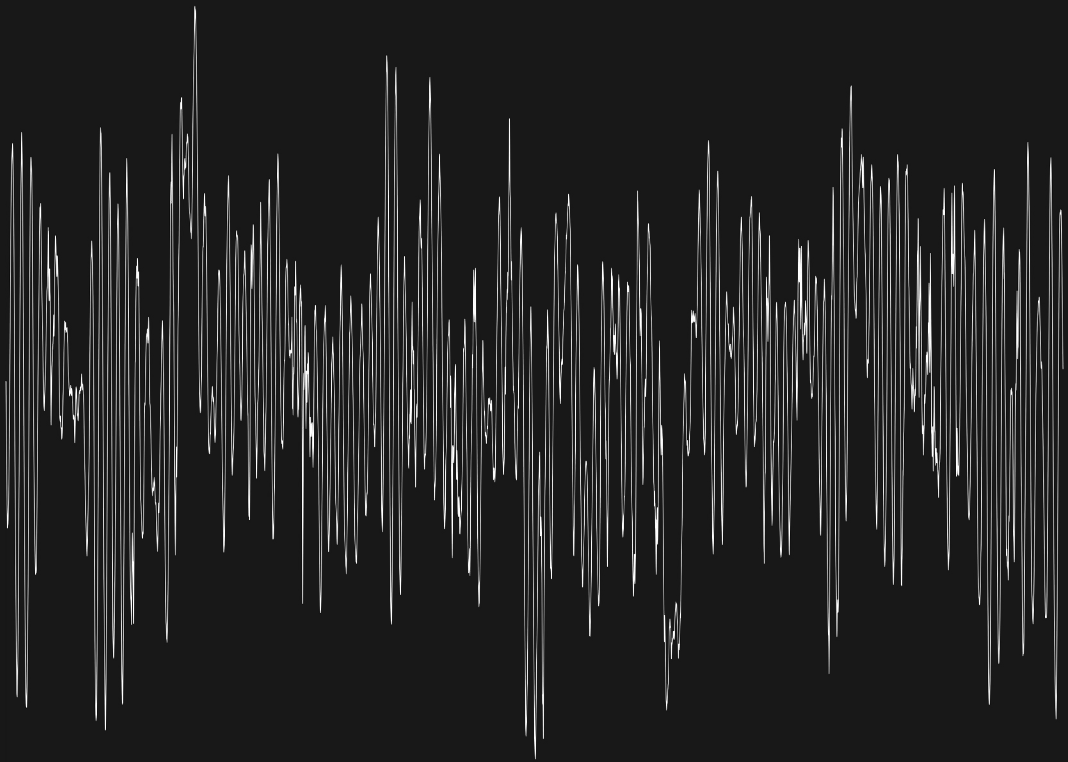
HOW TO OBSERVE OUTLIER NOISE?

TAKE AWAY

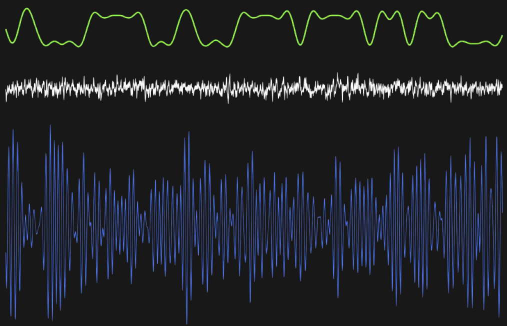
- Utilize excess band
- Block those signals that obscure

Complex signal+noise compositions

Complex signal+noise compositions



Complex signal+noise compositions: Deconstruction



Signal of interest

Wideband thermal noise
(ever-present)

Wideband interference
(e.g. adjacent transmitters)

Wideband outlier noise
(e.g. including such as platform, OOB, IMD, natural sources, etc.)
– may or may not be apparent in baseband

Narrow-band outlier interference
(e.g. intentional)

Mitigable beyond levels achievable by linear filtering

Complex signal+noise compositions

1. Mitigate wideband noise outliers first
   - before bandwidth reduction
2. Remove other wideband interference outside of signal's band
   - using linear filter(s)
3. Reduce narrow-band outliers
   - as appropriate from *a priori* knowledge of signal of interest's structure

What's so special about outlier noise/interference?

- Tricky to detect
- Hard to track and quantify
- Hides and reappears

- Enables "extra" mitigation

Part II

Methodology and tools for outlier noise mitigation

Part II: Methodology and tools for outlier noise mitigation

ADiC components and their implementation

- ADiC as main building block
- Basic ADiC structure
- QTFs for robust range
- Much better way: Feedback-based ADiC

ADiC-based outlier noise filtering

- Spectral reshaping by ADiC and *efecto cucaracha*
- CAF: Removing outlier noise while preserving signal of interest
- CAF vs linear: Effect on channel capacity
- "No harm" (default) CAF configurations

Analog vs digital

- Digital: Where to get bandwidth?
- Addressing complex interference scenarios
- Practical configurations: CAF for chirp signals
- Practical configurations: CAF for OFDM
- CAF for clipping distortions
- Designing development & testing platform

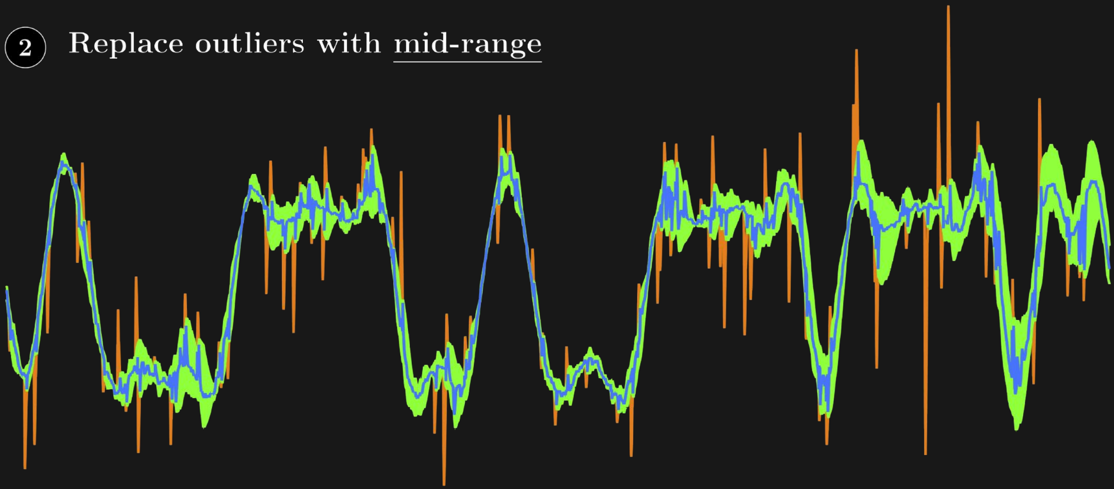
Broader picture

ADiC components and their implementation

Analog Differential Clipper (ADiC) as main building block

Removing outlier noise while preserving signal of interest:

1. Establish <u>robust range</u>
2. Replace outliers with <u>mid-range</u>

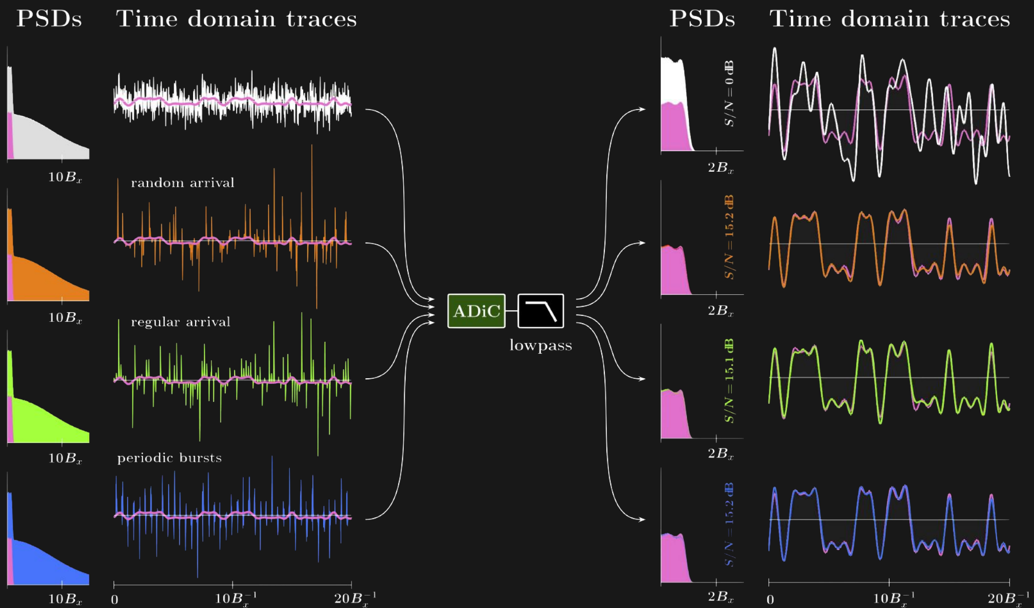


E.g. baseband SNR 20 dB → 30 dB (+50% capacity)

ADiC's basic function

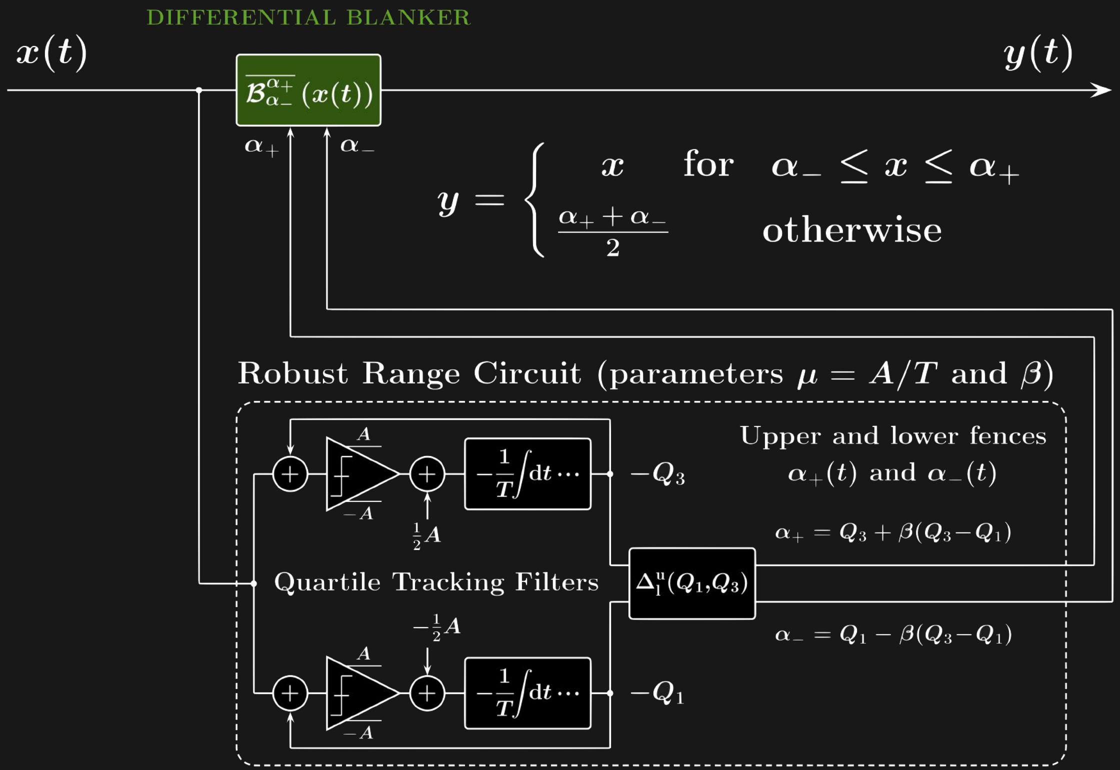
Do both – set range and remove outliers – **when noise dominates**

– Continuous-time ("analog") filtering akin to digital Hampel filtering

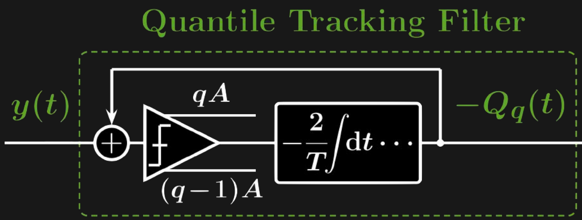


Digital ADiC is only $\mathcal{O}(1)$ per output value in both time and storage

Basic ADiC structure



Quantile Tracking Filters (QTFs) for robust range/mid-range



$$\frac{d}{dt} Q_q = \frac{A}{T}\left[\operatorname{sgn}(y - Q_q) + 2q - 1\right]$$

– approximates ("tracks") q-th quantile of $y(t)$

E.g. $[\alpha_-, \alpha_+] = \left[Q_{[1]} - \beta\left(Q_{[3]} - Q_{[1]}\right),\ Q_{[3]} + \beta\left(Q_{[3]} - Q_{[1]}\right)\right]$ – Tukey's fences

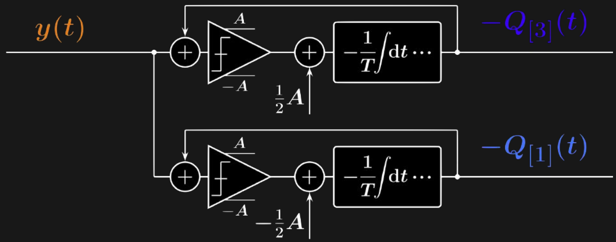
For mid-range, e.g., *Trimean Tracking Filter* (TTF) can be used:

$$\left(Q_{[1]} + w\, Q_{[2]} + Q_{[3]}\right)/(w + 2), \qquad w \geq 0$$

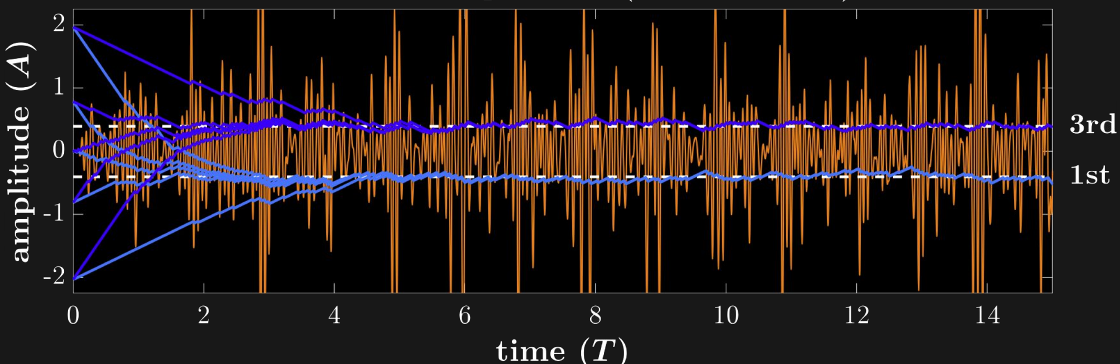
In practice, finite-gain comparators should be used, and/or small hysteresis should be added

QTFs for robust fences/range and mid-range

Quartile Tracking Filters ($q = 1/4$ & $q = 3/4$)

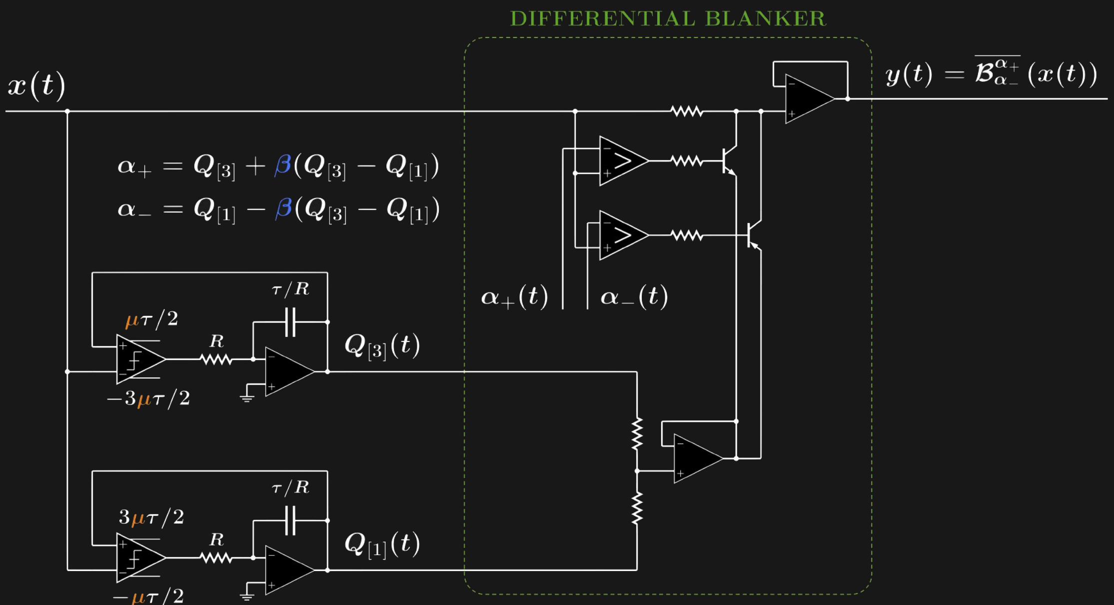


Input $y(t)$ (orange), QTF outputs $Q_{[1]}(t)$ and $Q_{[3]}(t)$ (blue), and "exact" quartiles (white dashed)

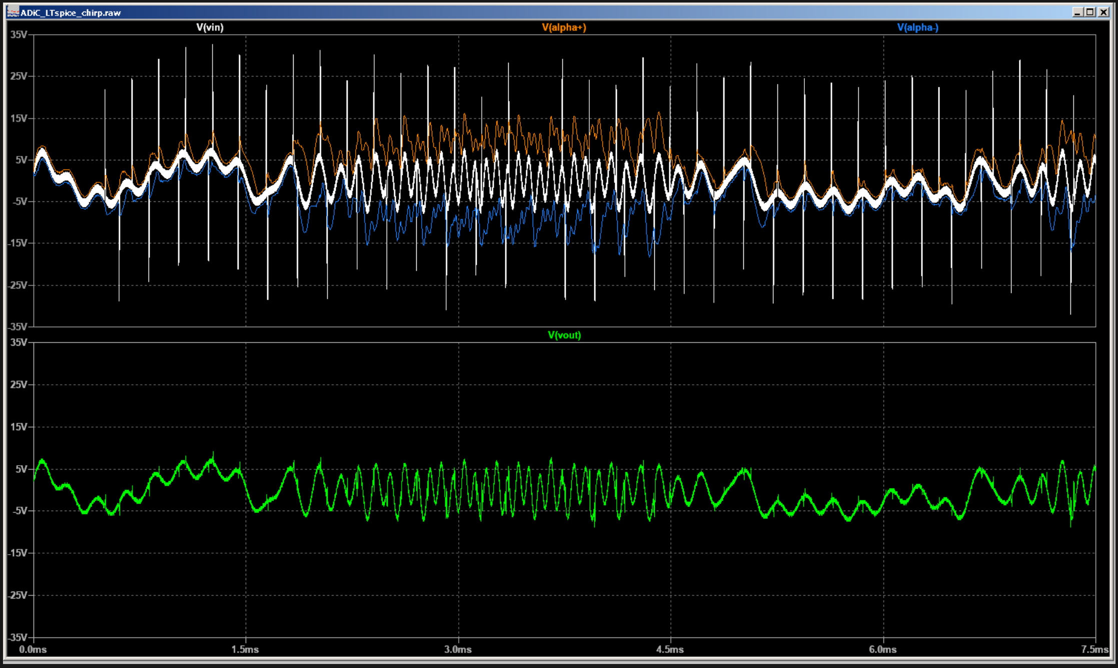


Basic ADiC structure

ADiC with parameters μ and β

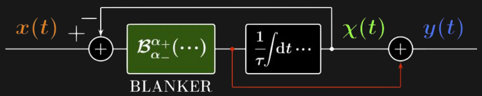


Basic ADiC structure

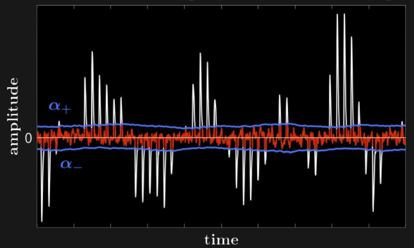


Illustrative signal traces from LTspice simulation of simple ADiC circuit

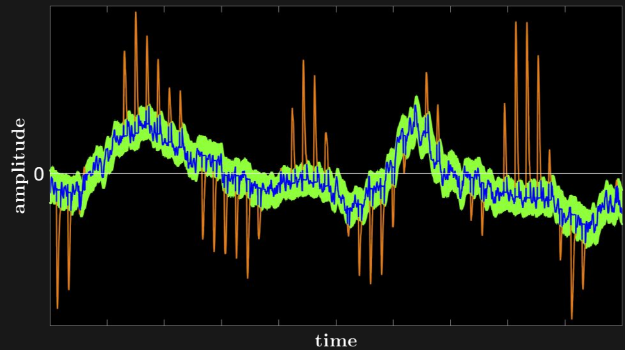
Much better way: Feedback-based ADiC



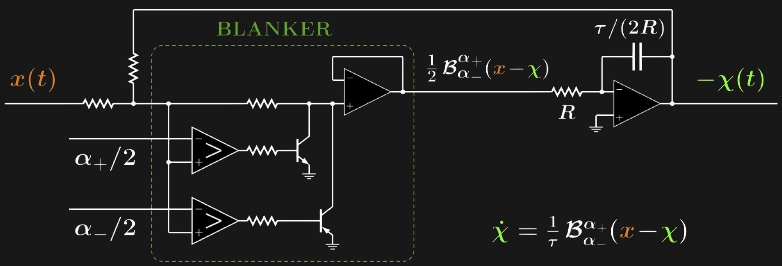
White – blanker input, red – blanker output



Orange – input w/ outlier noise, blue – ADiC output, green – transparency range



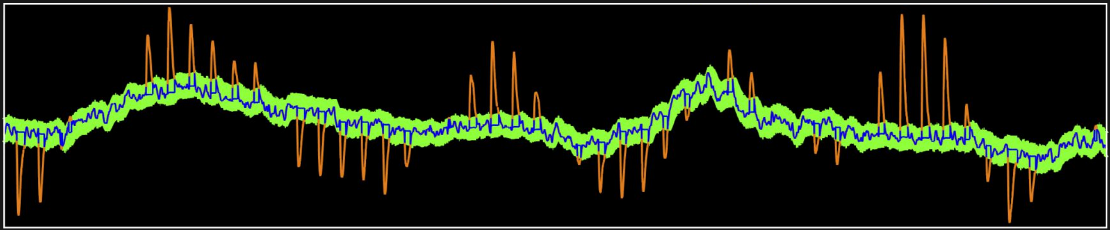
ADiC replaces outliers with $\chi(t)$, otherwise does not affect input signal



$$\dot{\chi} = \frac{1}{\tau}\mathcal{B}_{\alpha_-}^{\alpha_+}(x-\chi)$$

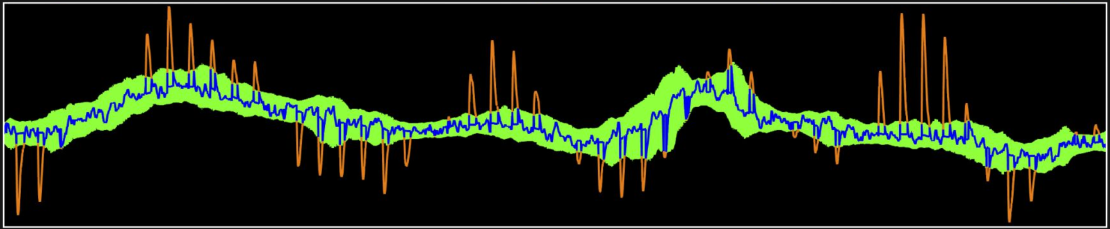
ADiC vs Hampel filter

Input w/ outlier noise, ADiC output, robust range



Feedback-based ADiC replacing outliers with DCL $\chi(t)$

Input w/ outlier noise, Hampel filter output, robust range



Hampel filter replacing outliers with running median

Hampel filter is $\mathcal{O}\left(TF_s \log(TF_s)\right)$ per output value in time, and $\mathcal{O}(TF_s)$ in storage

BASIC TOOLS

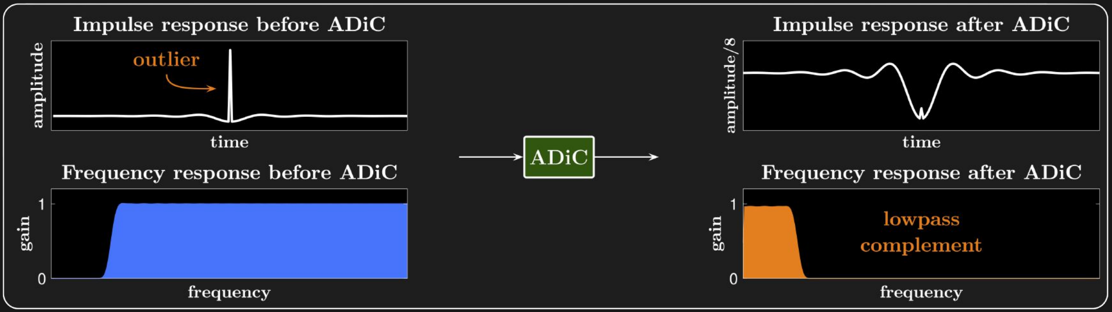
TAKE AWAY

- QTFs for range/mid-range
- Depreciators (e.g. blankers) for mitigation
- Feedback arrangements for enhancement

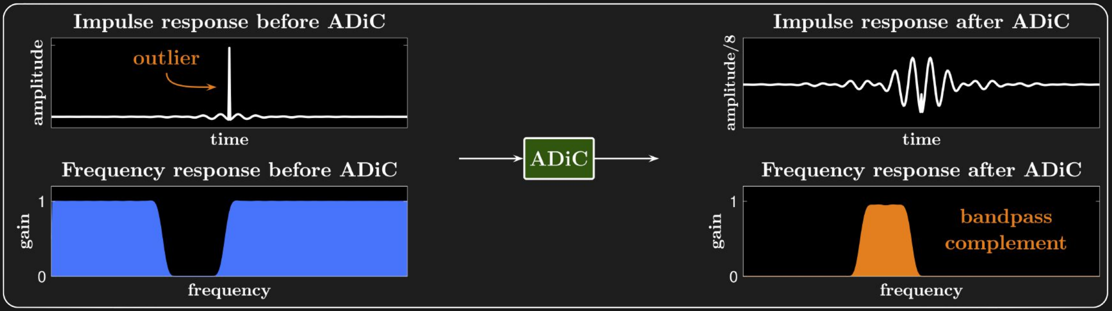
ADiC-based outlier noise filtering

Spectral inversion by ADiC

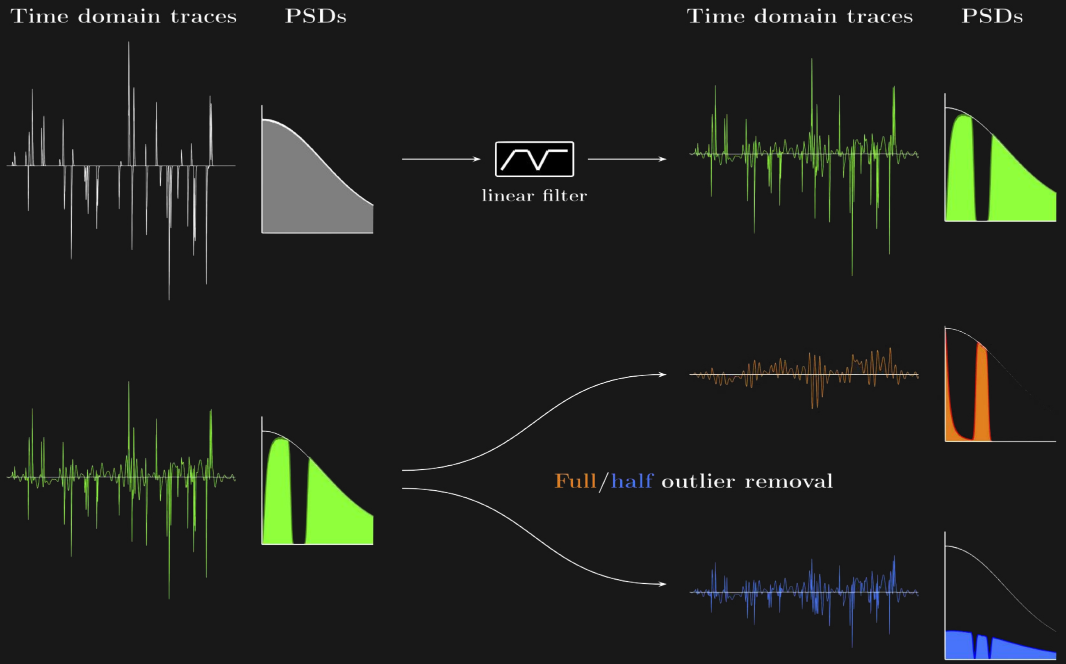
FIR highpass filter



FIR bandstop filter



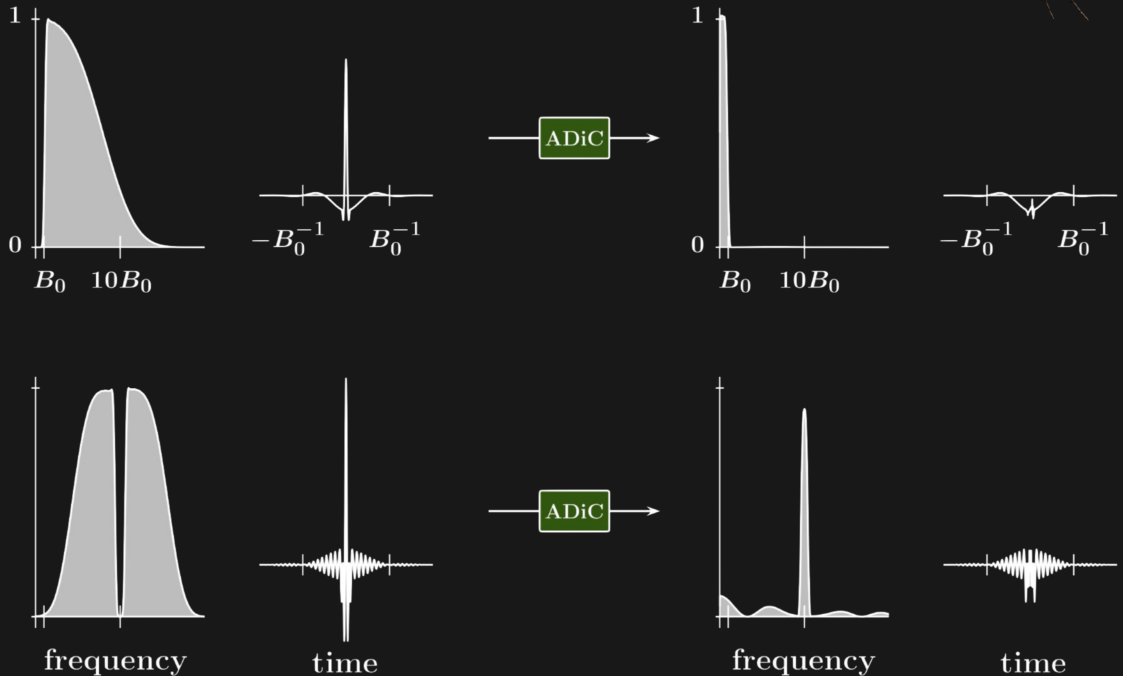
Capitalizing on spectral reshaping: *Efecto cucaracha*




Beware of spectrally-shaped outlier noise

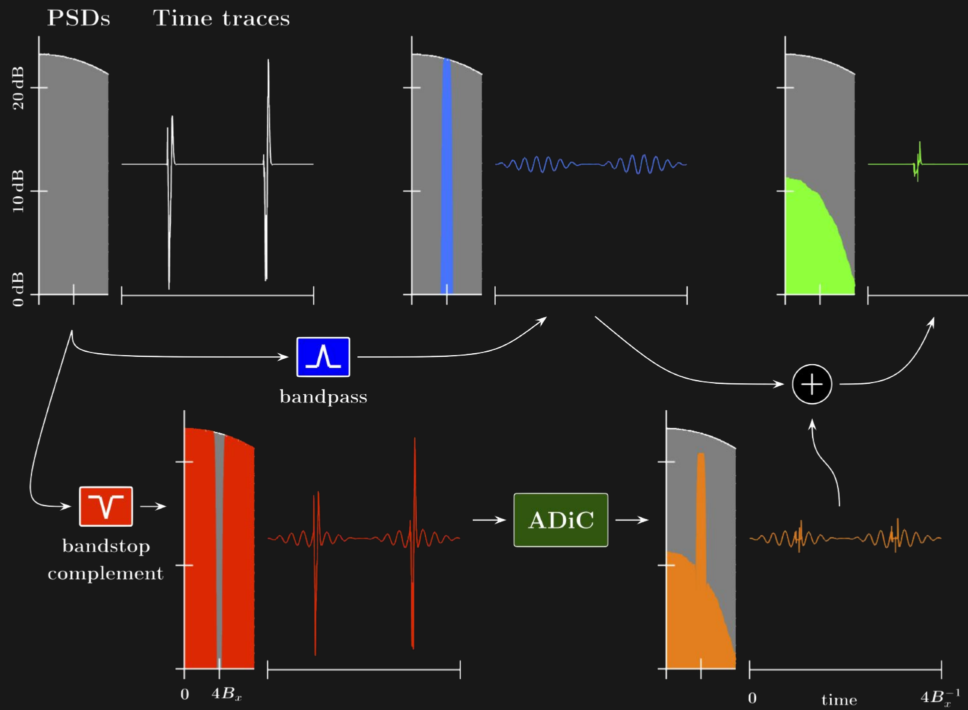
Capitalizing on spectral reshaping: *Efecto cucaracha*

“Excess band” responses



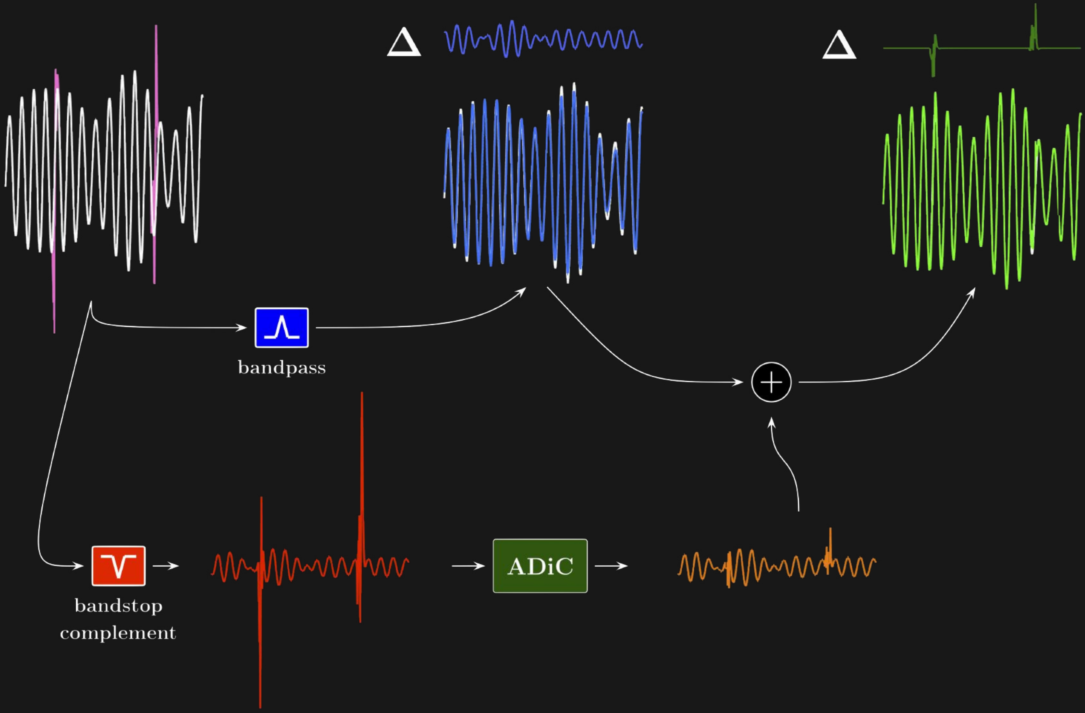
How to use spectral reshaping by ADiC?

E.g. to enable mitigation at high SNRs for signal in passband:



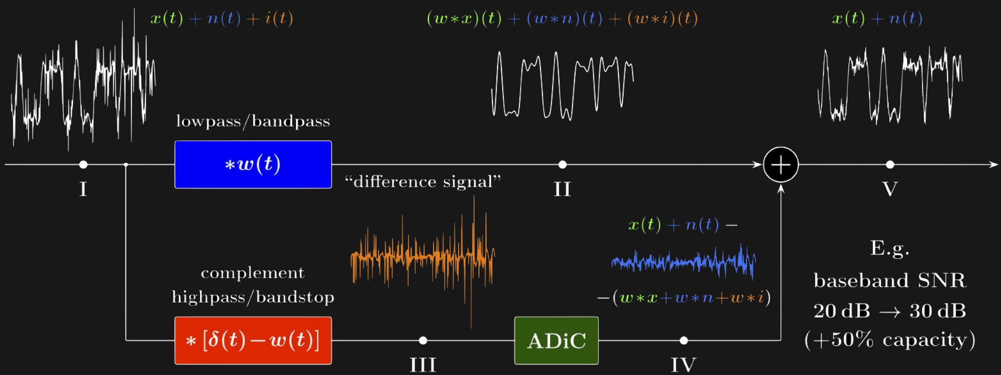
Removing outlier noise while preserving signal of interest

Outlier noise mitigation at high SNRs for signal in passband:



CAF: Removing outlier noise while preserving signal of interest

ADiC-based outlier noise removal from band-limited signals:

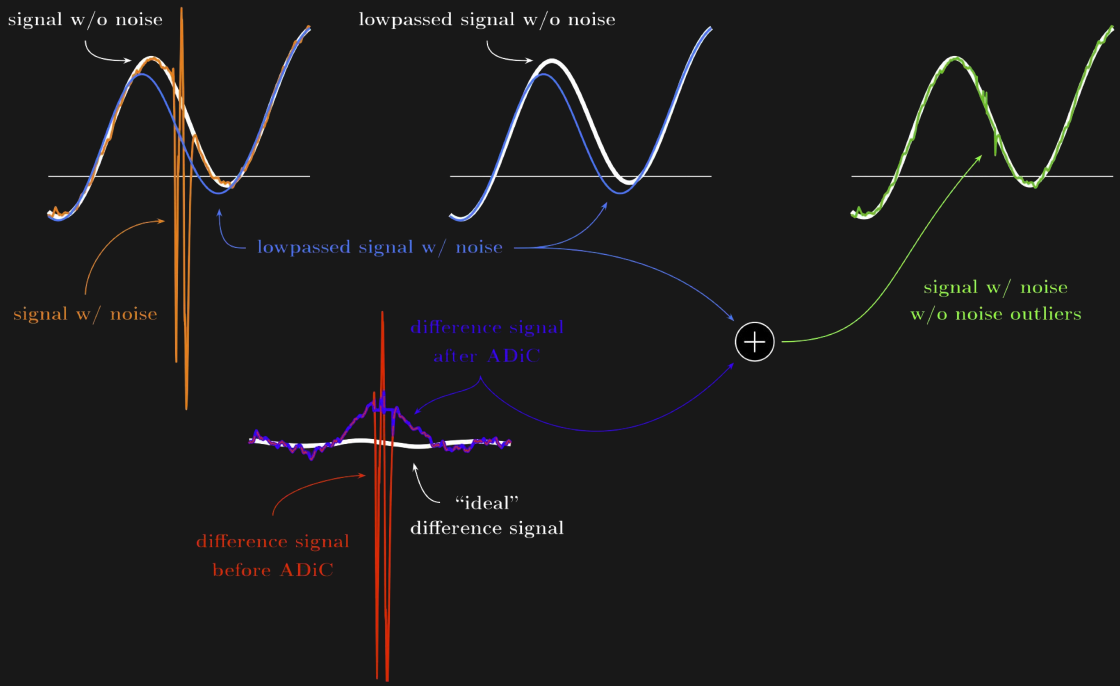


With 100% ADiC efficiency and zero group delay of $w(t)$:

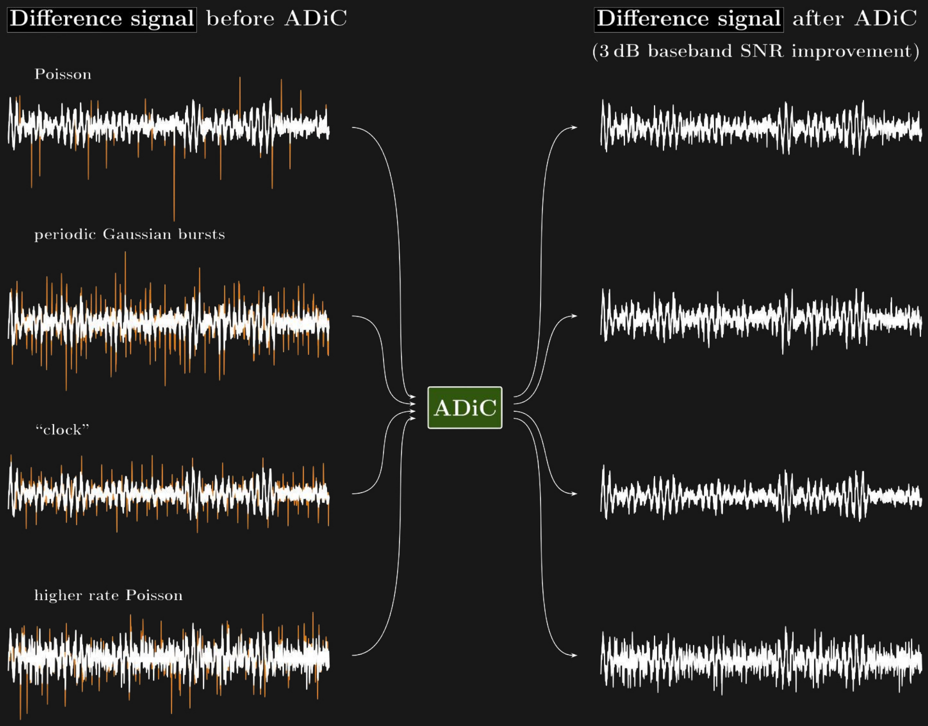
- **I** $x + n + i$ (signal + noise)
- **II** $w*x + w*n + w*i$ (lowpass/bandpass-filtered signal + noise)
- **III** $x - w*x + n - w*n + i - w*i$ (mainly highpass/bandstop-filtered noise)
- **IV** $x - w*x + n - w*n - w*i$ (ADiC removes $i(t)$)
- **V** $x + n$ (II+IV: signal + non-outlier noise)

Removing outlier noise while preserving signal of interest

ADiC-based outlier noise removal from band-limited signals:

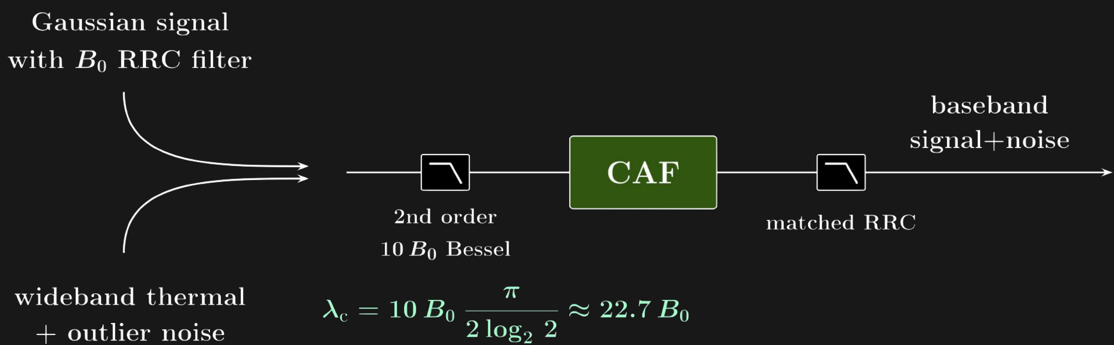


Removing outlier noise while preserving signal of interest



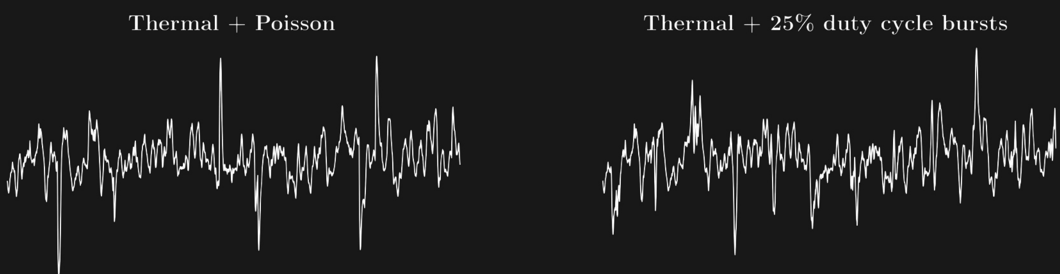
CAF vs linear: Effect on channel capacity

Simulation setup:



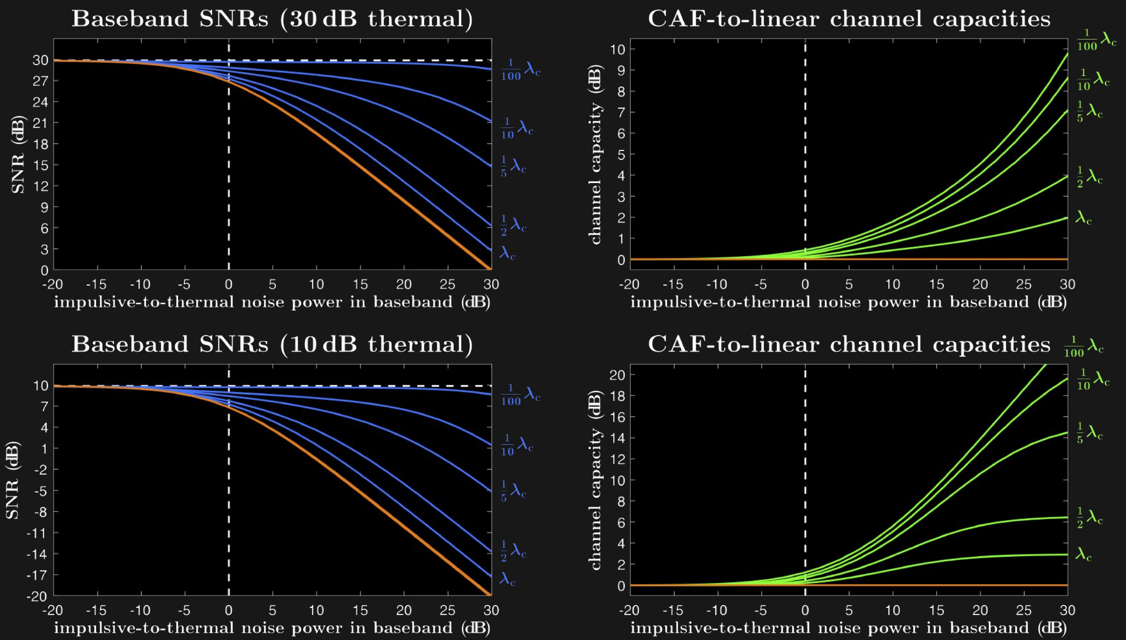
$$\lambda_c = 10\,B_0\,\frac{\pi}{2\log_2 2} \approx 22.7\,B_0$$

E.g. noise after Bessel for $\lambda = \lambda_c/10$ and 0 dB outlier-to-thermal noise powers:



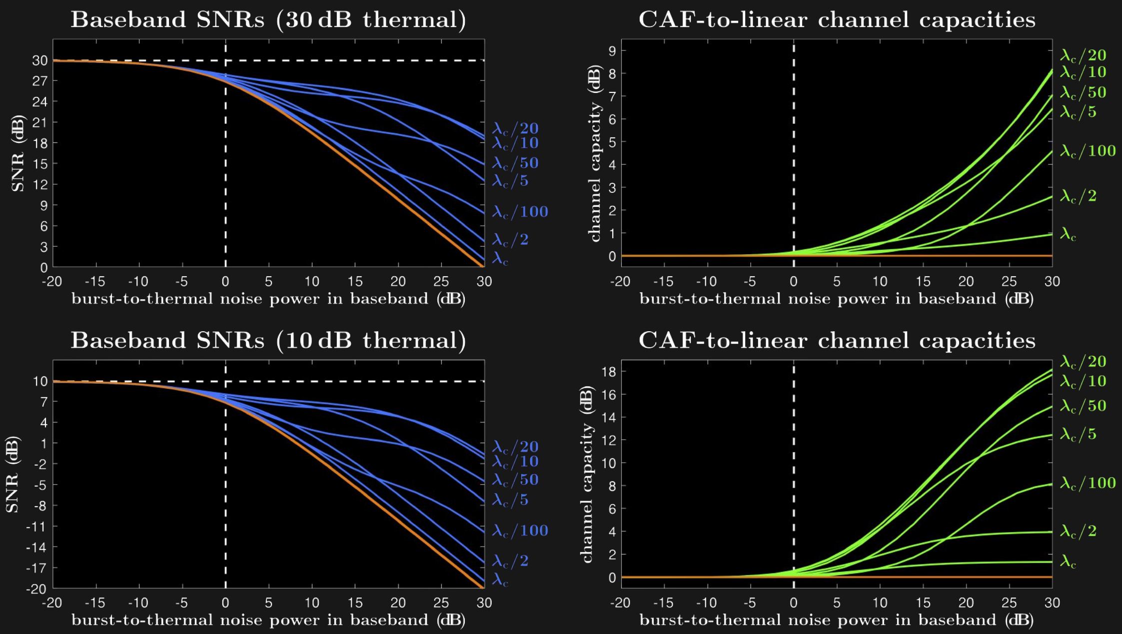
CAF vs linear: Channel capacity under impulsive noise

For Poisson noise with default (constant) set of ADiC parameters:



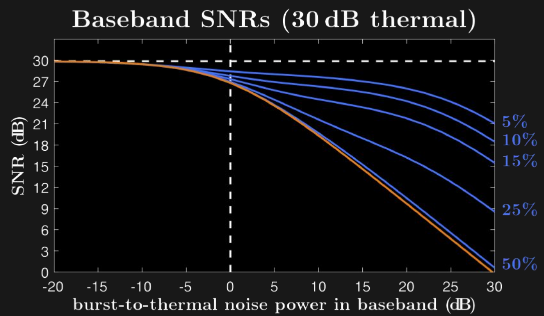
CAF vs linear: Channel capacity under outlier noise

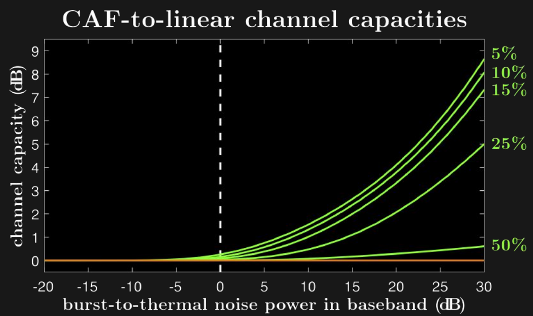
Same default ADiC parameters for periodic Gaussian bursts with 10% duty cycle:

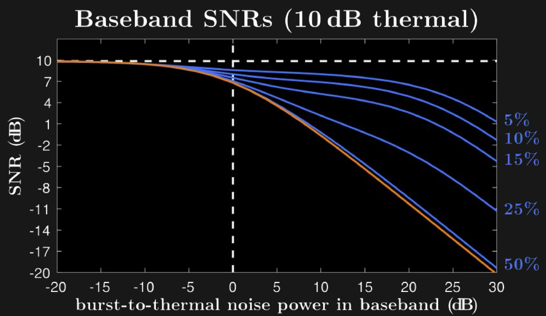


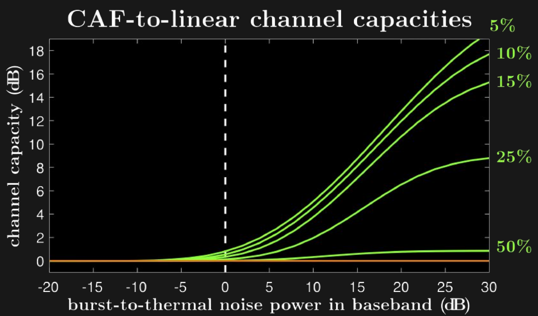
CAF vs linear: Channel capacity under outlier noise

Or for $\lambda = \lambda_c/10$ and different duty cycles:









“No harm” (default) CAF configurations

Why isn’t nonlinear filtering more commonly used?

- Can cause harm in complex, highly nonstationary interference scenarios
- Leading to distortions, instabilities, “cockroach effect” ...
- “Tuning” takes time and resources

CAFs enable default “no harm” nonlinear filtering

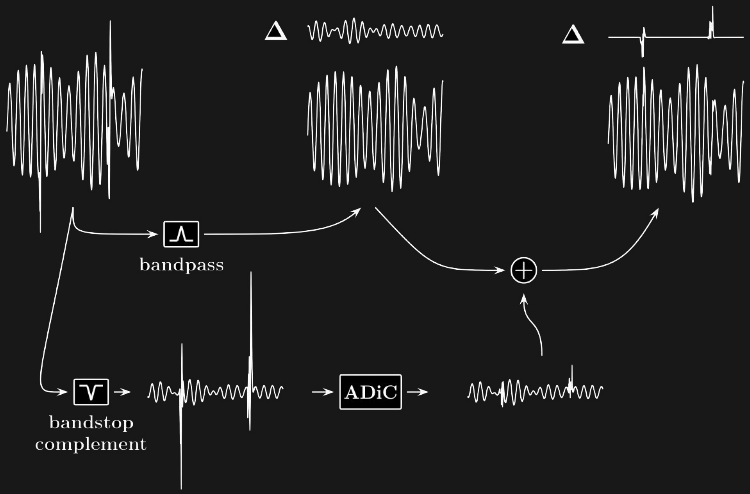
E.g. in mobile and cognitive communication systems

- where transmitter positions, powers, signal waveforms, and/or spectrum allocations vary dynamically
- + fading and multipath effects

BASIC METHODOLOGY

TAKE AWAY

- Use complementary ADiC filtering



Analog vs digital

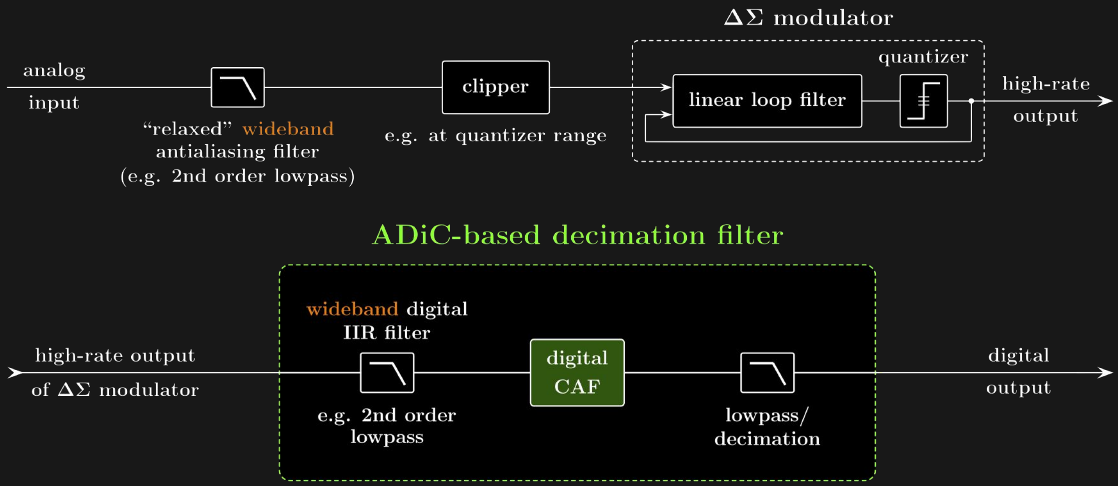
Analog vs digital: Sufficiently high sampling rate is needed for digital

For numerical implementations:

- Use finite-difference approximations of analog operations
  - differentiation, antidifferentiation, and convolution
- Employ IIR filters as needed for real-time processing
  - to reduce computations and memory requirements
- Trade amplitude resolution for higher sampling rate
  - before final decimation

Digital: Where to get bandwidth?

E.g. for inherently high oversampling rate of ΔΣ ADC:



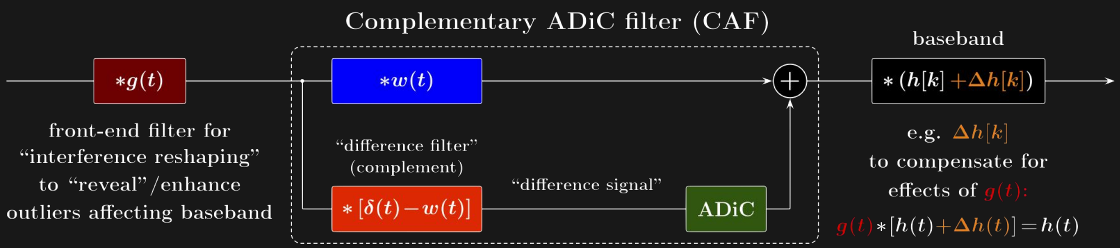
E.g. 20 MHz clock, 100 kS/s output, 500 kHz bandwidth of wideband digital IIR filter . . .

We can get creative with wideband "front-end" filters

E.g. combine responses of analog 2nd order antialiasing and digital wideband 2nd order IIR for wideband 4th order Bessel-Thomson filter

Addressing various “hidden interference” scenarios

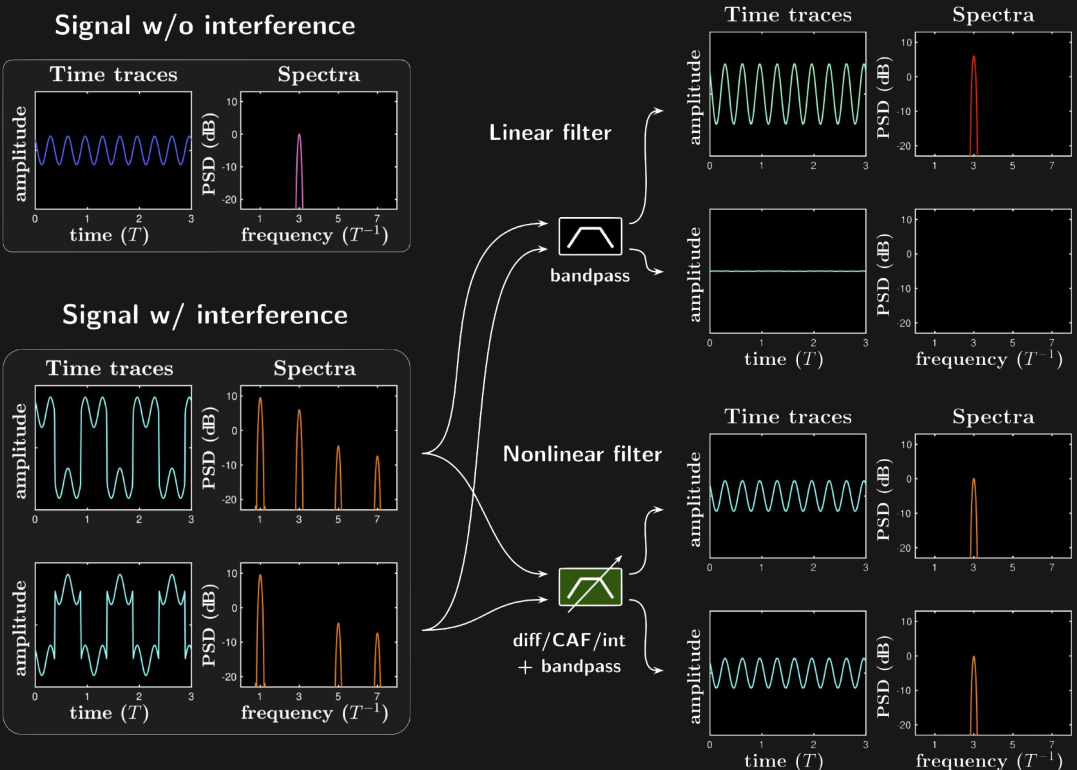
General outline:



E.g. for strong adjacent channel interference we can use bandstop $g(t)$+baseband $w(t)$ or, alternatively, “baseband+bandpass” $w(t)$

In special case of narrow-band outlier interference (e.g. intentionally confined to signal's band) we can reduce bandwidth of $w(t)$ to small fraction of signal's bandwidth, or set $w(t)$ to zero – Akin to conventional “blanking” of outliers

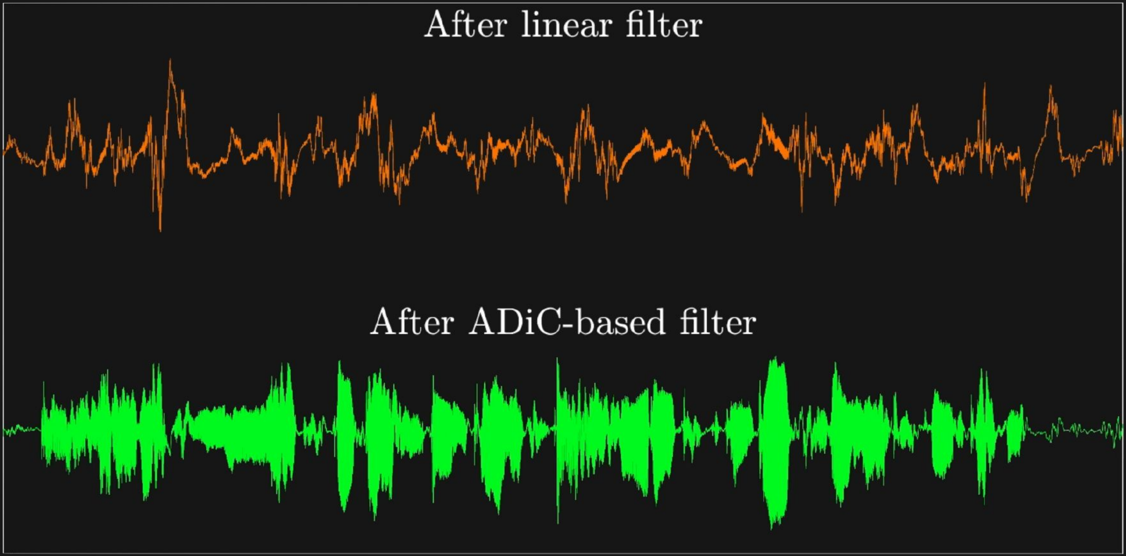
Toy example



CLICK ON FILTER SYMBOLS FOR AUDIO

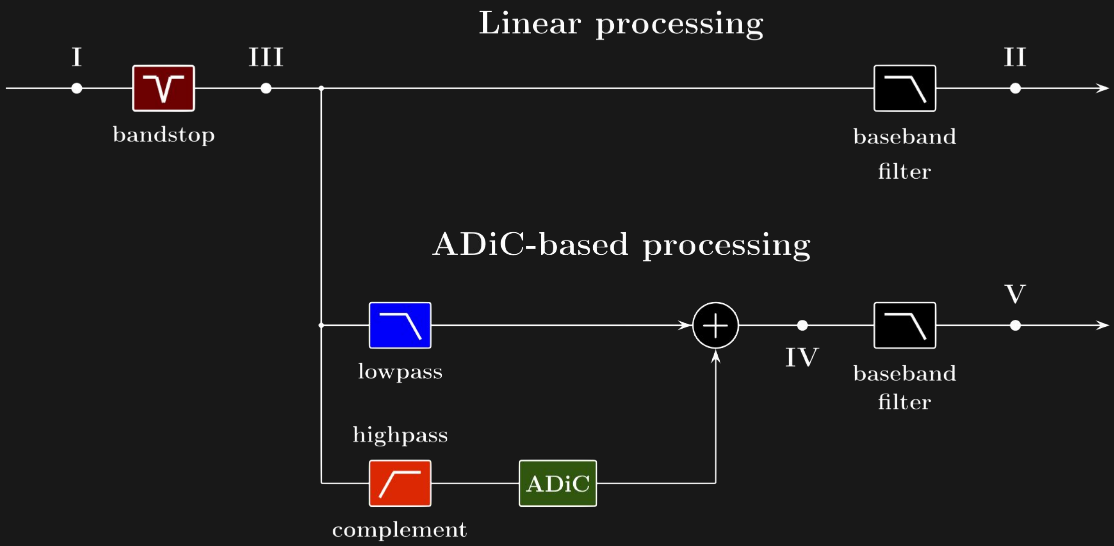
Toy audible demo

CLICK ON FIGURE BELOW TO PLAY MOVIE



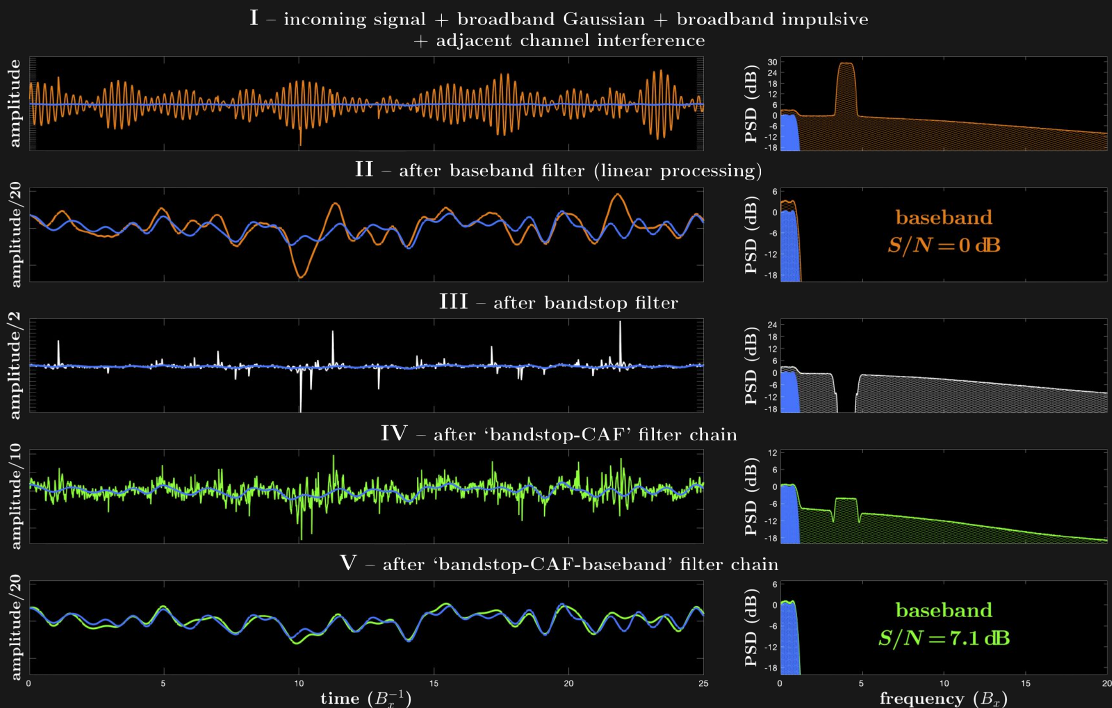
Addressing various "hidden interference" scenarios

E.g. spectral reshaping for adjacent channel interference:



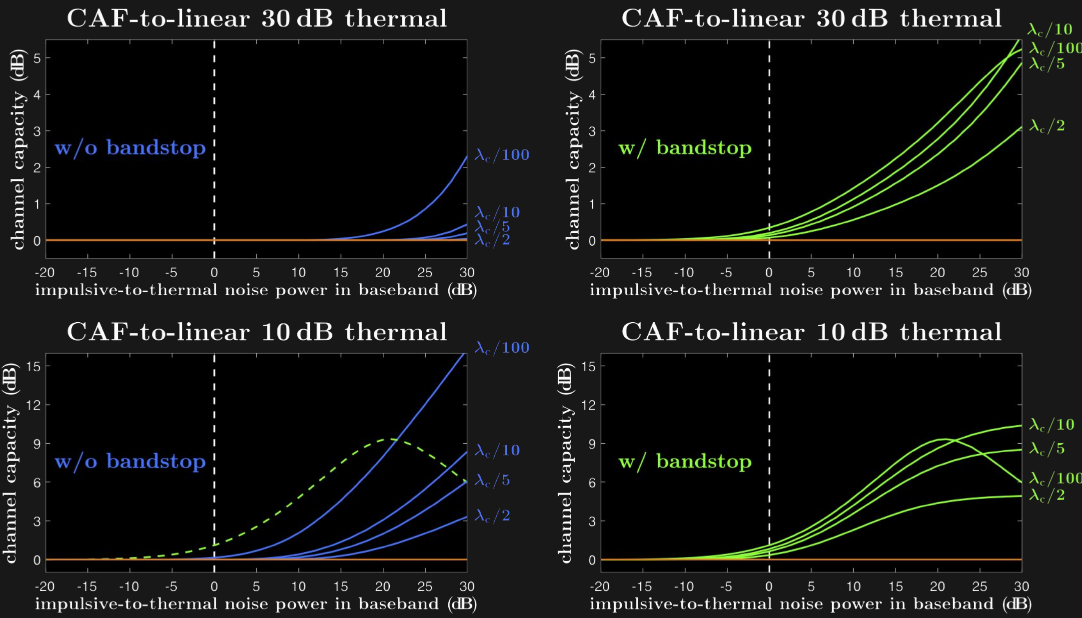
Impulsive noise with strong adjacent channel interference

Example: More than $\times$**2.5** channel capacity increase in comparison with linear filtering



Impulsive noise with strong adjacent channel interference

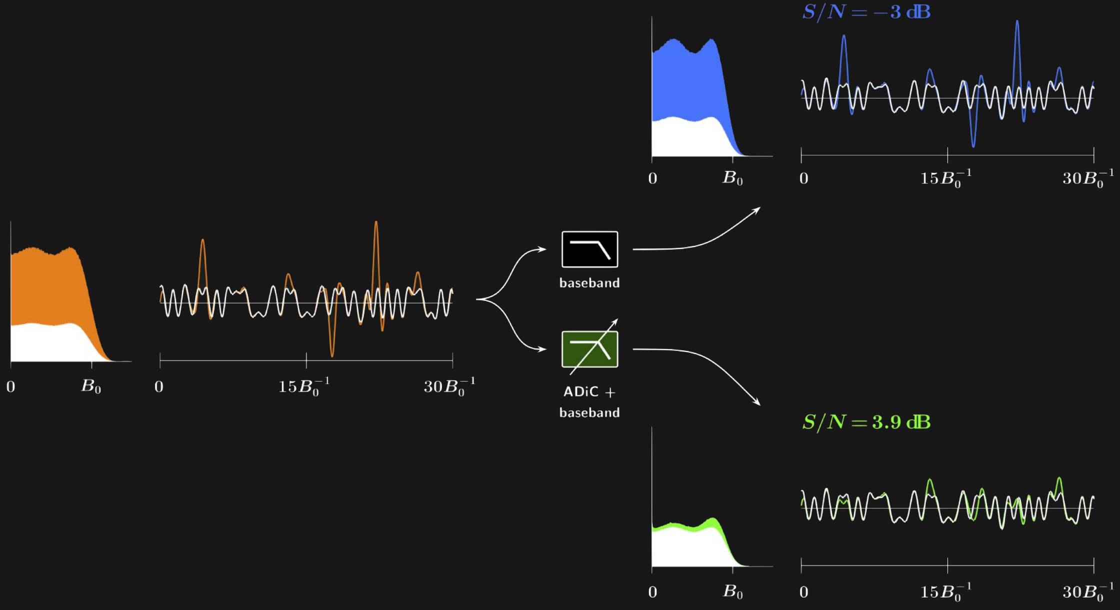
Channel capacities for ADiC-based filter w/ and w/o front-end bandstop:



B_0 baseband, $\mathbf{3.5}B_0$-$\mathbf{4.5}B_0$ adjacent, 30 dB adjacent/baseband;
Poisson noise, default ADiC parameters

Addressing "special" interference scenarios

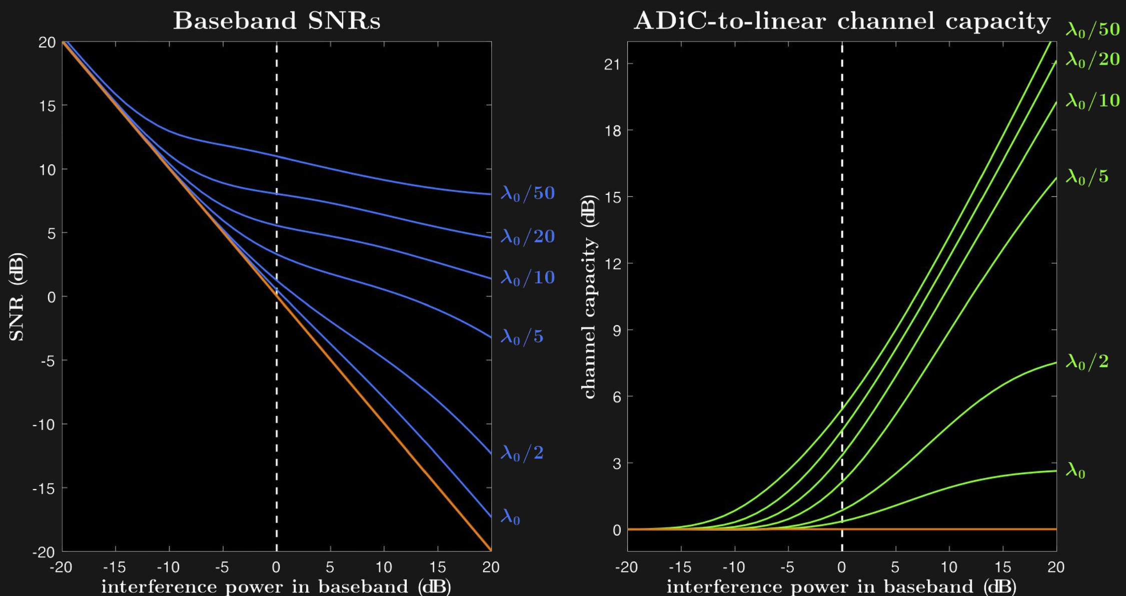
E.g. in special case of same spectral band for signal and impulsive interference:



Without excess bandwidth, "pileup rates" and "mitigable SNRs" are much lower

ADiC vs linear: Channel capacity in "shared band" case

Gaussian signal, narrow-band Poisson impulsive noise,
$\lambda_0 = 2.27\, B_0$, default ADiC parameters:

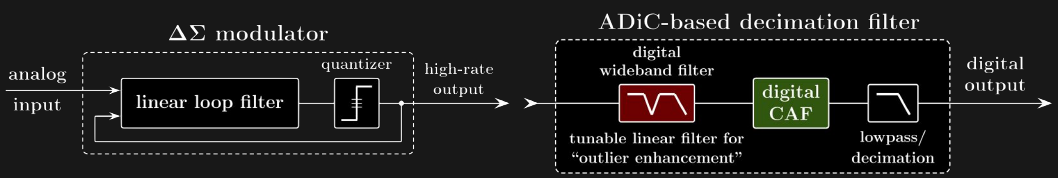


Performance can be enhanced by optimizing ADiC parameters for particular scenarios

Addressing various "hidden interference" scenarios

1. Employ wideband filter(s) ahead of CAF to enhance outliers in signal's band
2. Use CAF to mitigate outlier noise before final digital filtering
3. Modify, if needed, output digital filter to compensate for wideband filter(s)

Example: ΔΣ ADC with ADiC-based decimation for strong adjacent channel interference



High oversampling rate allows use of tunable wideband "spectral reshaping" linear filters in combination with ADiC-based filtering to achieve interference mitigation levels unattainable by linear filtering alone

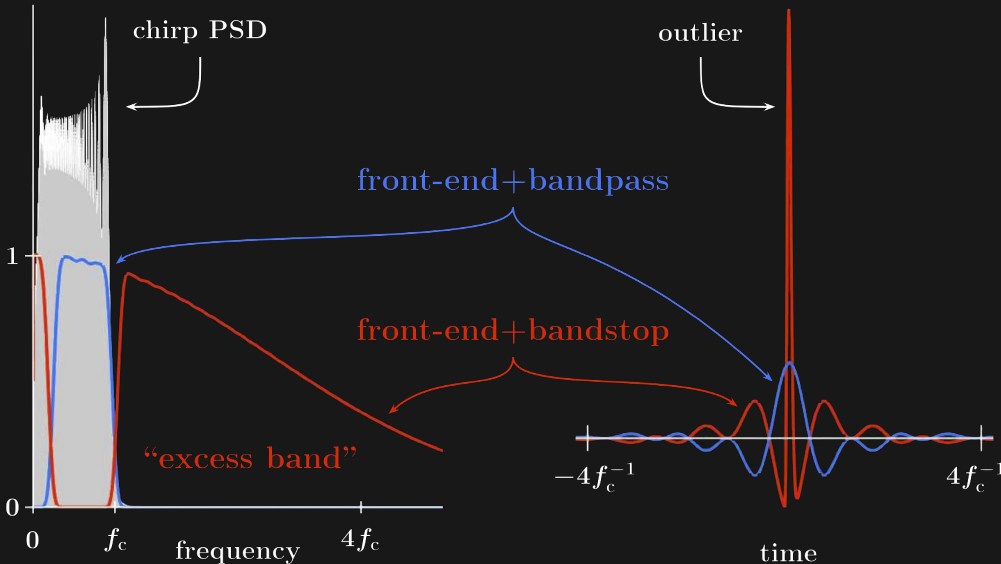
DIGITAL METHODOLOGY

TAKE AWAY

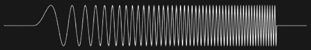
- Oversample $\Rightarrow$ Wider excess band
- Trade amplitude for time resolution
- Use front-end filters to manage excess band

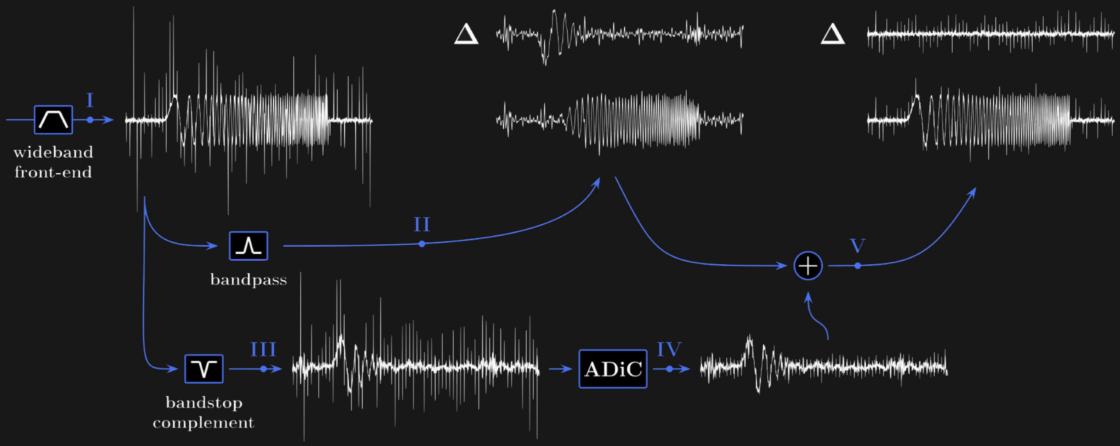
Practical configurations: CAF for chirp

1. Front-end filter with wide bandwidth and small time-bandwidth product
2. Stopband $[f_c/5, f_c]$ reduces average slew rate of linear chirp by about order of magnitude



Practical configurations: CAF for chirp



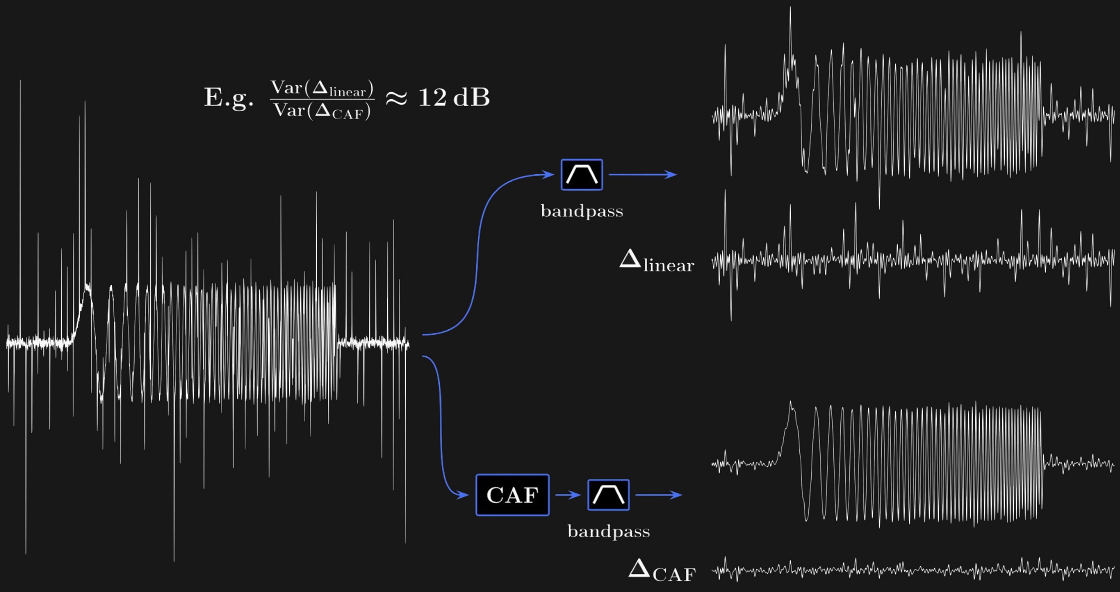


For constant group delay Δt of bandpass filter $w(t)$:

- **I** $x(t) + n(t) + i(t)$ (signal + wideband noise with outlier component $i(t)$)
- **II** $\underline{(w*x)(t) + (w*n)(t) + (w*i)(t)}$ (bandpass-filtered signal + noise)
- **III** $x(t-\Delta t) - (w*x)(t) + n(t-\Delta t) - (w*n)(t) + i(t-\Delta t) - (w*i)(t)$ (predominantly noise in excess band)
- **IV** $\underline{x(t-\Delta t) - (w*x)(t) + n(t-\Delta t) - (w*n)(t) + \delta i(t-\Delta t) - (w*i)(t)}$ (ADiC mitigates $i(t)$, $i(t) \to \delta i(t)$)
- **V** $x(t-\Delta t) + n(t-\Delta t) + \delta i(t-\Delta t)$ (II+IV: delayed signal + wideband noise with reduced outlier component $\delta i(t)$)

Practical configurations: CAF for chirp

E.g. $\frac{\mathrm{Var}(\Delta_{\mathrm{linear}})}{\mathrm{Var}(\Delta_{\mathrm{CAF}})} \approx 12\,\mathrm{dB}$

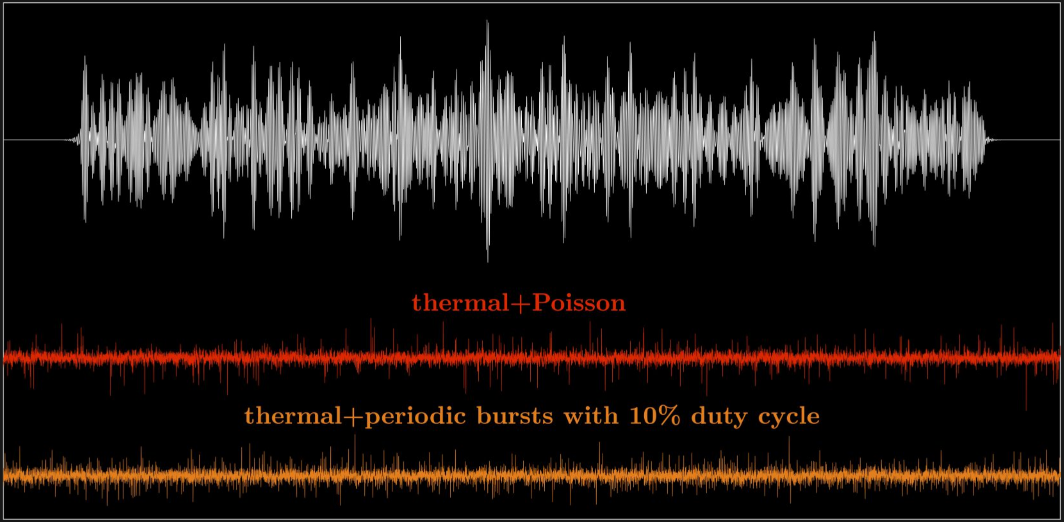


CLICK ON FILTER SYMBOLS FOR TOY AUDIBLE ILLUSTRATION

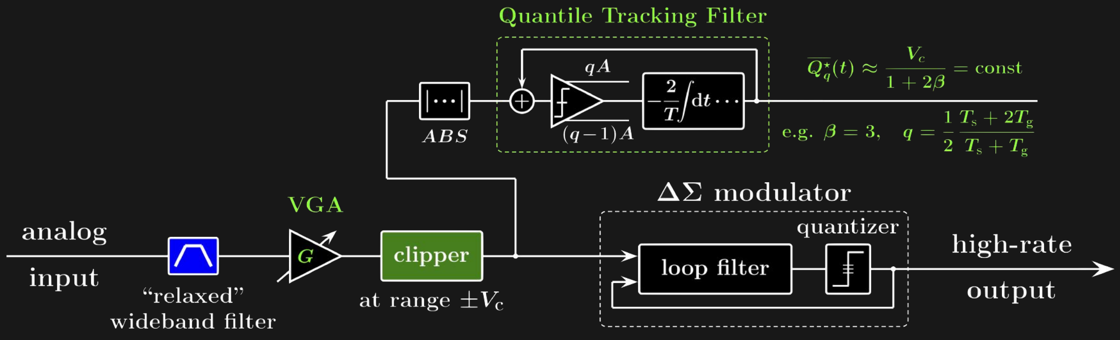
Practical configurations: CAF for OFDM

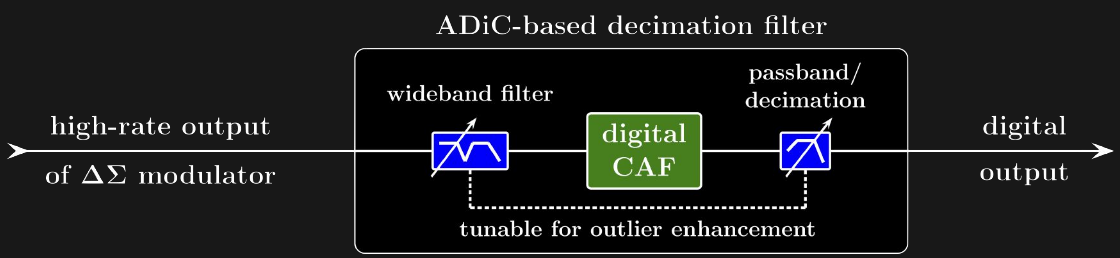
OFDM signal and noise traces at onset of outlier interference mitigability:
Further increase in power of outlier component results in significantly larger relative improvement in signal quality

OSDM symbol and noise examples for 30 dB thermal SNR, $\lambda = \lambda_c/10$, and 0 dB outlier-to-thermal noise powers



For "bursty" and high-crest-factor signals

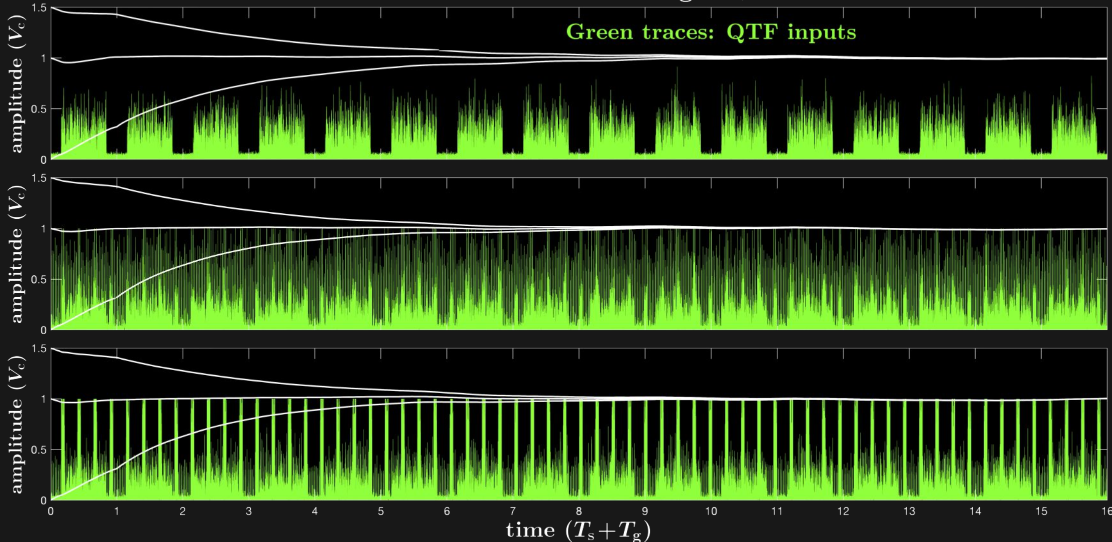




Practical configurations: CAF for OFDM

QTF circuit for gain control

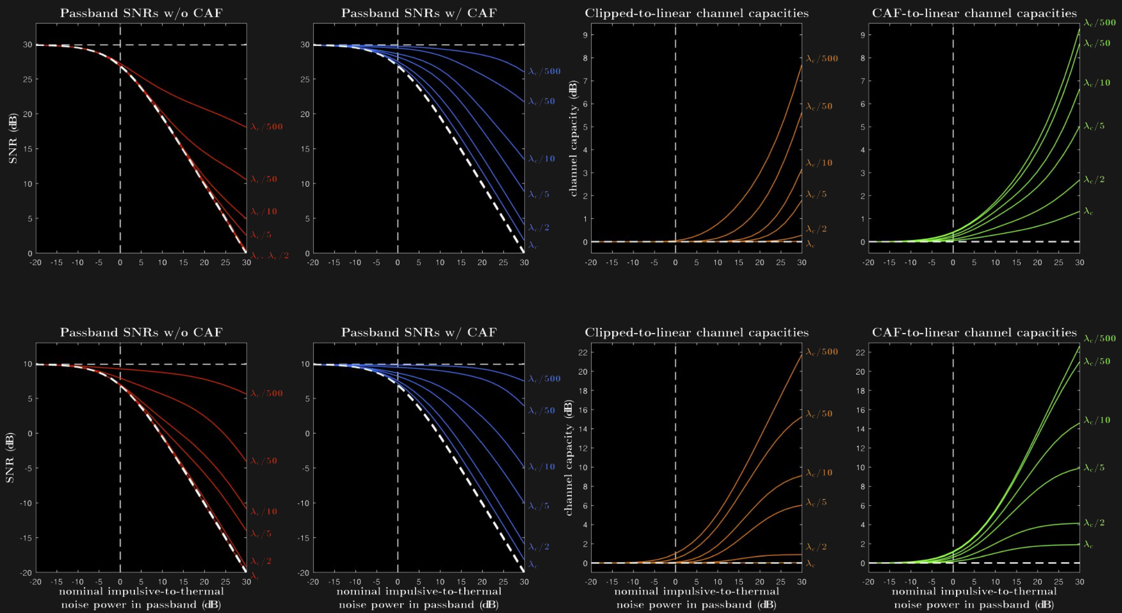
QTF outputs $7\,\overline{Q_q^\star}(t)$, for $\mu = \frac{1}{10} V_\mathrm{c}/(T_\mathrm{s}+T_\mathrm{g})$ and for different initial conditions and signal+noise mixtures



OFDM signal is not being clipped, while excessively strong outliers are limited to $\pm V_\mathrm{c}$

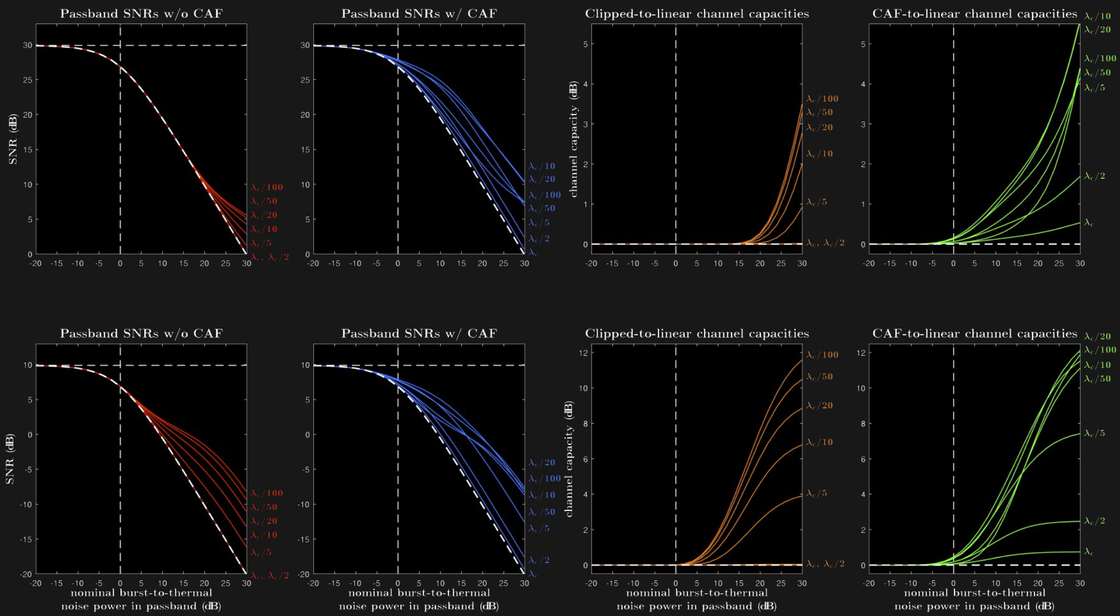
OFDM: Poisson noise with normally distributed amplitudes

CAF-based filtering following analog clipper noticeably increases effectiveness of mitigation, especially for high SNRs and event occurrence rates



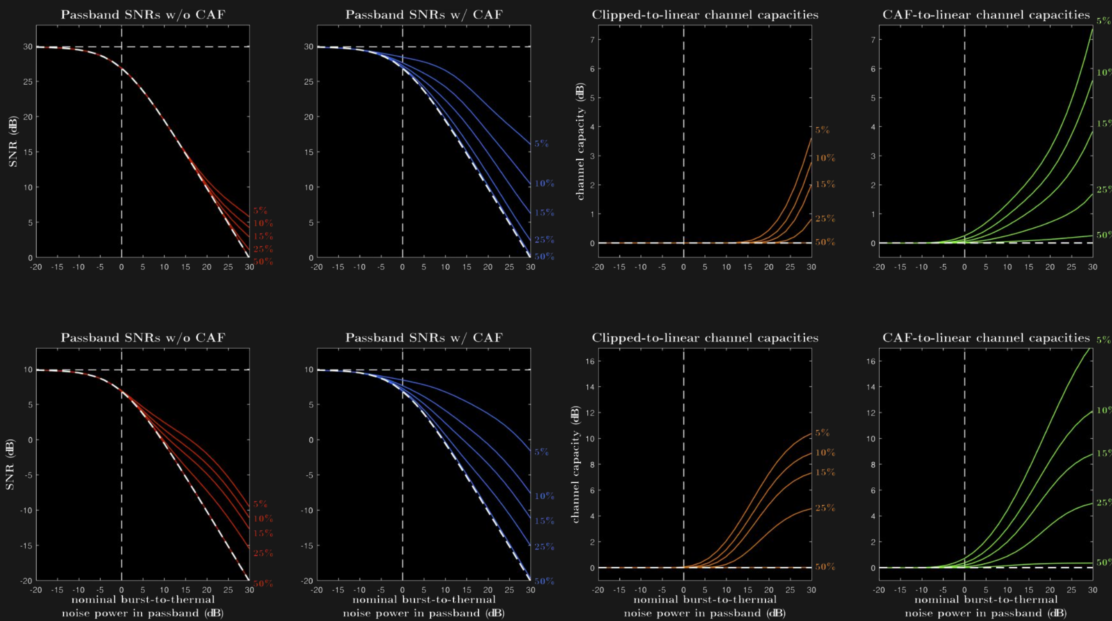
OFDM: Periodic Gaussian bursts with 10% duty cycle

CAF-based filtering following analog clipper significantly further improves signal quality and extends mitigability, but its effectiveness is no longer monotonic with respect to outlier occurrence rates (since burst duration is inversely proportional to rate)



OFDM: Burst noise with $\lambda = \lambda_c/20$ and different duty cycles

For bursts with duty cycles larger than 50% CAF-based filtering with default parameters becomes ineffective



Nonlinear
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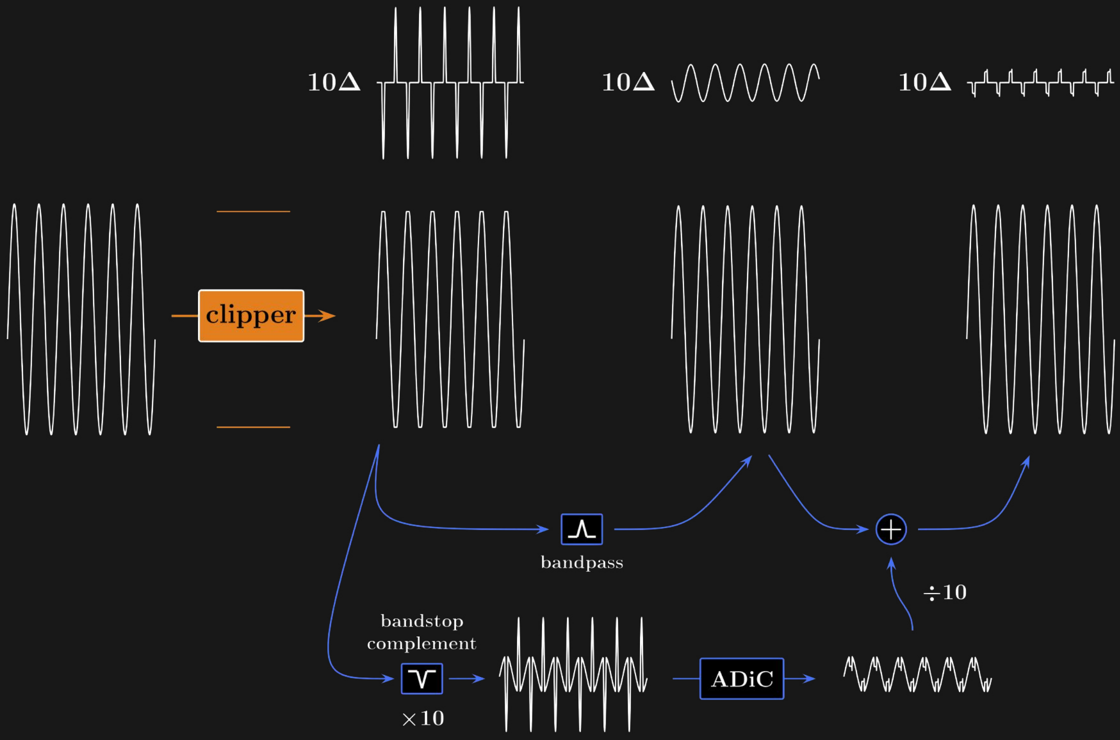
PRACTICAL IMPLEMENTATIONS

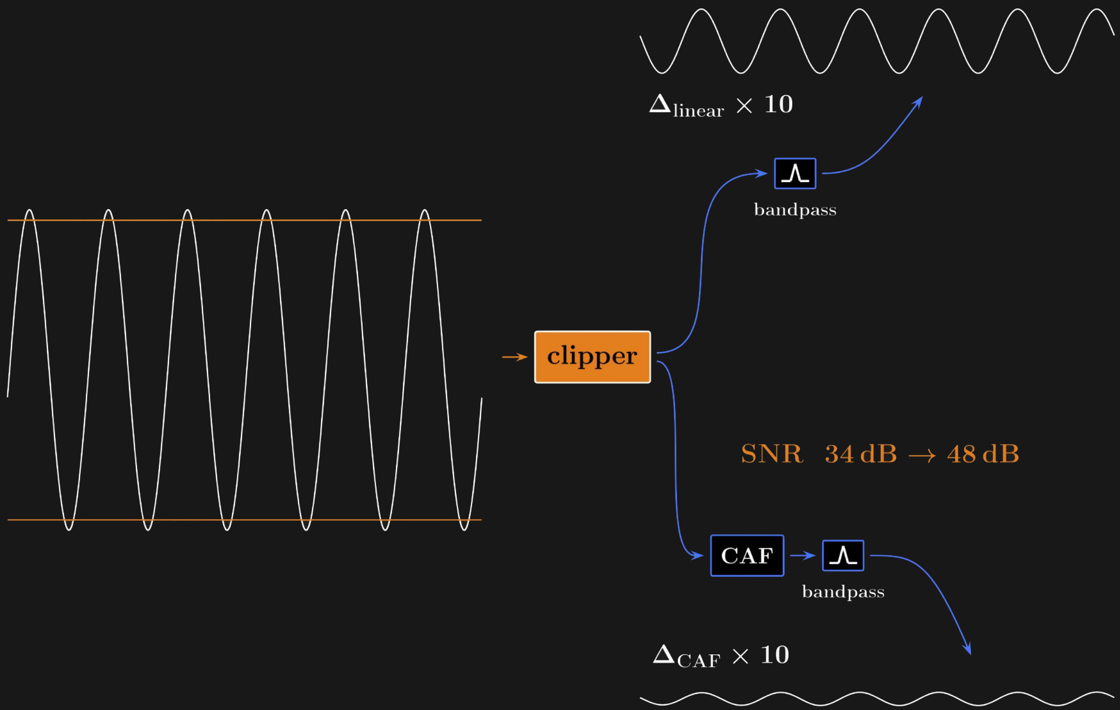
TAKE AWAY

- Co-design antialiasing and pre-CAF filters
- Use analog front-end clipper (e.g. combined with QTF-based AGC)

CAF for clipping distortions: Toy example

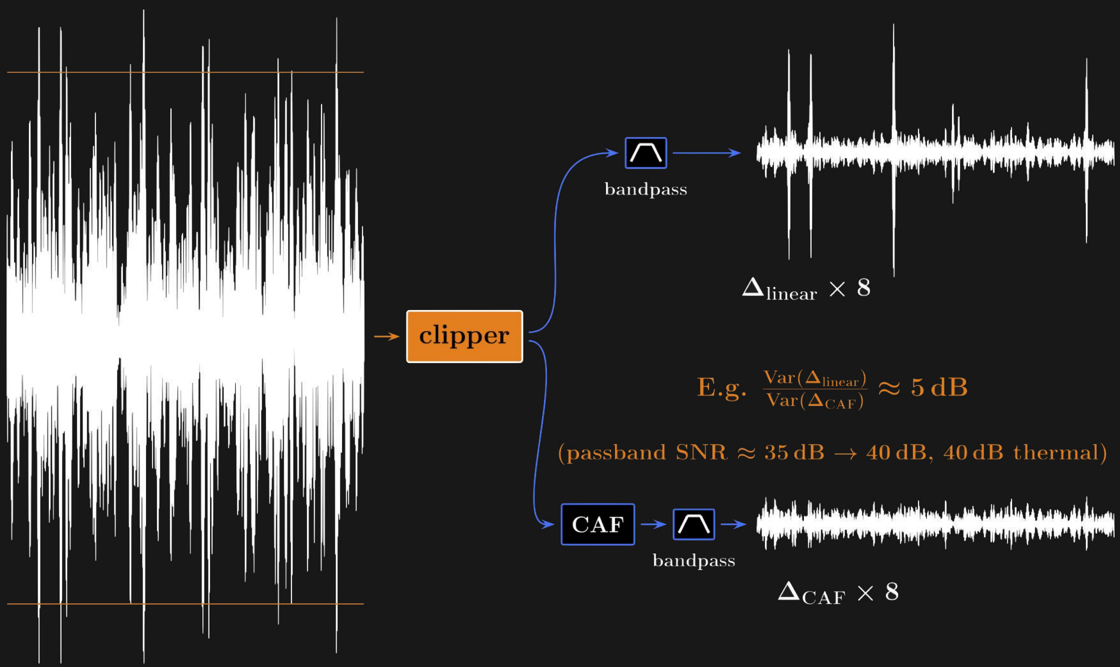


CAF for clipping distortions: Toy example



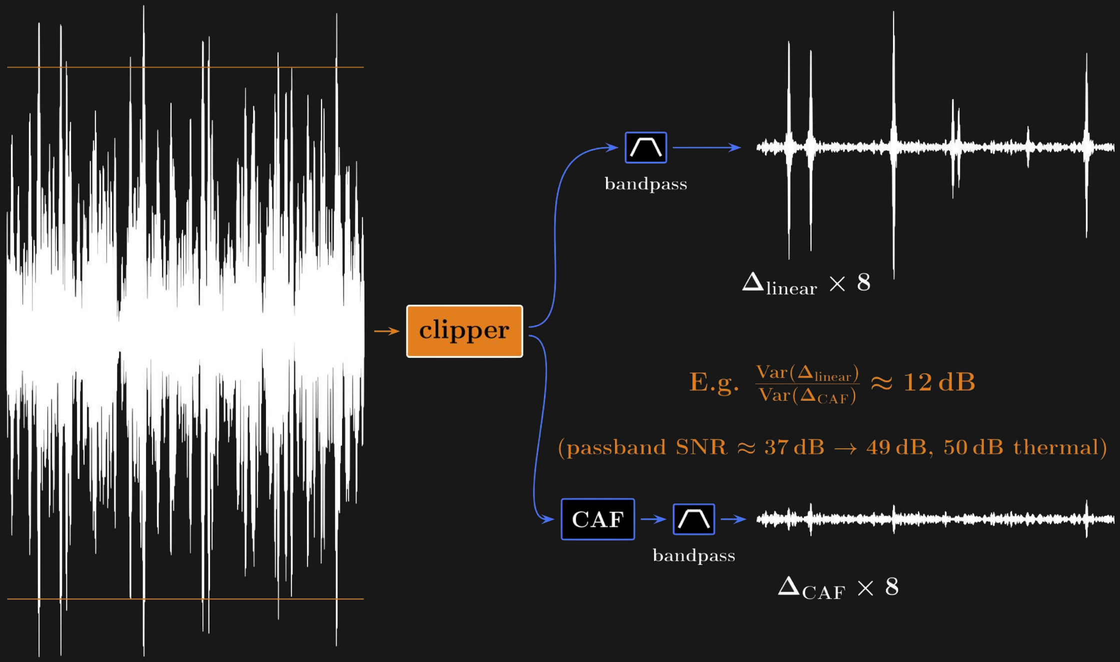
Practical configurations: CAF for OFDM

Mitigating clipping distortions



Practical configurations: CAF for OFDM

Mitigating clipping distortions

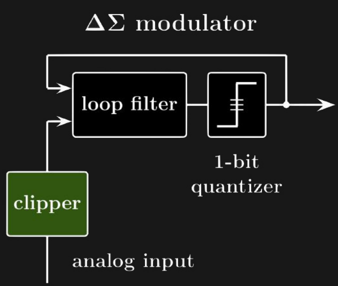


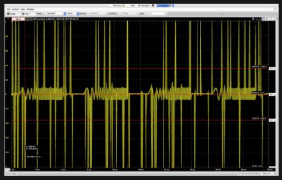
IMD is part of

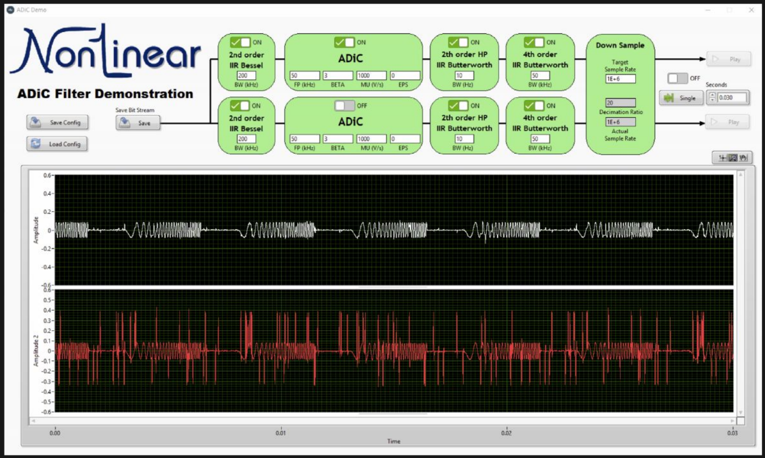
mitigable outlier interference

Designing development & testing platform

Early prototype of development board incorporating ADiC filtering into ΔΣ ADC





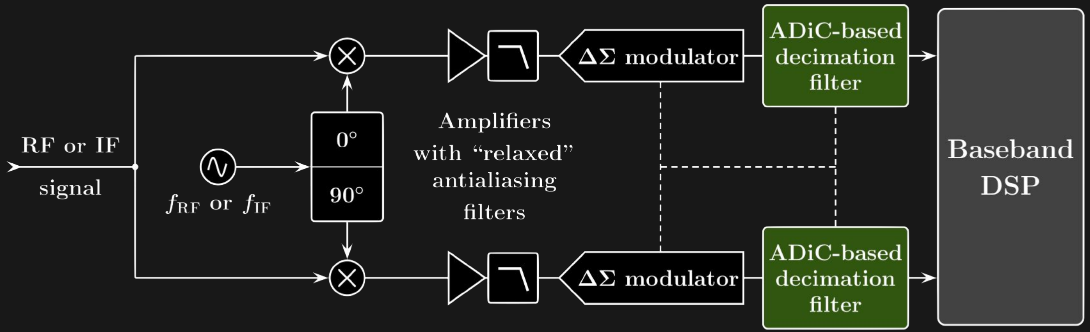


- 1-bit isolated second-order ΔΣ modulator AD7403
- Filters implemented in FPGA on NI sbRIO-9637 (LabVIEW)
- Mostly for real-time audio range demonstrations and up to 500 kHz output bandwidth
- "Effectively analog" MATLAB simulation tools

Designing development & testing platform

Next steps:

- Application-specific setups

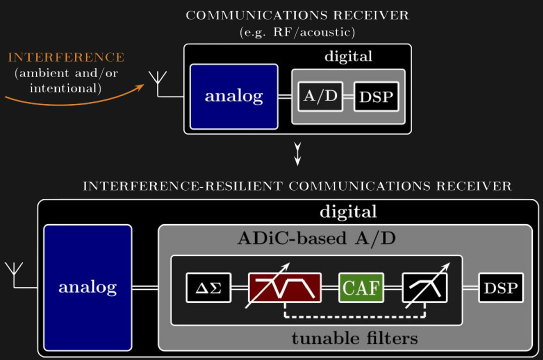


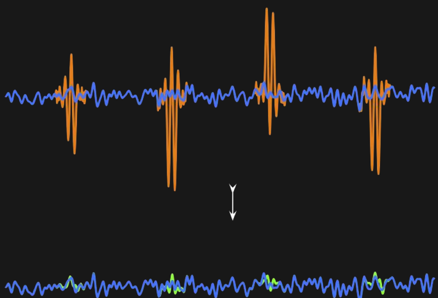
- "Effectively analog" MATLAB simulation tools in parallel

Broader picture

Short-term development goals

1. Address **complex practical interference scenarios**
2. Achieve **real-time** mitigation levels **unattainable by linear filtering**
3. Ensure **compatibility with existing systems & mitigation techniques**
4. Facilitate various **spectrum sharing & coexistence** applications
5. Apply to RF/acoustic **battlefield communications** and **radar/sonar**





Broader picture

ADiC-based filtering:

- Is intended as **"first line of defense"** against interference
  - can be used **in addition or as low-cost alternative** to other interference mitigation methods
  - **"blind"** yet **adaptable** to nonstationary signal & noise conditions
- Mitigates various types of **co-site interference** and/or **platform noise**
  - e.g. noise generated by on-board digital circuits, clocks, buses, and switching power supplies
- Addresses various **spectrum sharing & coexistence applications**
  - e.g. radar-communications, radar-radar, narrowband/UWB, etc.
  - including **dual function systems** (e.g. radar/comms as mutual signals of opportunity)
- Can benefit various other military, scientific, industrial and consumer systems
  - e.g. sensors/sensor networks and coherent imaging systems
  - auditory tactical communications (e.g. in military ground combat applications)
  - radiation detection, powerline communications, navigation & ToA techniques
- Allows **simple analog** and/or **real time digital** implementations
  - can be integrated into and manufactured as IC components for use in different products
  - e.g. as A/D converters with incorporated interference suppression

A/D with incorporated interference suppression

TAKE AWAY

Appendices

Appendix I: Acknowledgments

Many thanks to following individuals for their valuable suggestions and critical comments:

- Keith W. Cunningham of Atkinson Aeronautics & Technology Inc., Fredericksburg, VA
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- Earl McCune of Eridan Communications, Santa Clara, CA
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- Kyle D. Tidball of Textron Aviation, Wichita, KS

The authors would also like to express their sincere appreciation to Suzanne Vega for producing one of the best songs for testing noise mitigation: Tom's Diner (1987)

Appendix II: Key references

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Nikitin AV
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