Cognitive Radio Transceiver Chips

Eric Klumperink

University of Twente, CTIT, IC Design,
Enschede, The Netherlands

e-mail: e.a.m.klumperink@utwente.nl
papers: http://icd.ewi.utwente.nl

Traditional versus Cognitive Radio

Nokia Research

Cognitive Radio terminology

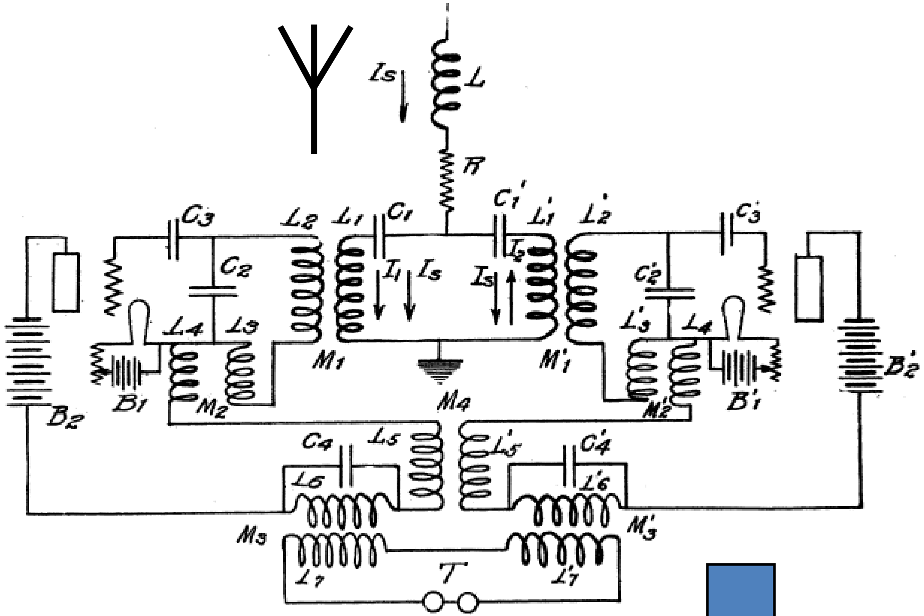
- Original: any smart radio device
- RF hardware community:
  Software Defined Radio for Dynamic Spectrum Access
- US/UK Rulings FCC & OFCOM
- IEEE802.22 and IEEE802.15.2
- Key RF hardware Challenges:
  - Flexible clean Transmitter:
    reduce interference
  - Find "white spaces" :
    sensitive spectrum sensing
  - Flexible Receiver:
    ***cope with* interference!**

Cognitive Radio

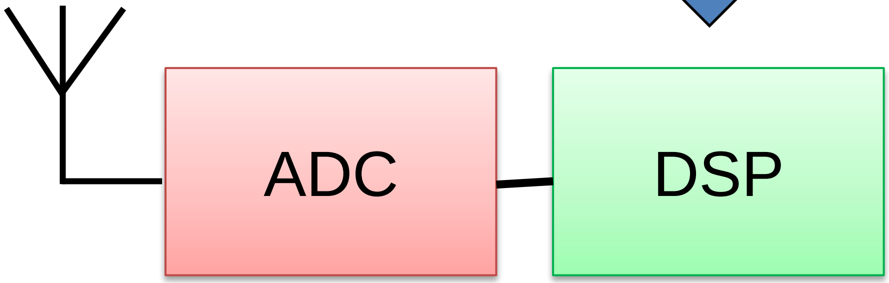
Mitola and Maguire (1999)

Trend to remove dedicated filtering

- Armstrong 1915



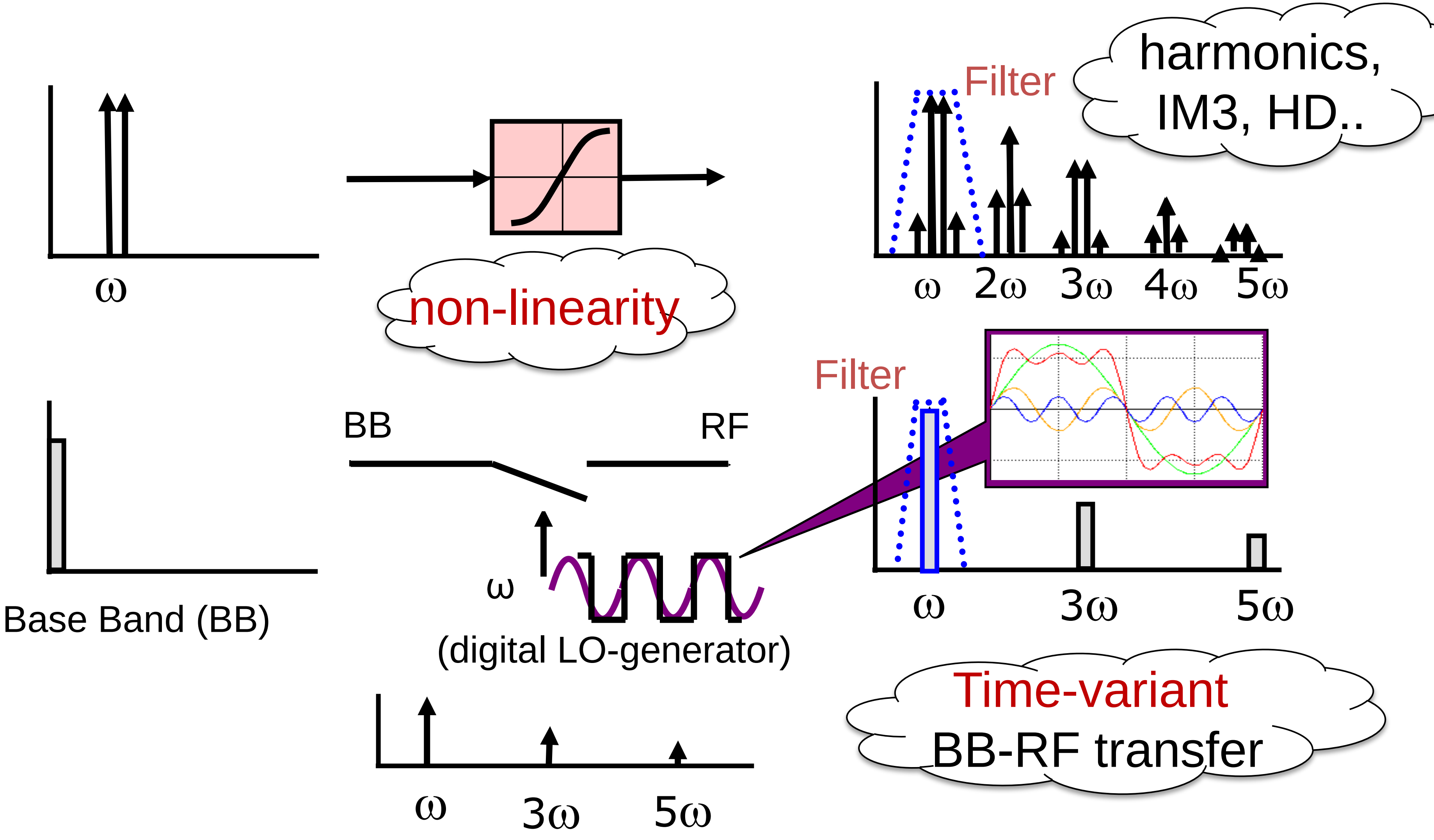
- Dream


ADC
DSP

- Trend Analog ⇒ Digital
- Still analog needed for feasibility
- Flexibility ⇔ less RF pre-filtering
- Different names:
  - Software Defined Radio (SDR)
  - Reconfigurable radio
  - “wideband”, “Inductorless”, “SAW-less” (no SAW-filters)
  - Cognitive Radio

Challenge 1:
Agile but Clean Transmission ...

Reasons for band-filtering - Transmitter



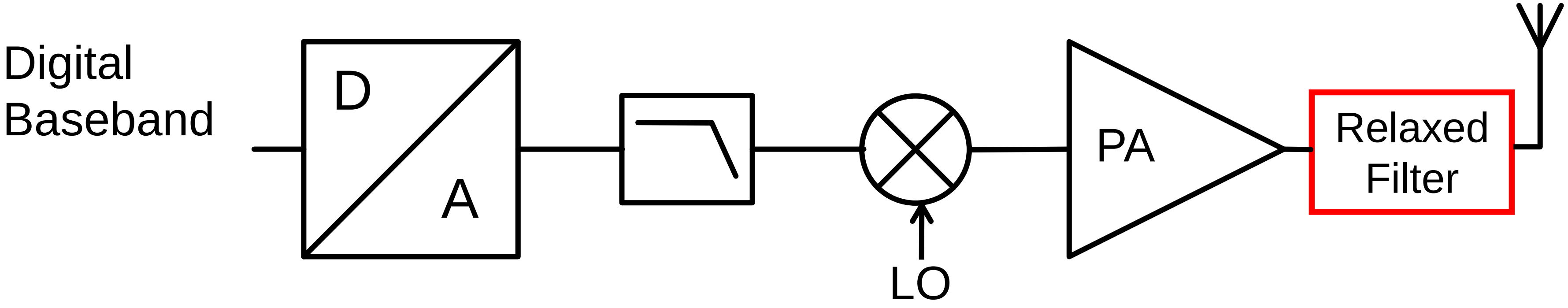
harmonics, IM3, HD..

non-linearity

Time-variant BB-RF transfer

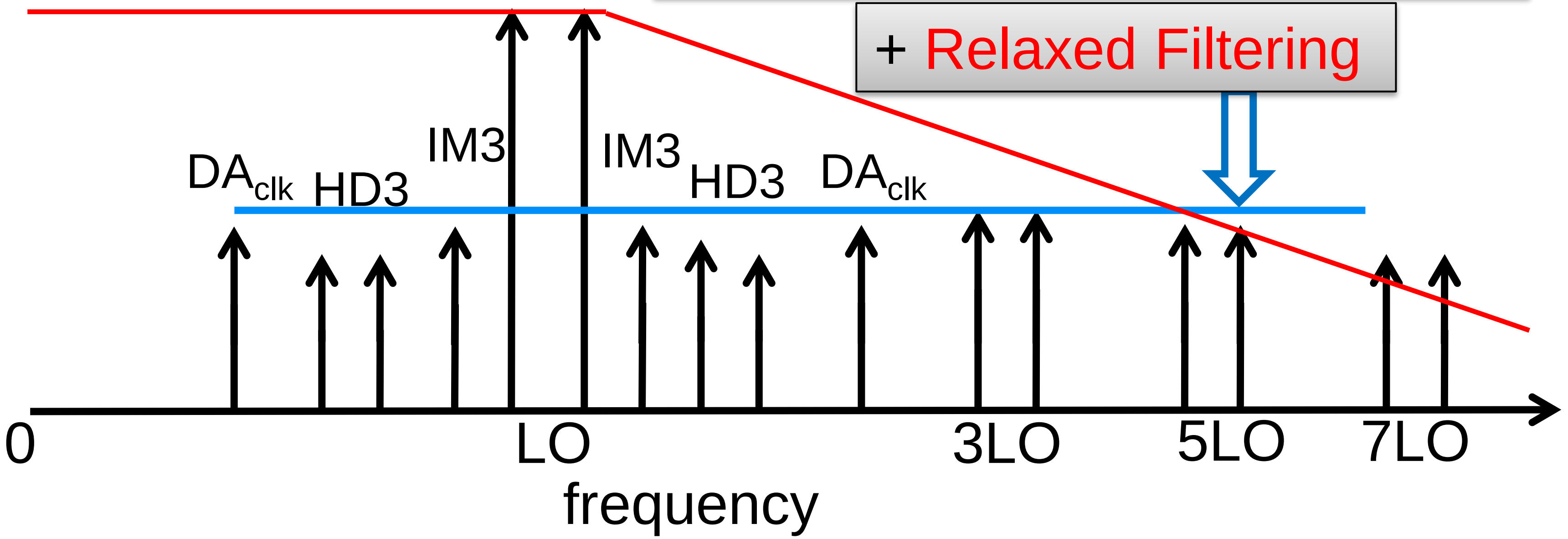
[*Klumperink-ComMag07*]

Motivation/Problem



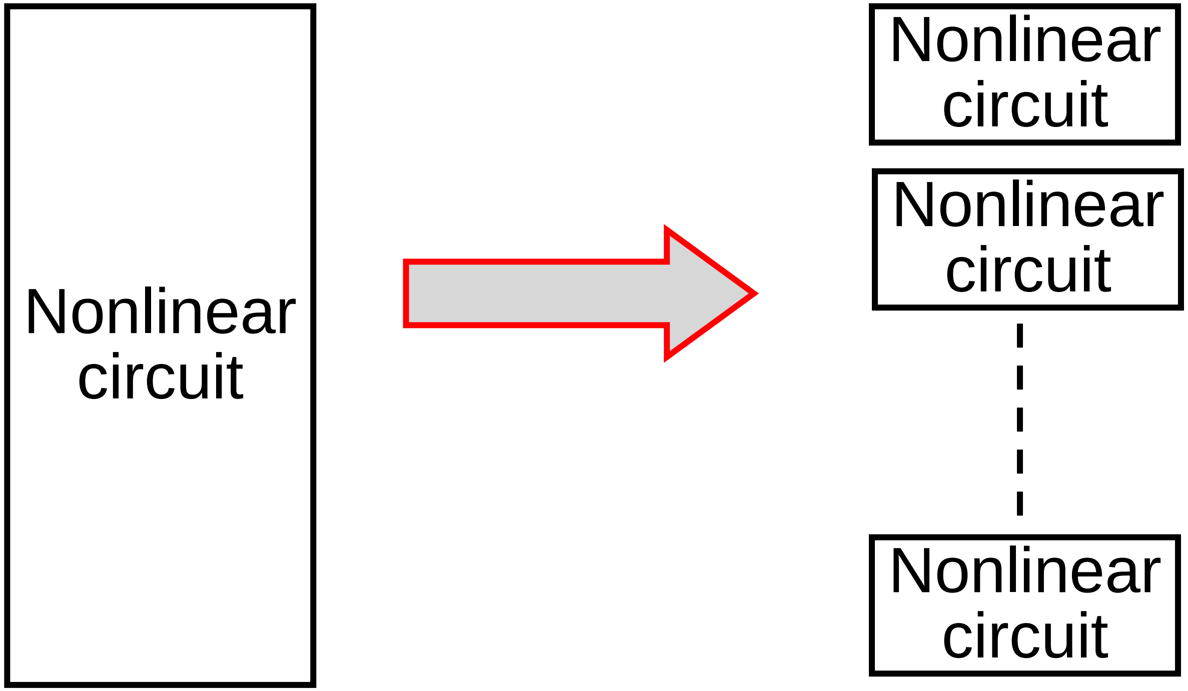
Suppression without Filtering

+ Relaxed Filtering



Multipath Polyphase Technique

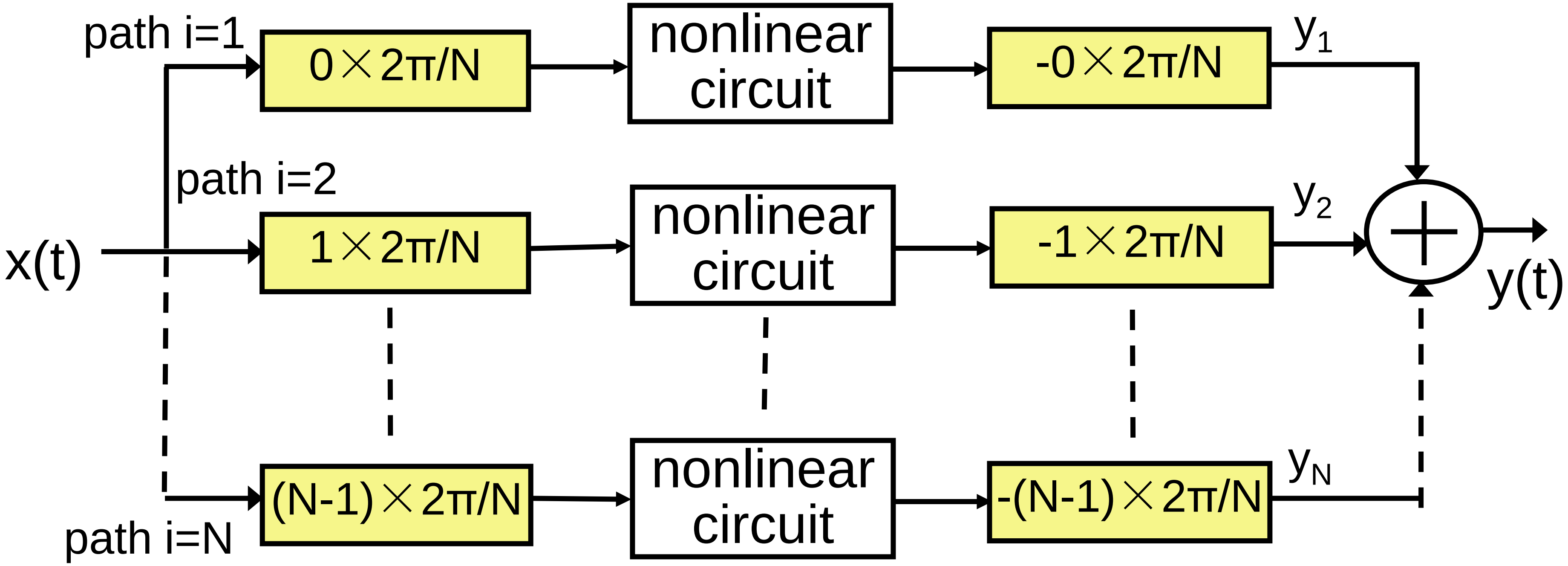
1) Divide the nonlinear circuit into ‘N’ equal smaller pieces



2) Add equal but *opposite* phase shift before and after piece

Multipath Polyphase Technique(2)

Equal *opposite* phase shifts before and after nonlinearity:



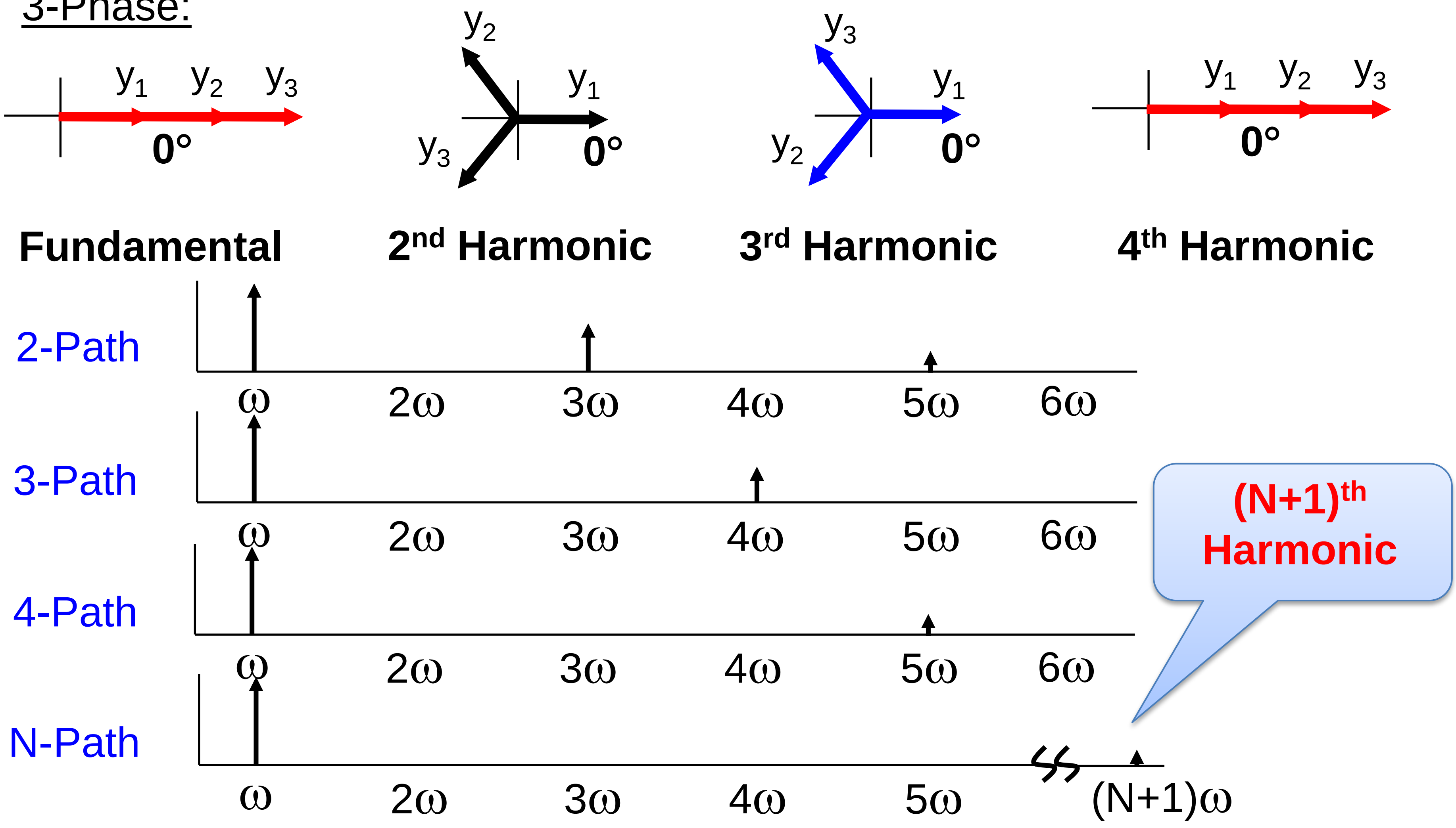
$$\cos(\omega t+\varphi) \longrightarrow \boxed{a_1x(t)+a_2x^2(t)+a_3x^3(t)+\ldots} \longrightarrow b_k\cos(\underbrace{k.\omega t+k.\varphi})$$

“Phase rotation for k^{th} harmonic is $k\times\varphi$”

[Mensink, ISCAS 04, TCAS 05]

Output for N-Path Polyphase

3-Phase:

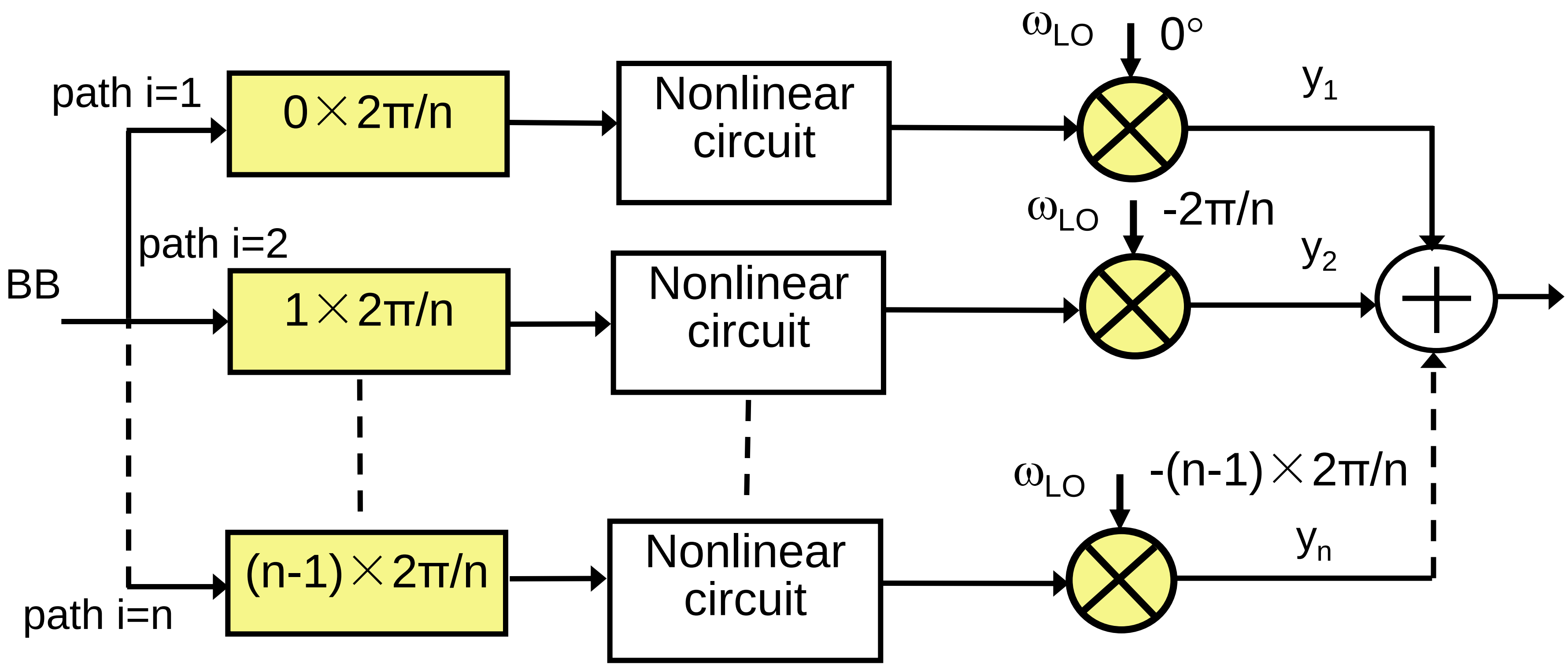


(N+1)th Harmonic

Multi-tone input: cancels $p \cdot \omega_1 \pm q \cdot \omega_2$, unless: $p+q=j \times N+1$

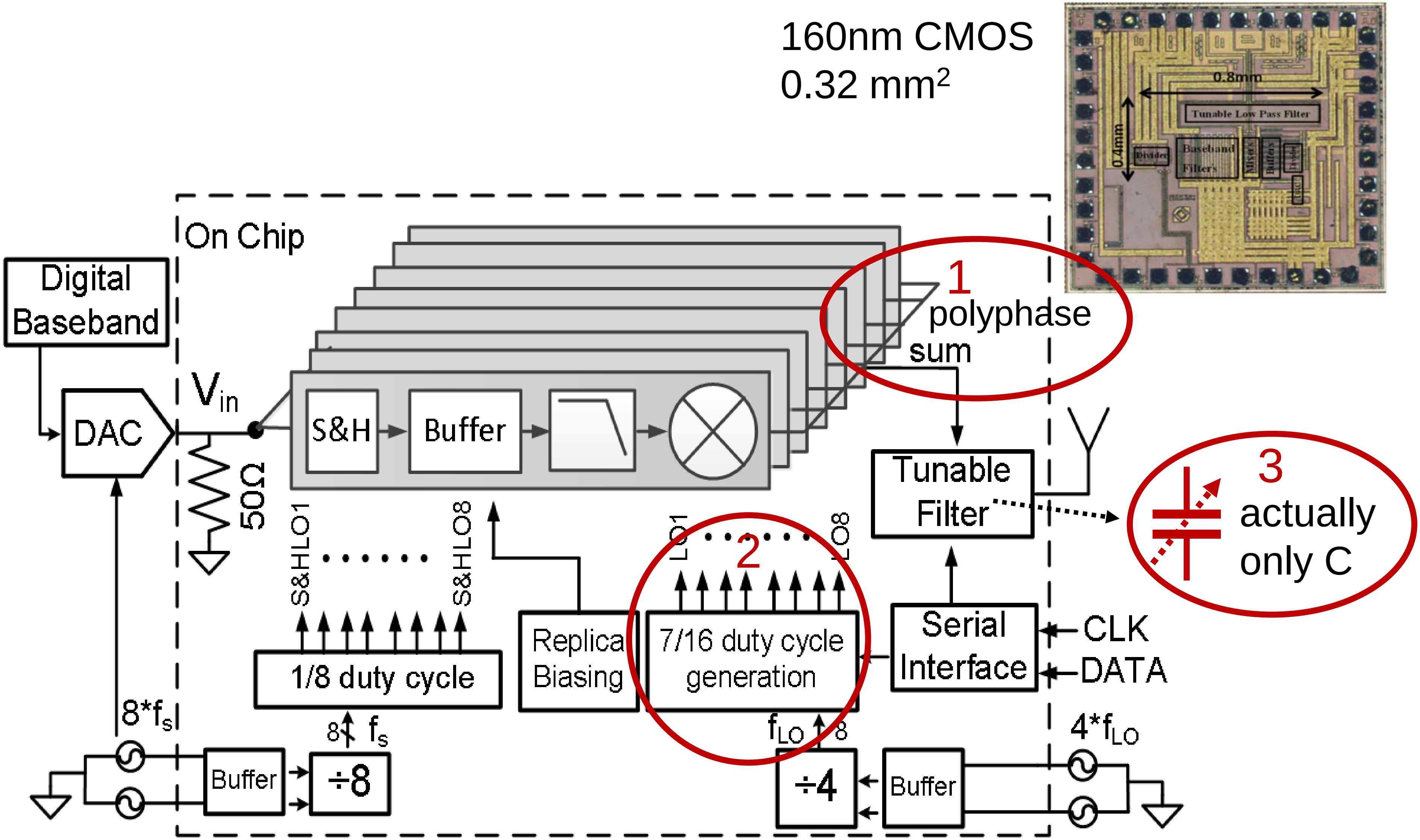
How to realize wideband Phase Shift?

Solution: 1) Digital BB phase shifter
2) Mixer wideband phase shifter

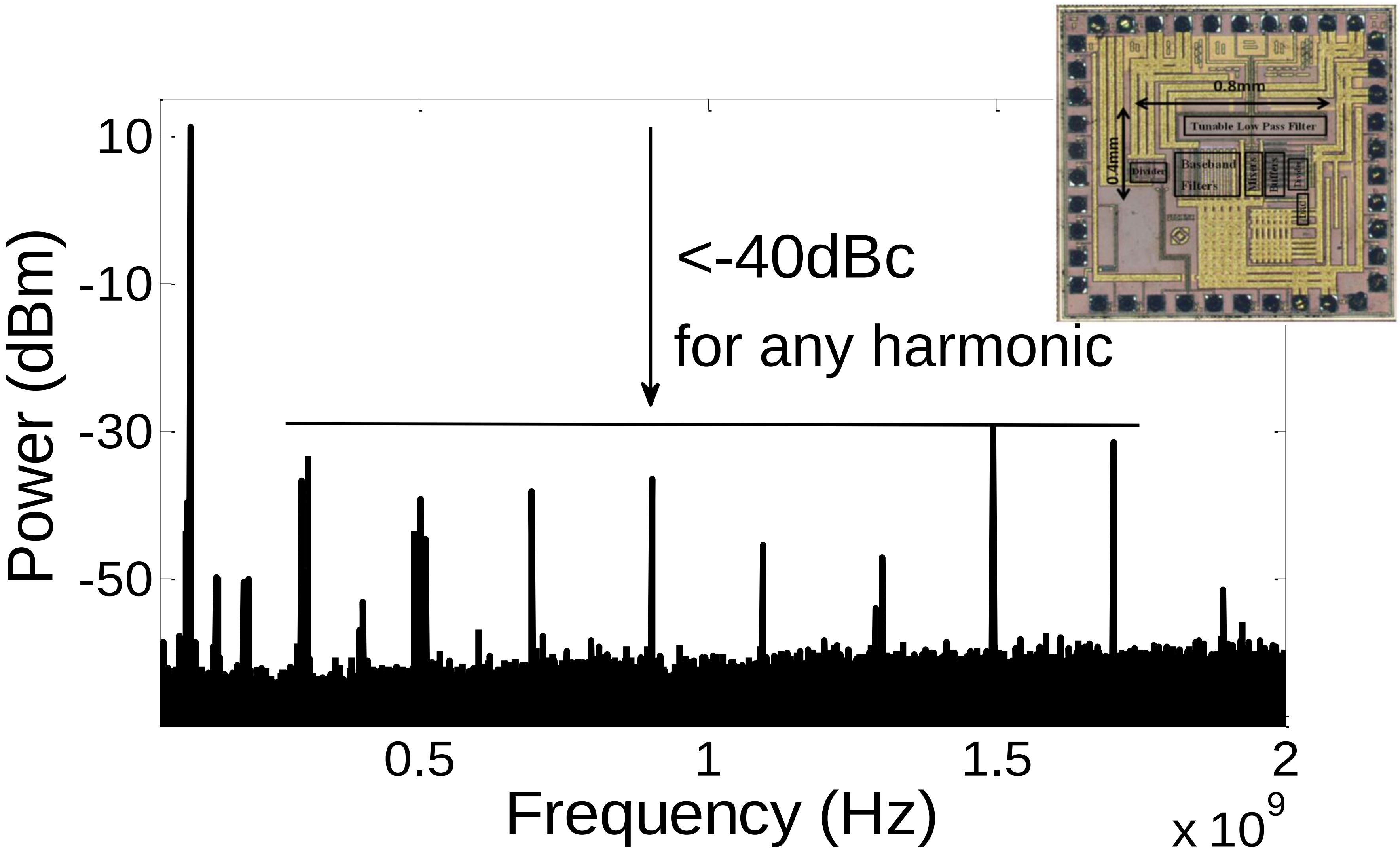


One Baseband to RF path (8 slices on chip)

160nm CMOS
0.32 mm^2



Flexible 100-800MHz Transmitter Chip



<-40dBc

for any harmonic

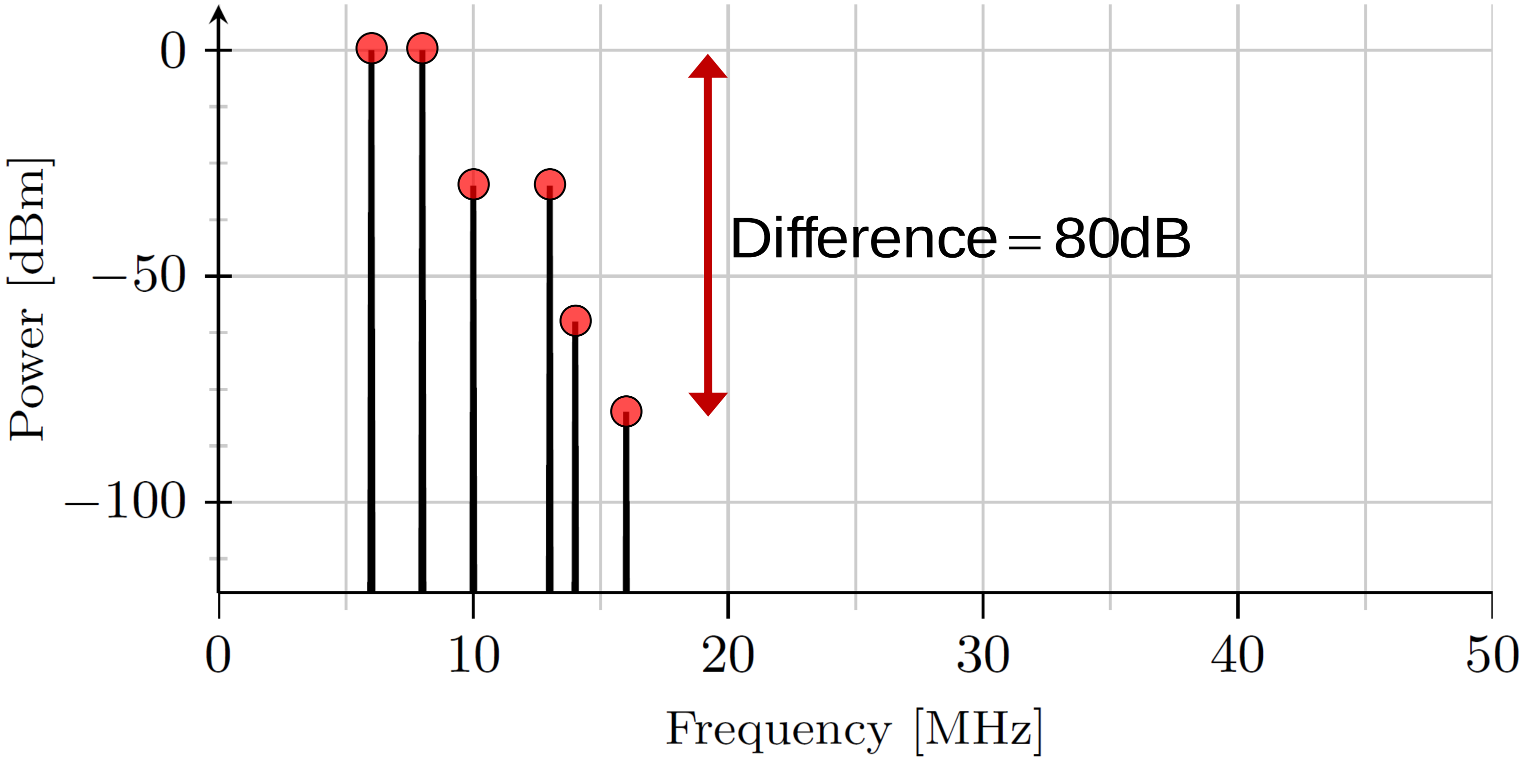
Challenge 2:
Find the “white spaces”

Spectrum Sensing

Dynamic Range Problem

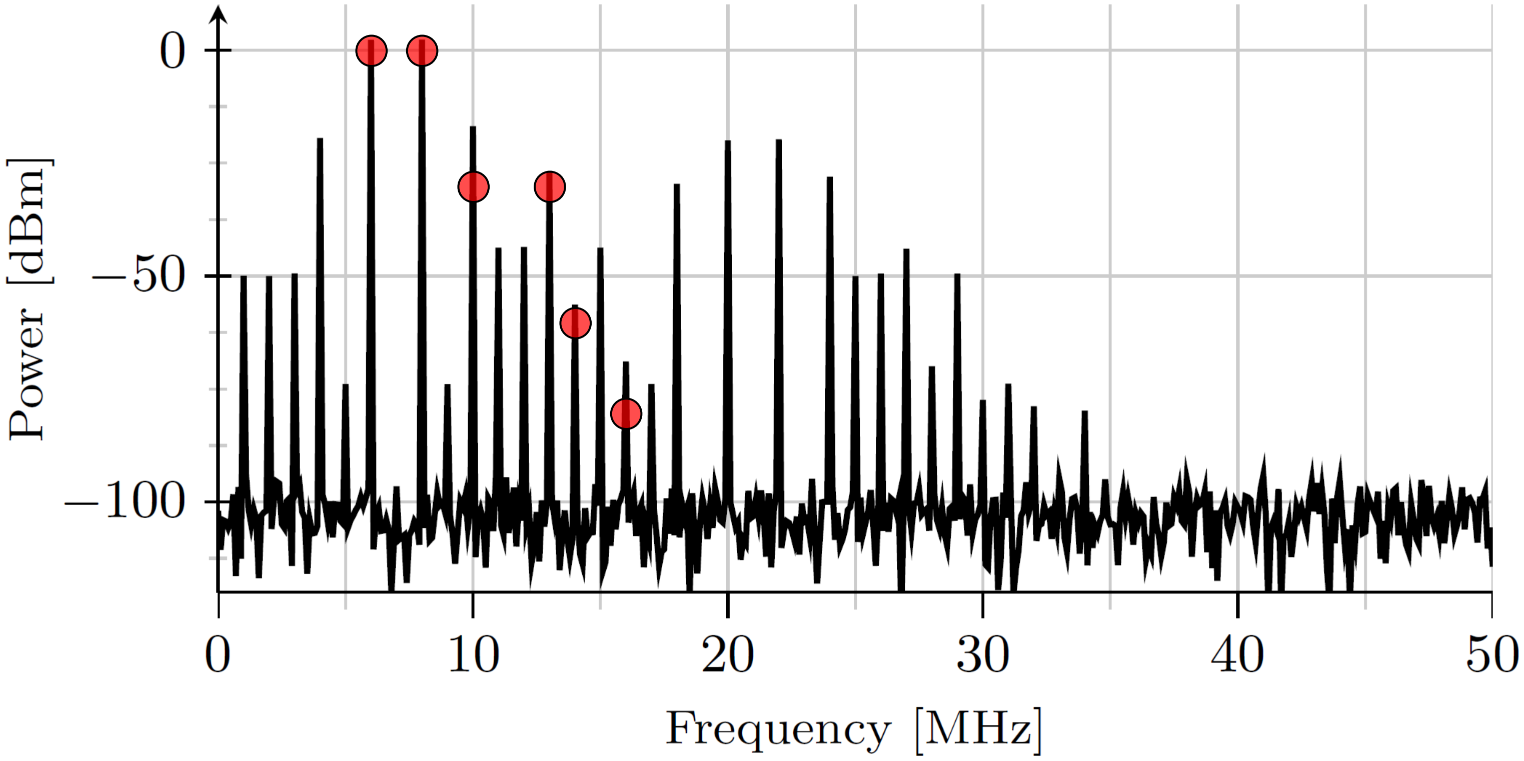
Similar issue: Spectrum Sensing: SFDR (I)

- Input of SA (= output of ideal SA)
  - NF=0dB, IIP3=+∞dBm, RBW=100kHz



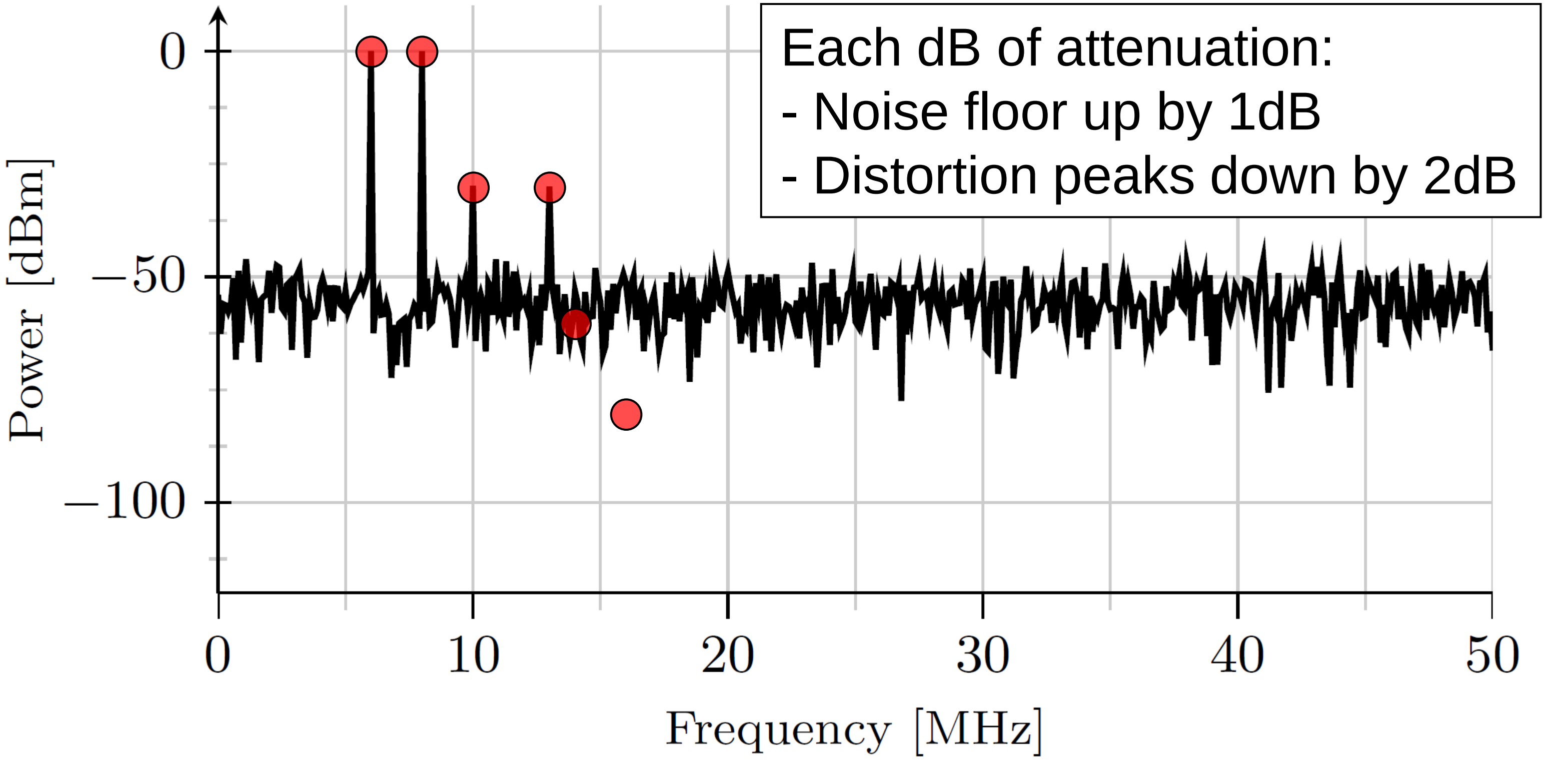
SFDR (II)

- Output of SA: non-linearity is dominant
  - NF=20dB, IIP3=+10dBm, RBW=100kHz, att.=0dB



SFDR (III)

- Output of SA: noise is dominant
  - NF=20dB, IIP3=+10dBm, RBW=100kHz, att.=48dB

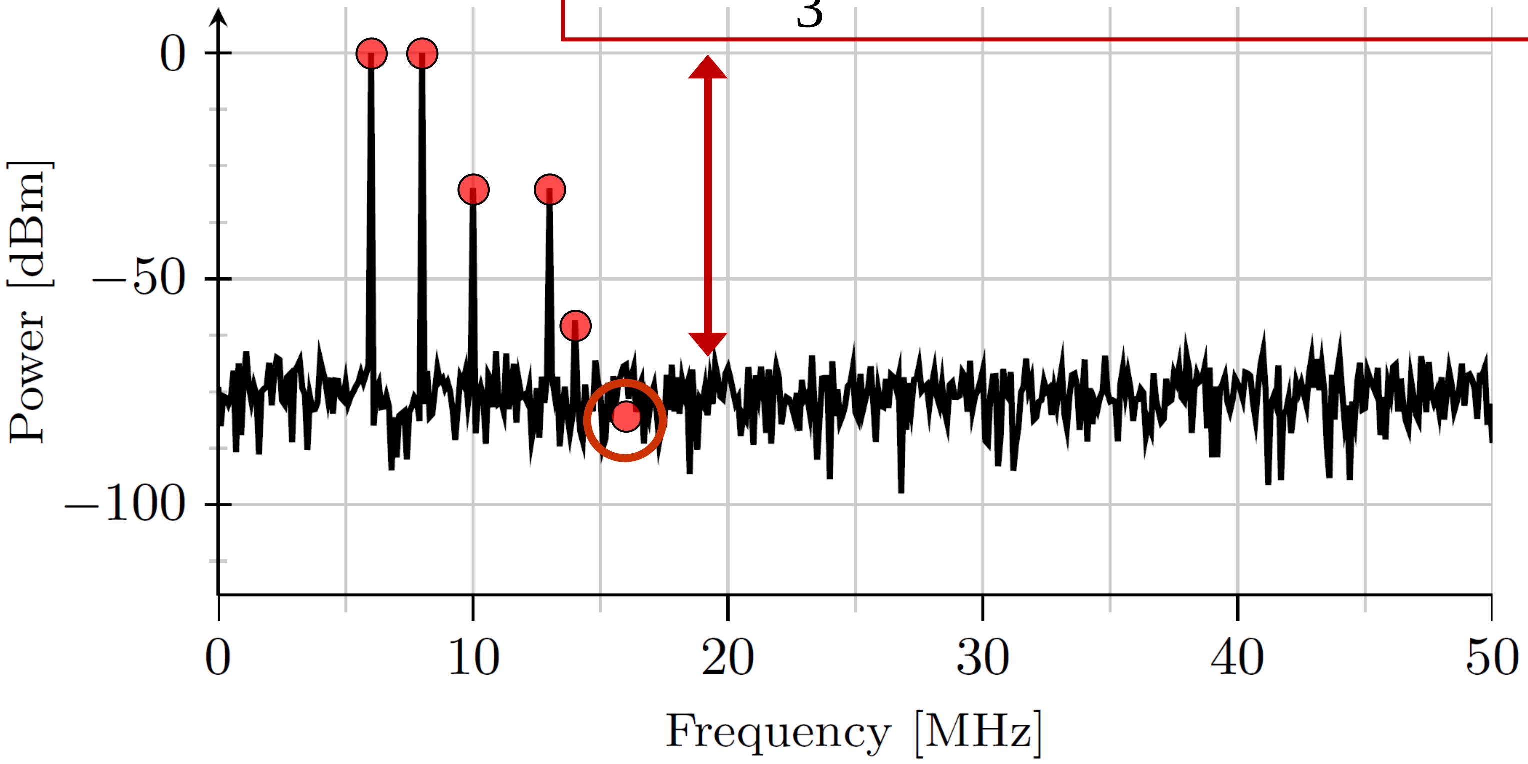


Each dB of attenuation:
- Noise floor up by 1dB
- Distortion peaks down by 2dB

SFDR (IV)

- ❑ Noise and IM3 products are equal ⬄ SFDR
  - NF=20dB, IIP3=+10dBm, RBW=100kHz, att.=28dB

$$\boxed{\mathrm{SFDR} = \frac{2}{3}\left(\mathrm{IIP3} - \mathrm{NF} - 10\log_{10}\mathrm{RBW} + 174\right) = 76\mathrm{dB}}$$



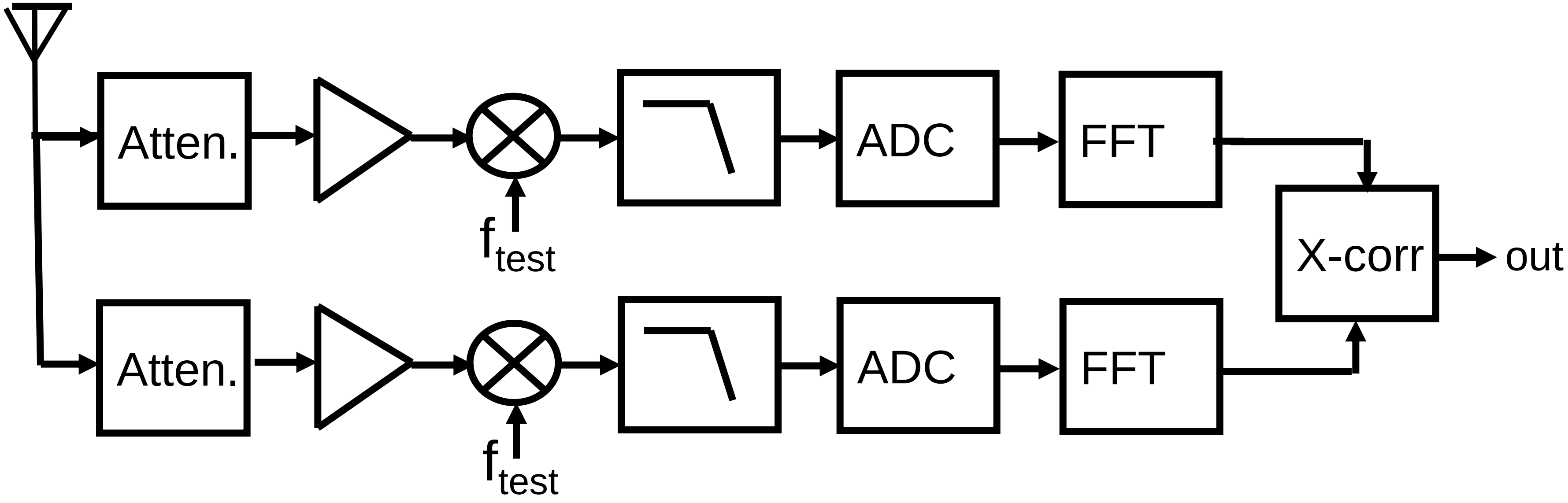
Cross-Correlation Idea

1) Attenuate input to improve IIP3

2) “get rid of the noise”:

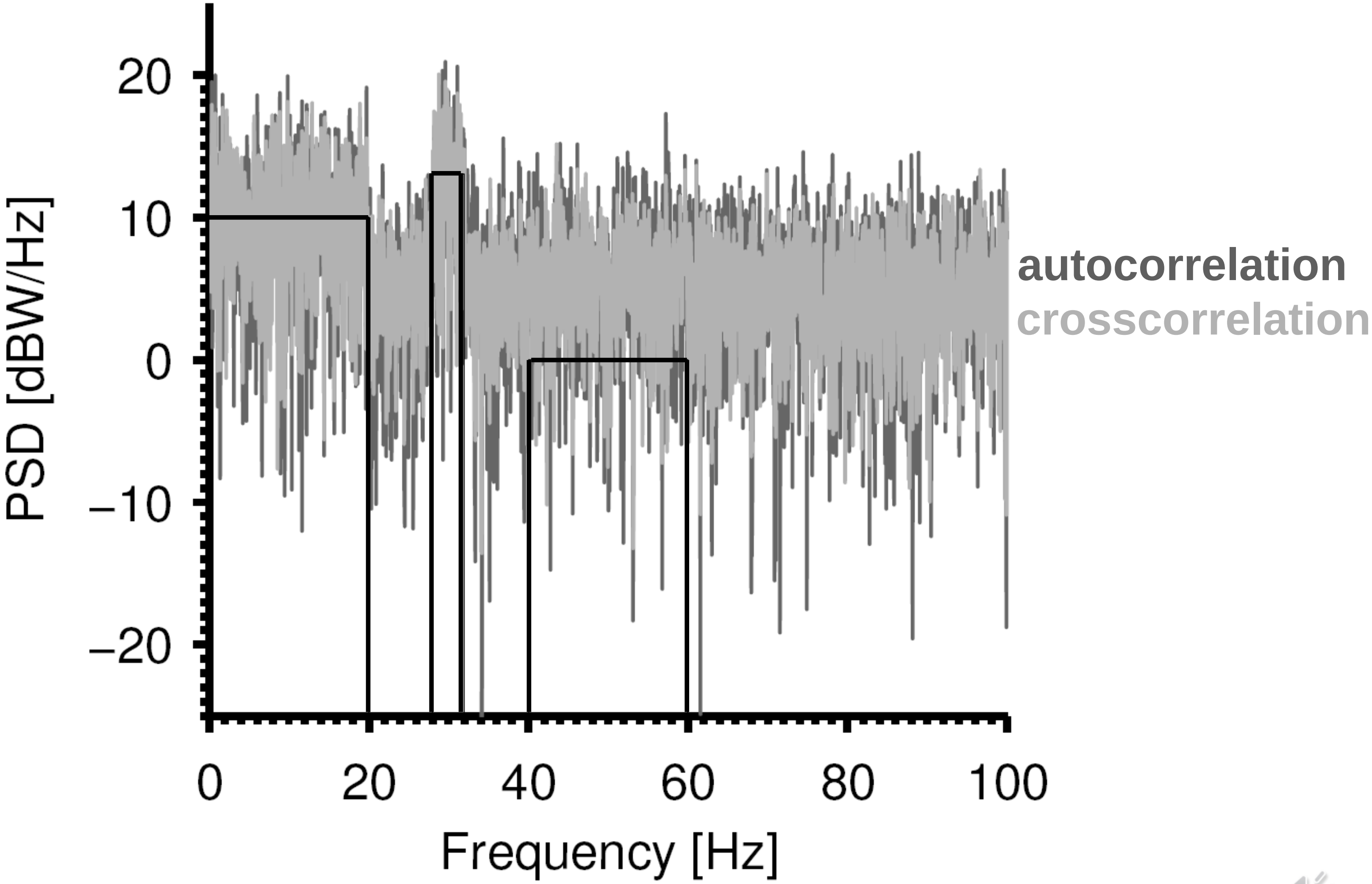
- a) Duplicate receiver
- b) Cross-correlate outputs

Result: correlated signal remains

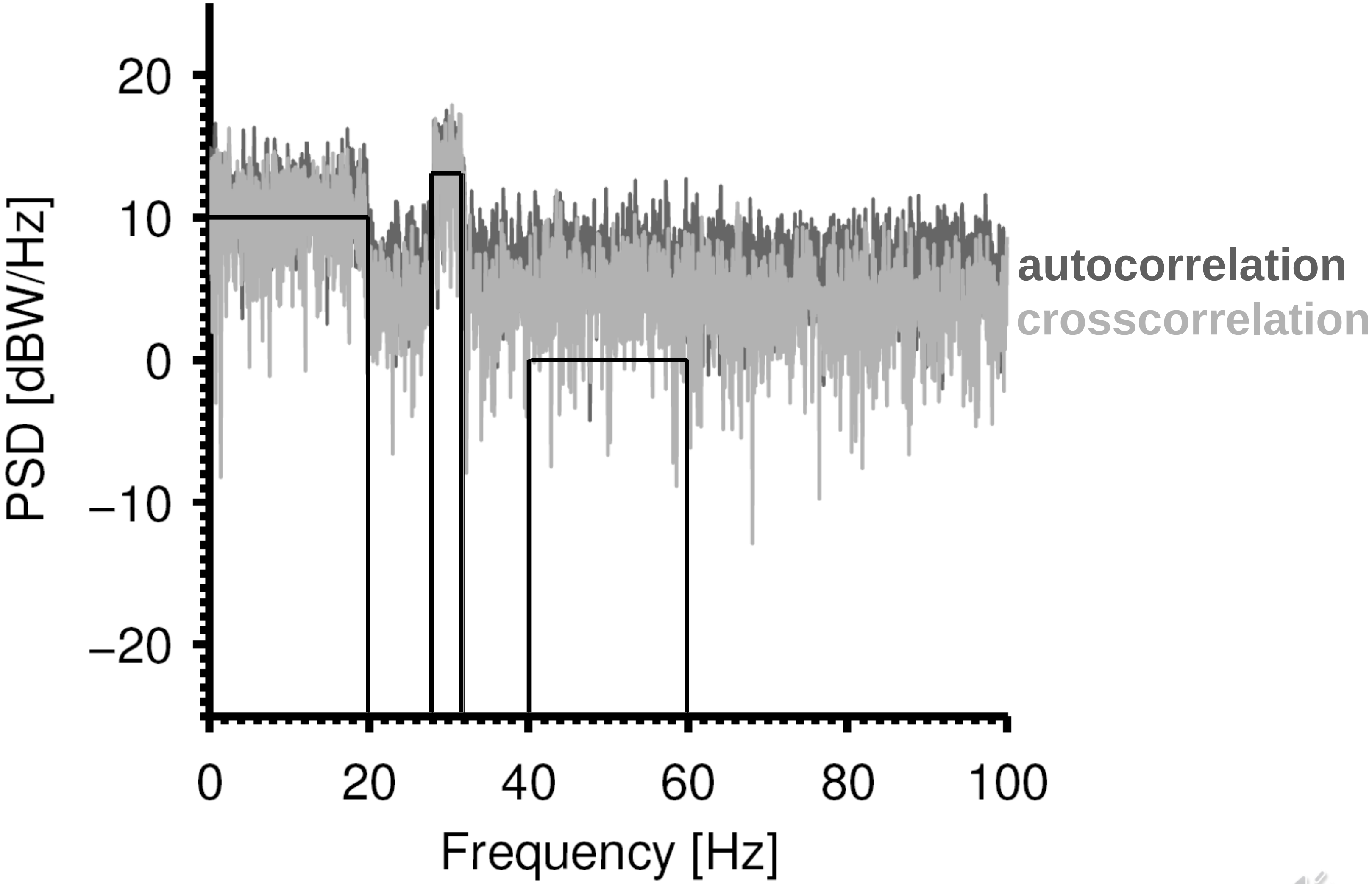


[OudeAlinkTCAS12][OudeAlinkMTT13]

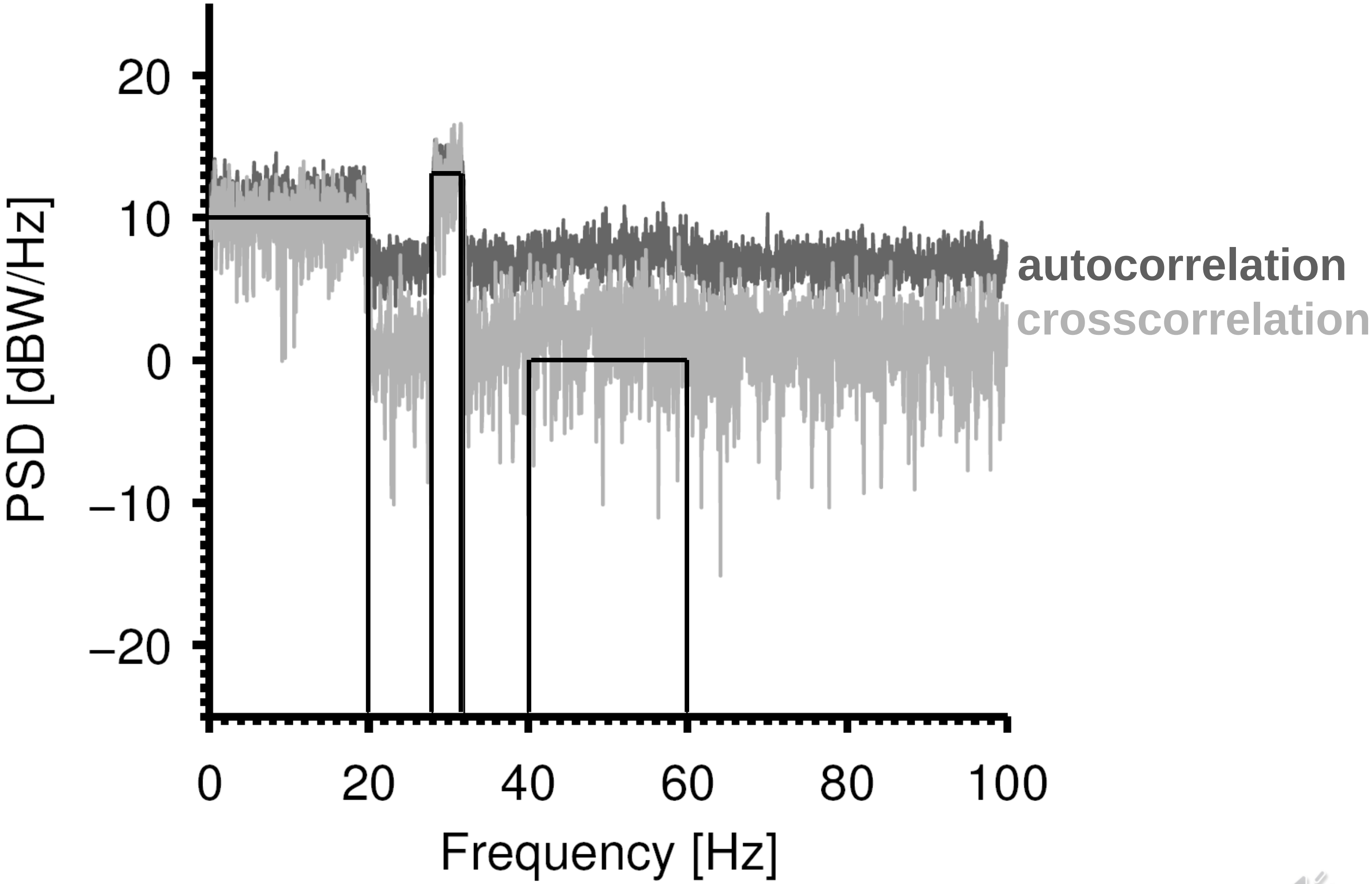
Auto- versus Cross-correlation



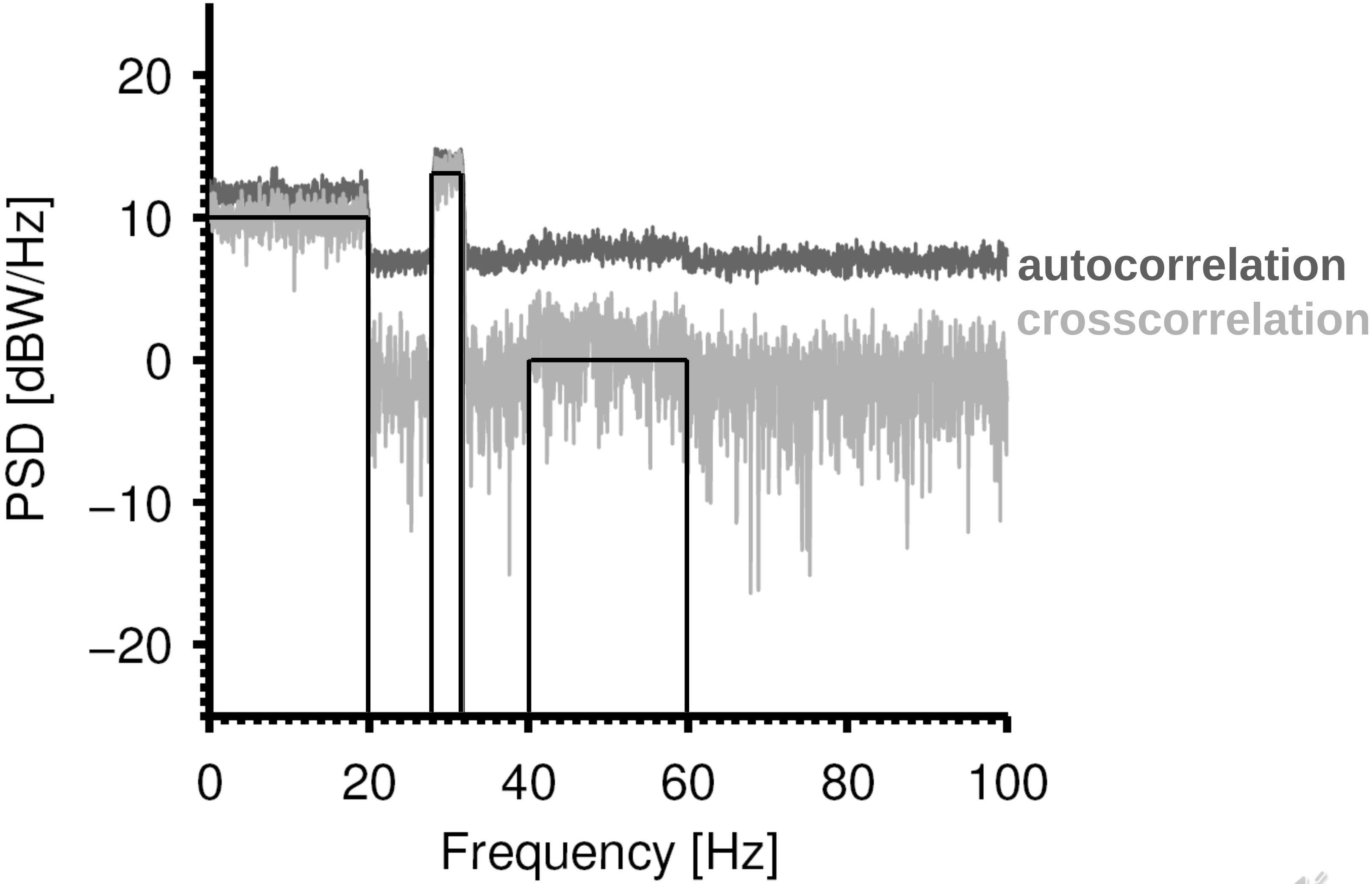
Auto- versus Cross-correlation



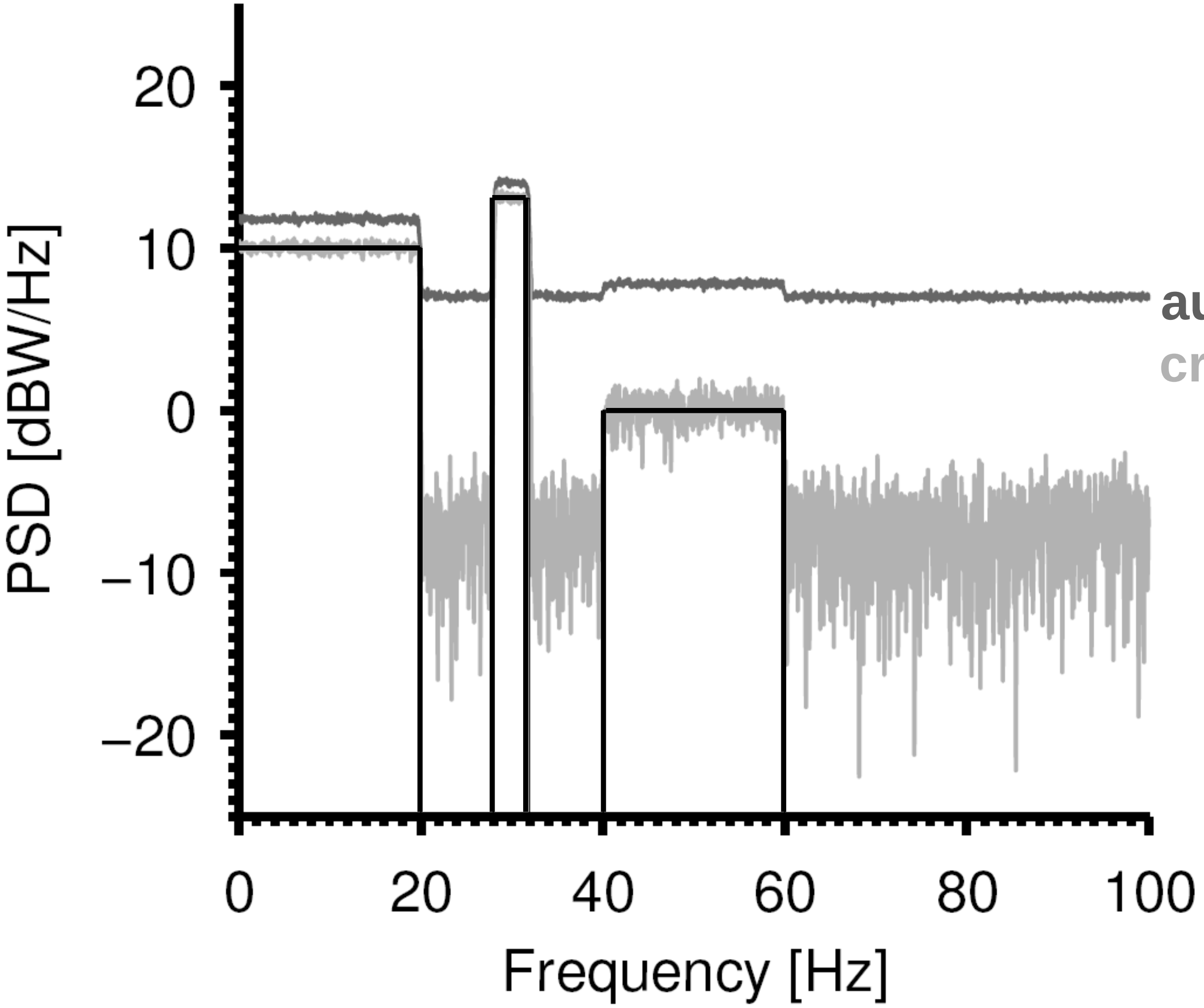
Auto- versus Cross-correlation



Auto- versus Cross-correlation



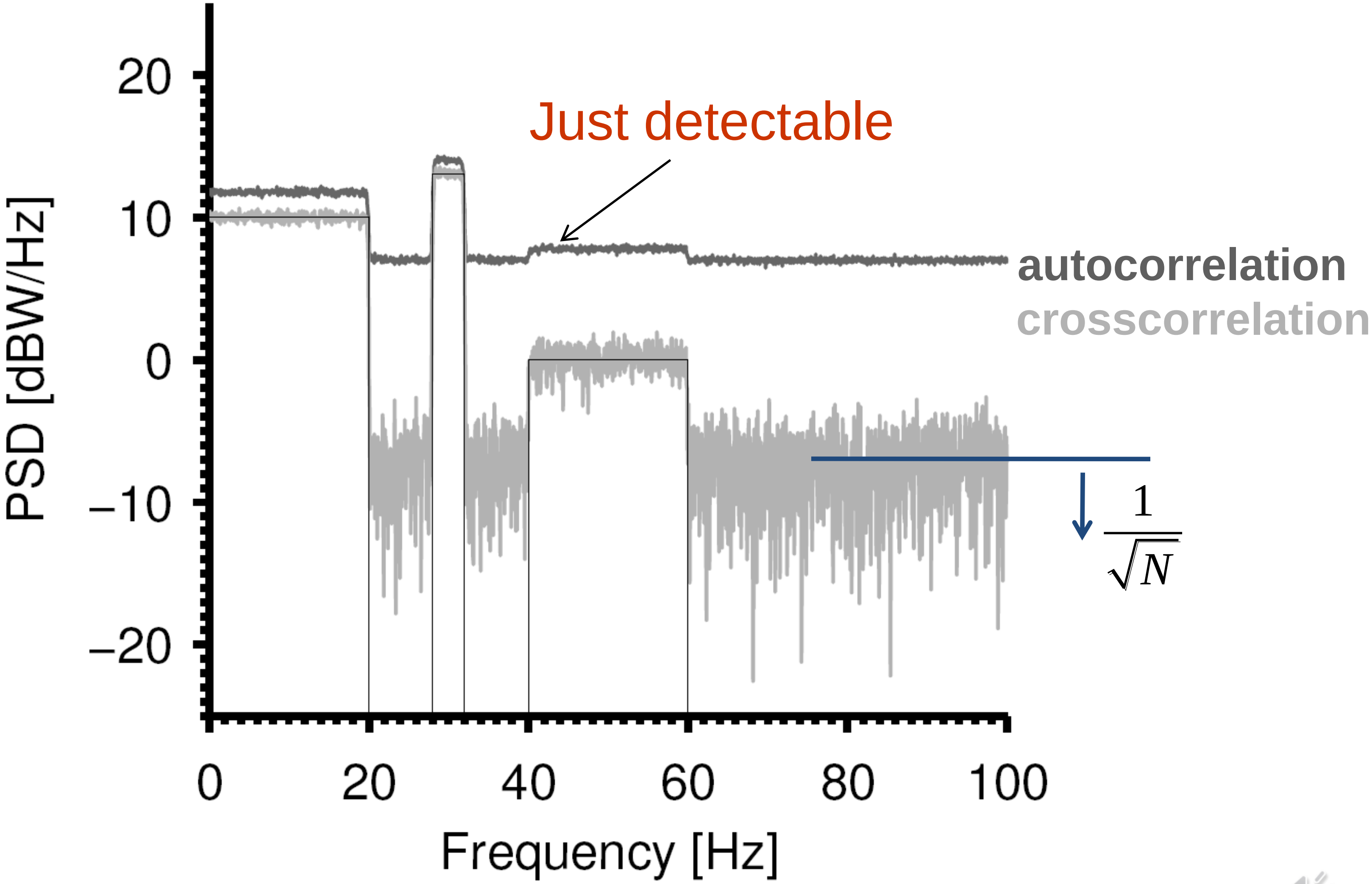
Auto- versus Cross-correlation



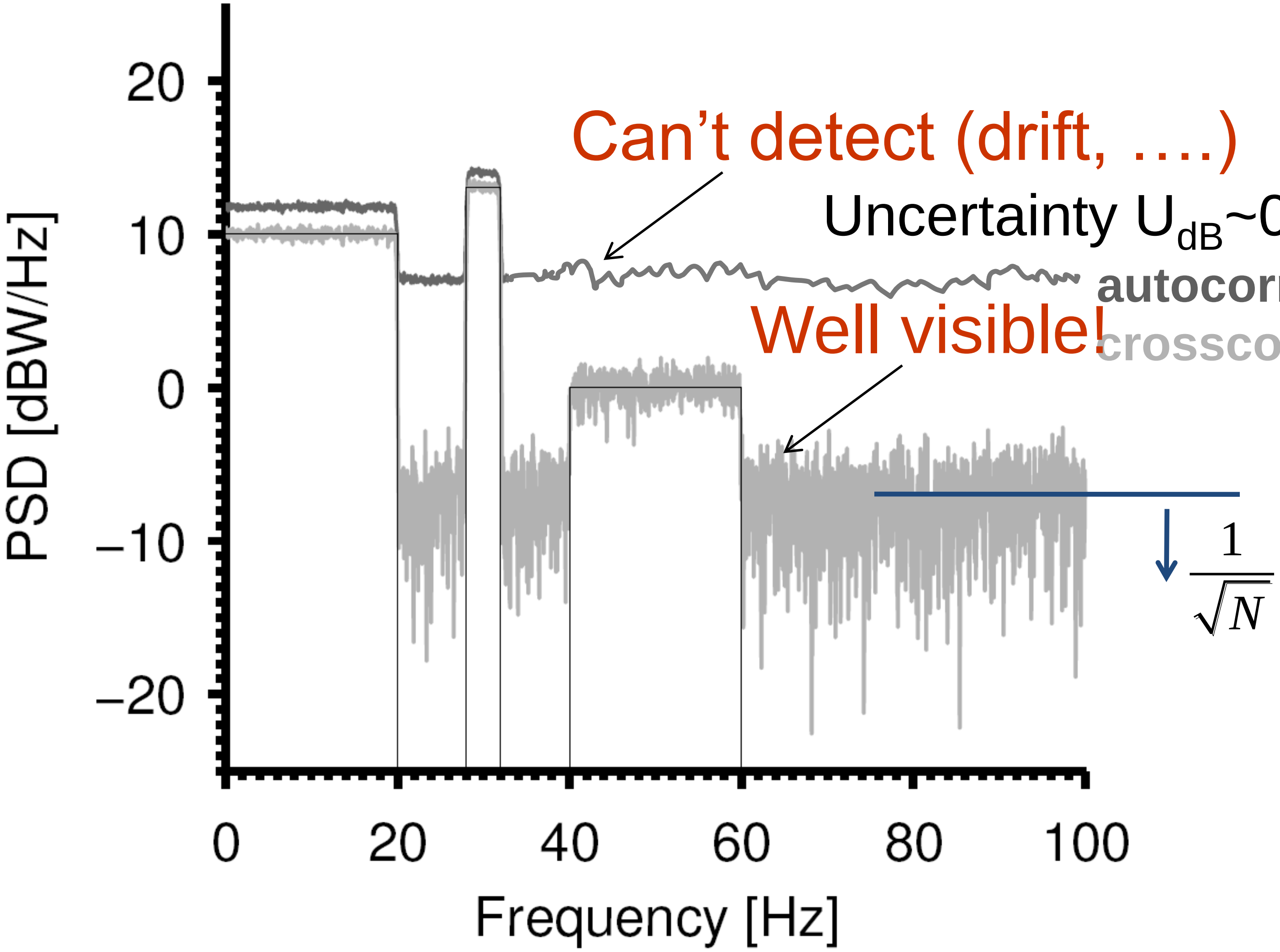
autocorrelation

crosscorrelation

Auto- versus Cross-correlation



Practice: Noise not perfectly white



Can’t detect (drift, ….)

Uncertainty U_{dB}~0.13dB

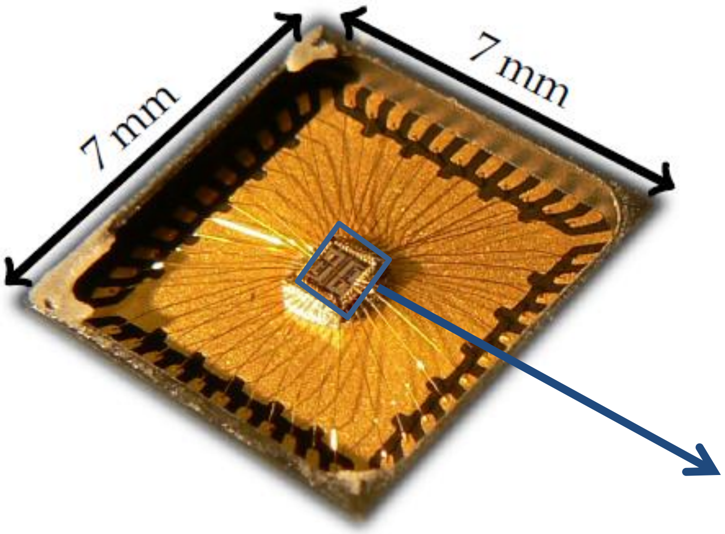
autocorrelation

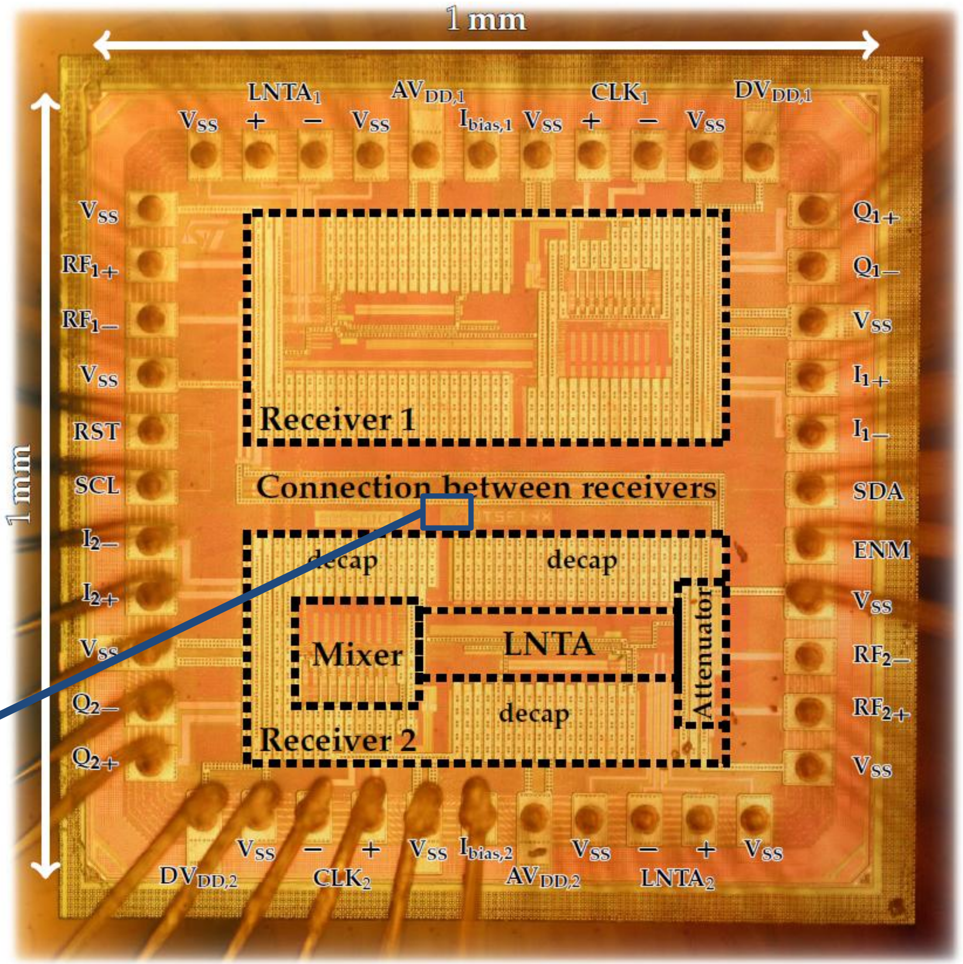
crosscorrelation

Well visible!

$$\frac{1}{\sqrt{N}}$$

1mm x 1mm XC-Chip in 65nm CMOS

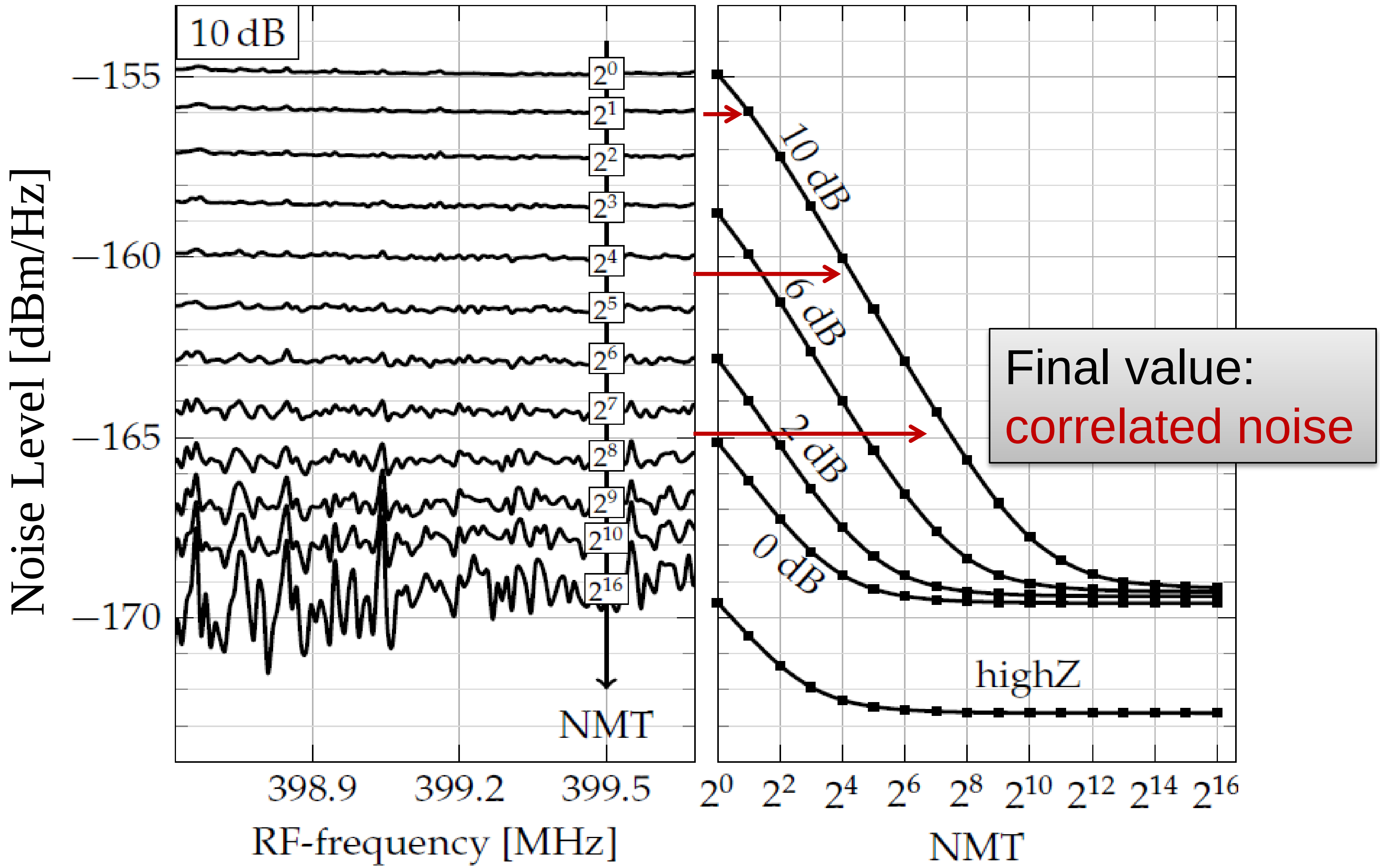




"UTSFINX" =
Univ. Twente Spectrum... X-Correlation

Noise Performance

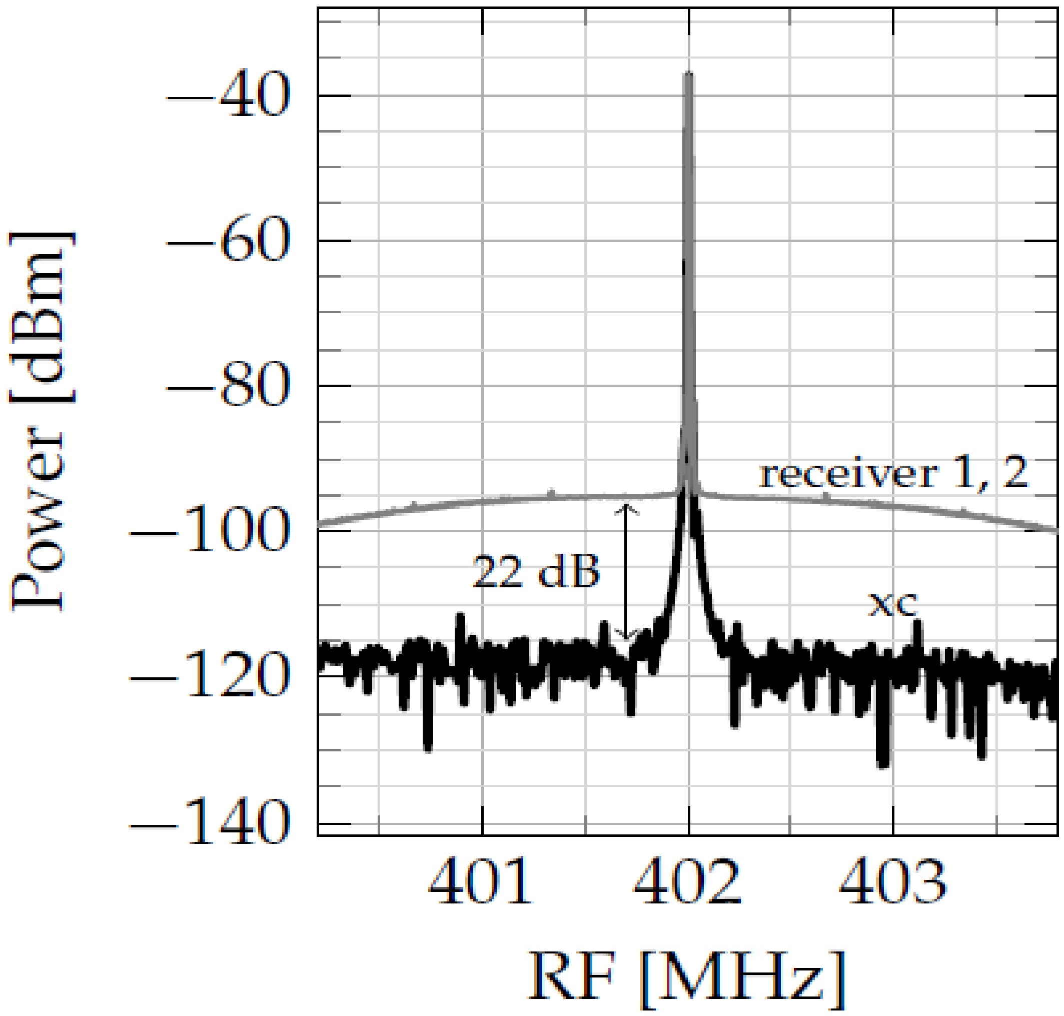
Attenuation: 10, 6, 2, 0dB



Final value:
correlated noise

NMT=Normalized Measurement Time (1 ⬄ acquisition time for 1 FFT)

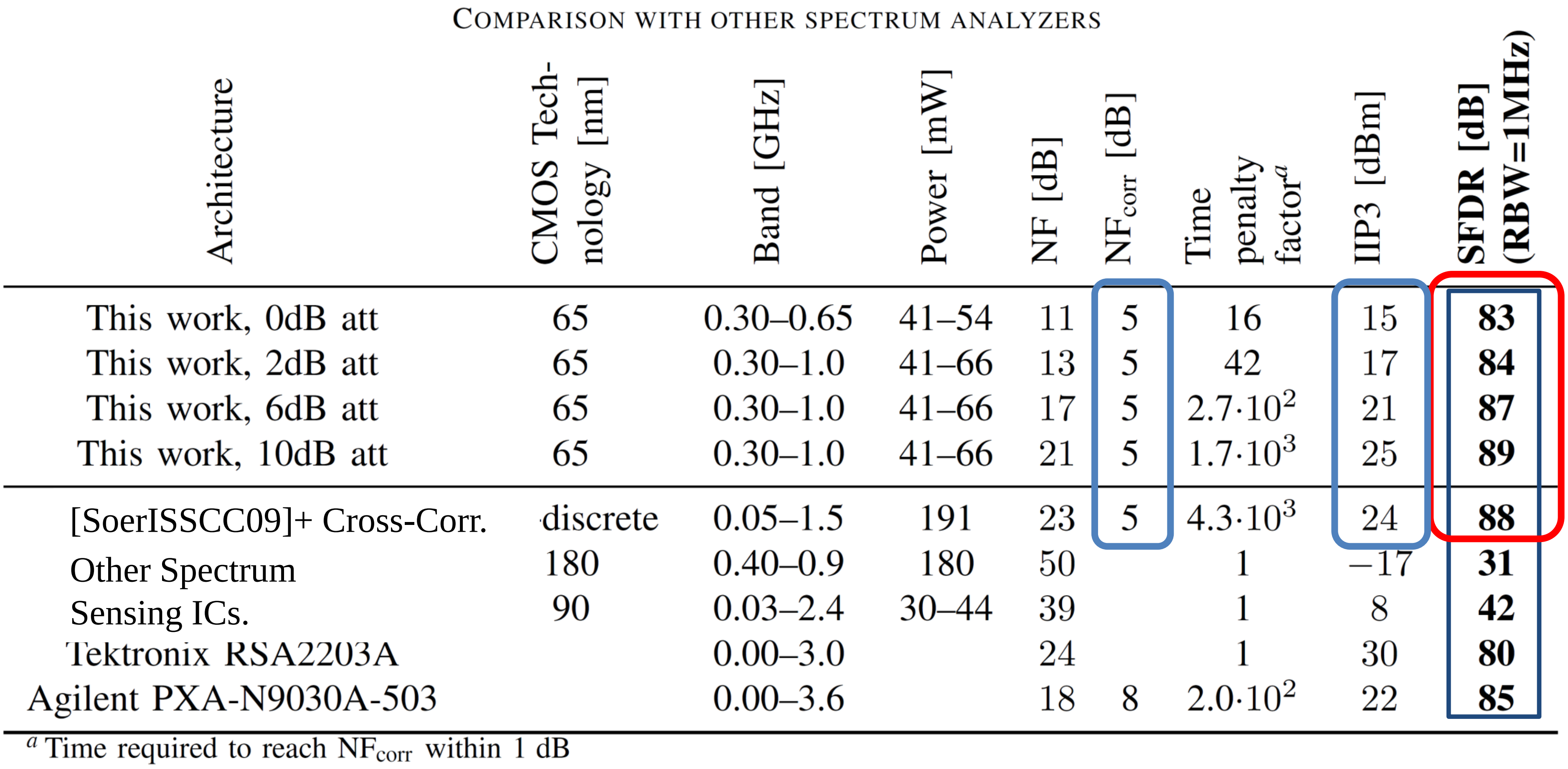
Phase Noise is also Reduced



Before

After XC

Benchmarking



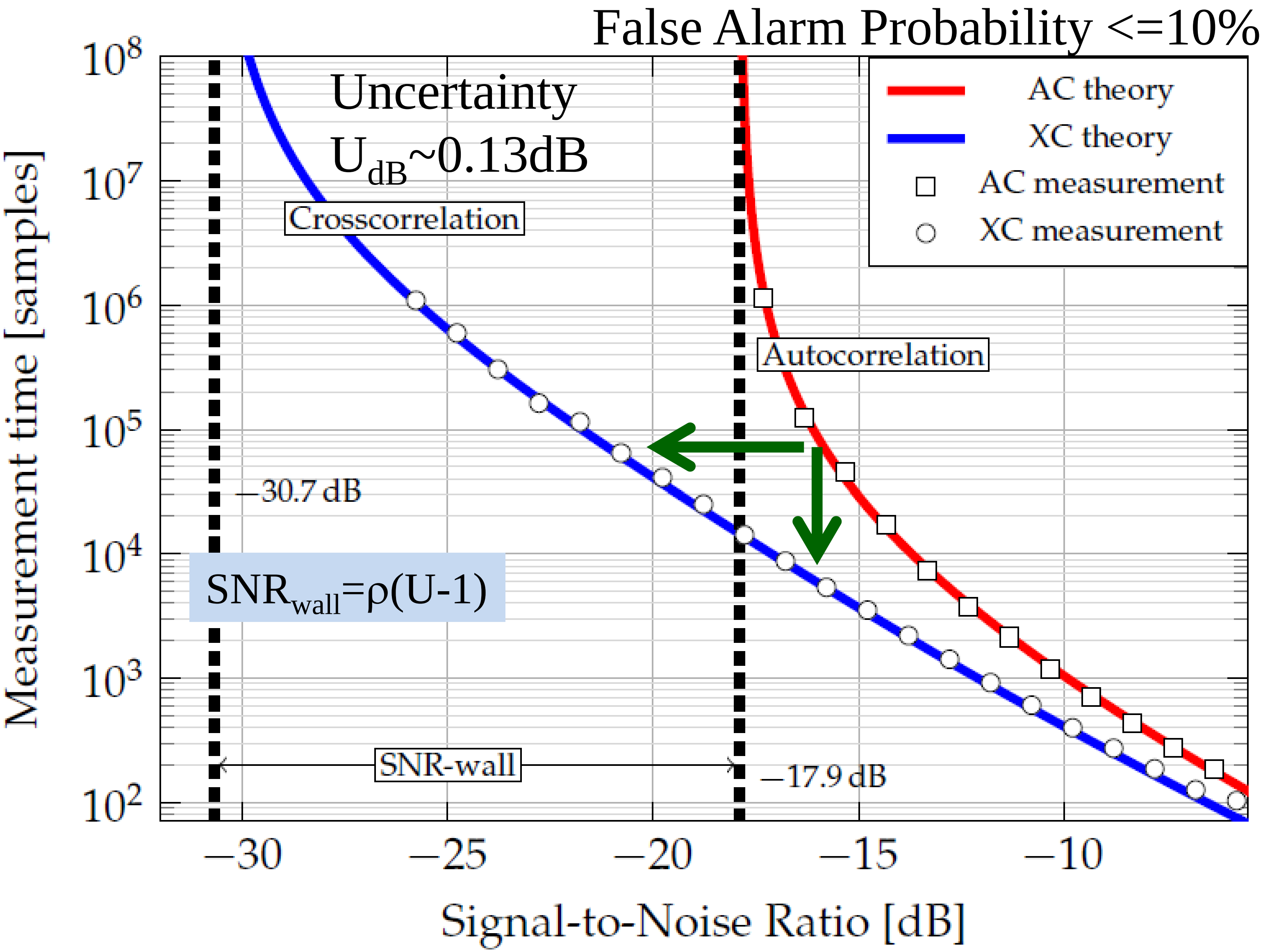
COMPARISON WITH OTHER SPECTRUM ANALYZERS

Architecture	CMOS Technology [nm]	Band [GHz]	Power [mW]	NF [dB]	NF_{corr} [dB]	Time penalty factor[a]	IIP3 [dBm]	**SFDR [dB] (RBW=1MHz)**
This work, 0dB att	65	0.30–0.65	41–54	11	5	16	15	**83**
This work, 2dB att	65	0.30–1.0	41–66	13	5	42	17	**84**
This work, 6dB att	65	0.30–1.0	41–66	17	5	$2.7 \cdot 10^2$	21	**87**
This work, 10dB att	65	0.30–1.0	41–66	21	5	$1.7 \cdot 10^3$	25	**89**
[SoerISSCC09]+ Cross-Corr.	discrete	0.05–1.5	191	23	5	$4.3 \cdot 10^3$	24	**88**
Other Spectrum Sensing ICs.	180	0.40–0.9	180	50		1	−17	**31**
	90	0.03–2.4	30–44	39		1	8	**42**
Tektronix RSA2203A		0.00–3.0		24		1	30	**80**
Agilent PXA-N9030A-503		0.00–3.6		18	8	$2.0 \cdot 10^2$	22	**85**

[a] Time required to reach NF_{corr} within 1 dB

[OudeAlinkMTT13]

Detection below the noise floor: SNR-wall



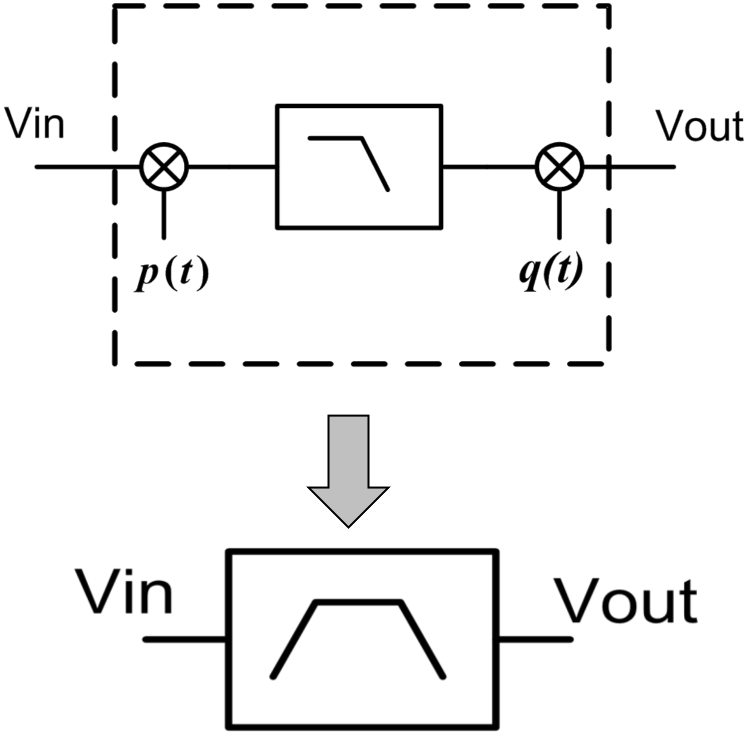
X-Correlation is more sensitive but also faster

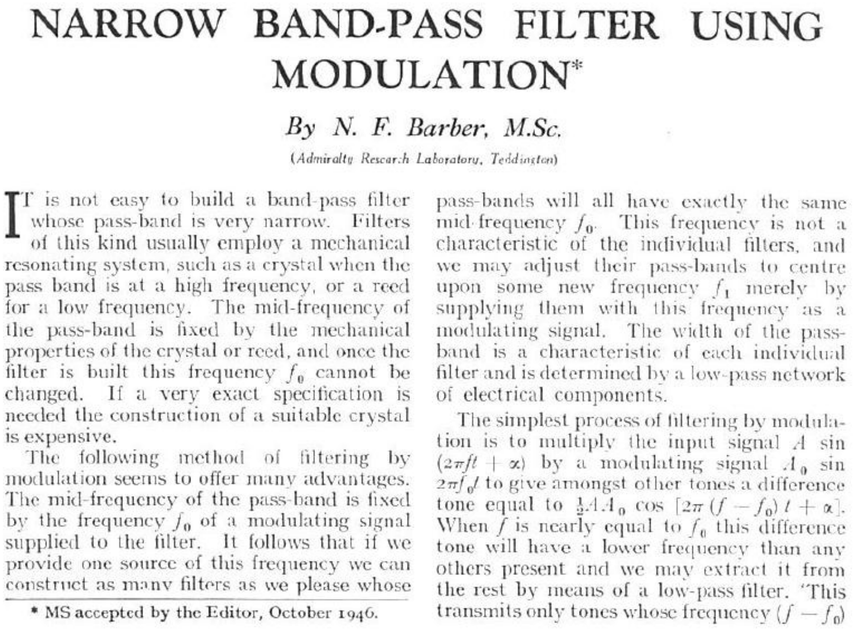
Flexibly Tunable High-Q Filters

N-path Filters

Idea from 1947: Band Pass Filters

- Downconvert + LPF + Upconvert = BPF





NARROW BAND-PASS FILTER USING MODULATION*

By N. F. Barber, M.Sc.

(Admiralty Research Laboratory, Teddington)

IT is not easy to build a band-pass filter whose pass-band is very narrow. Filters of this kind usually employ a mechanical resonating system, such as a crystal when the pass band is at a high frequency, or a reed for a low frequency. The mid-frequency of the pass-band is fixed by the mechanical properties of the crystal or reed, and once the filter is built this frequency f_0 cannot be changed. If a very exact specification is needed the construction of a suitable crystal is expensive.

The following method of filtering by modulation seems to offer many advantages. The mid-frequency of the pass-band is fixed by the frequency f_0 of a modulating signal supplied to the filter. It follows that if we provide one source of this frequency we can construct as many filters as we please whose pass-bands will all have exactly the same mid-frequency f_0. This frequency is not a characteristic of the individual filters, and we may adjust their pass-bands to centre upon some new frequency f_1 merely by supplying them with this frequency as a modulating signal. The width of the pass-band is a characteristic of each individual filter and is determined by a low-pass network of electrical components.

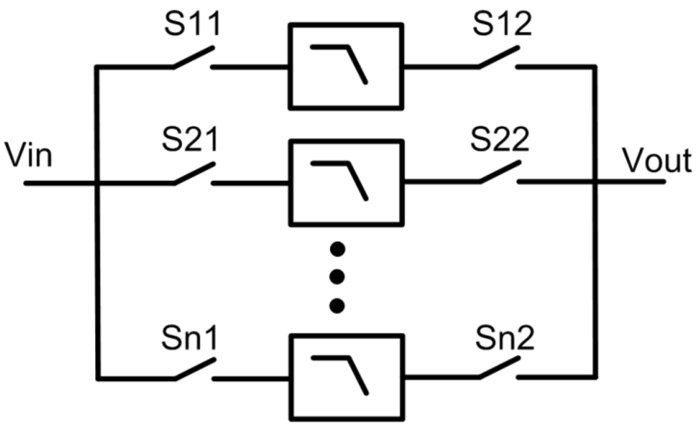
The simplest process of filtering by modulation is to multiply the input signal $A \sin (2\pi ft + \alpha)$ by a modulating signal $A_0 \sin 2\pi f_0 t$ to give amongst other tones a difference tone equal to $\frac{1}{2} A A_0 \cos [2\pi (f - f_0) t + \alpha]$. When f is nearly equal to f_0 this difference tone will have a lower frequency than any others present and we may extract it from the rest by means of a low-pass filter. This transmits only tones whose frequency $(f - f_0)$

---

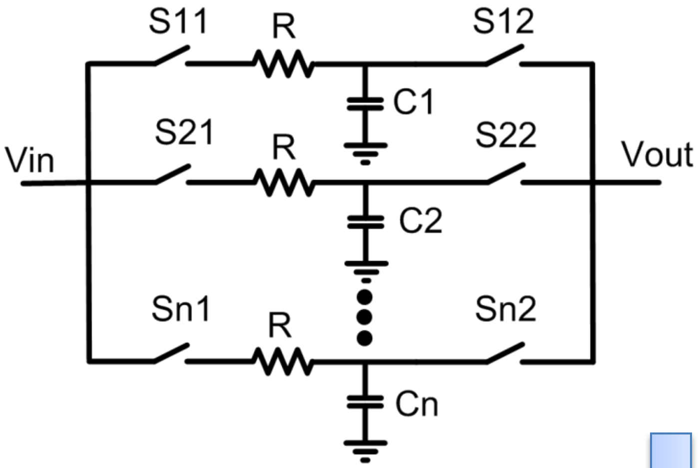
* MS accepted by the Editor, October 1946.

[Barber, Wireless Engineer, May 1947]

“N-path Filter”

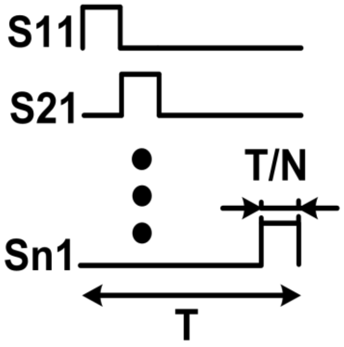


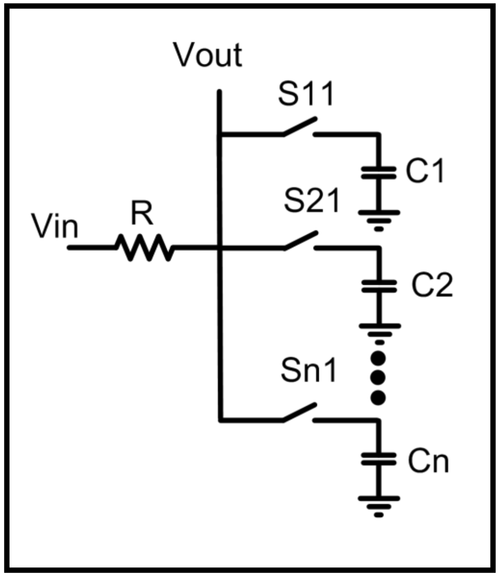
RC filter

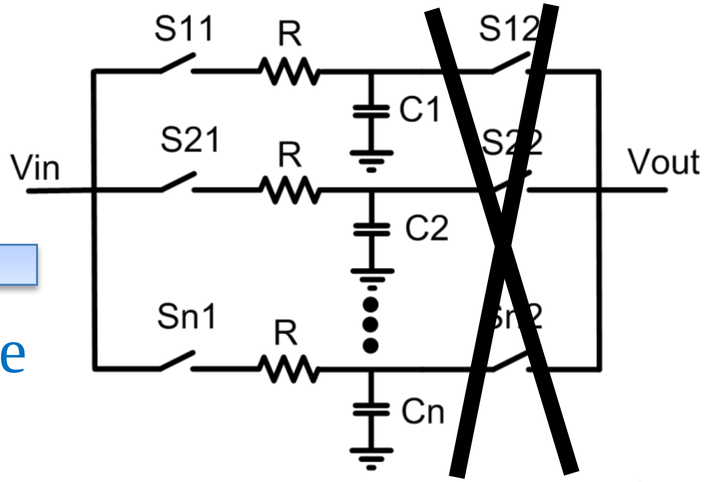


- N time-variant paths, 1/N duty cycle

clock Si1=Si2





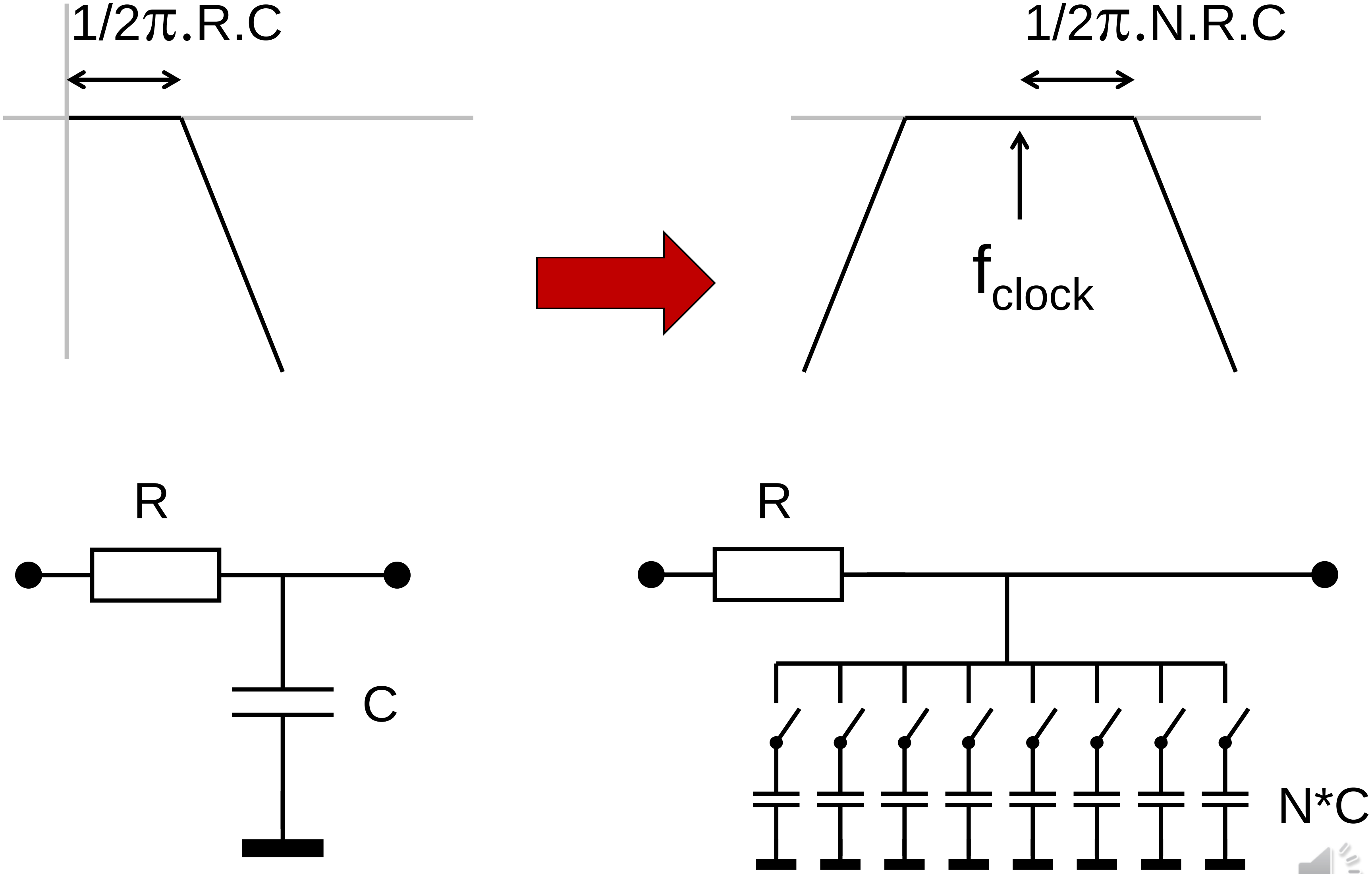


share R

- mix down
- filter
- mix up

[FranksISSCC60]

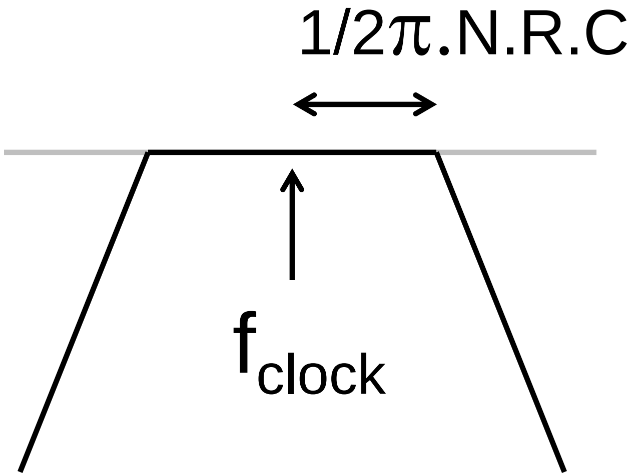
Low pass – Bandpass transformation

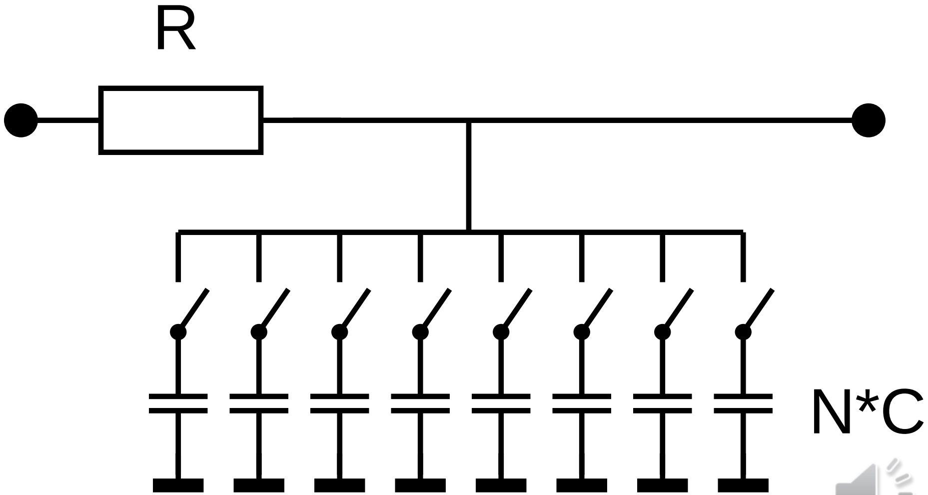


Quality factor is high!

$$Q = \frac{\overset{\text{GHz}}{\text{centerfrequency}}}{\underset{\text{MHz}}{\text{bandwidth}}}$$

$$\boxed{Q = 2\pi.RC.N.f_{clock}}$$





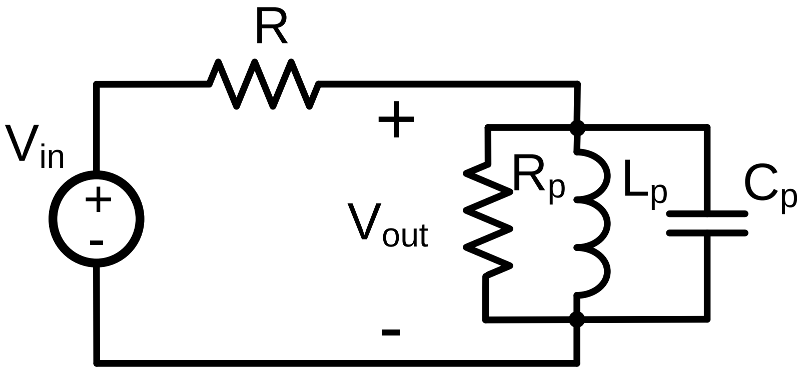
Equivalent Bandpass filter model

If $f \approx f_s$ then:

$$\boxed{R_P \approx \frac{N^2(1-\cos(2\pi/N))\cdot R}{2\pi^2 - N^2(1-\cos(2\pi/N))}}$$

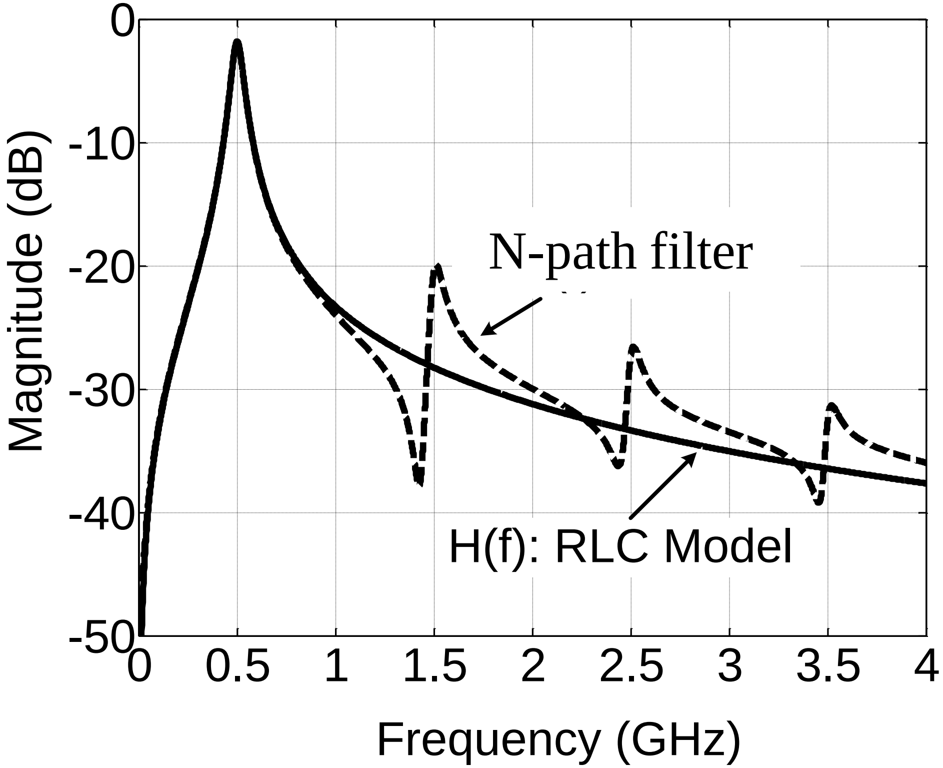
$$\boxed{C_p \approx \frac{N(R_p+R)}{2R_p}C}$$

$$\boxed{L_p \approx \frac{1}{(2\pi f_s)^2 C_p}}$$



[GhaffariJSSC11]

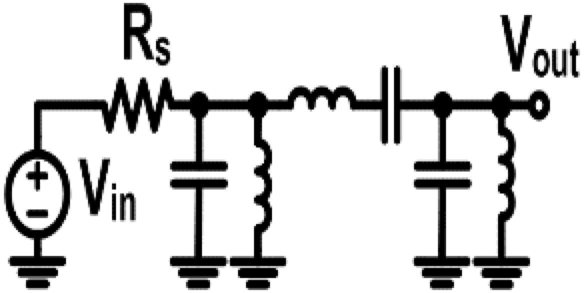
Example: differential input 4-path filter @f_s=0.5GHz:



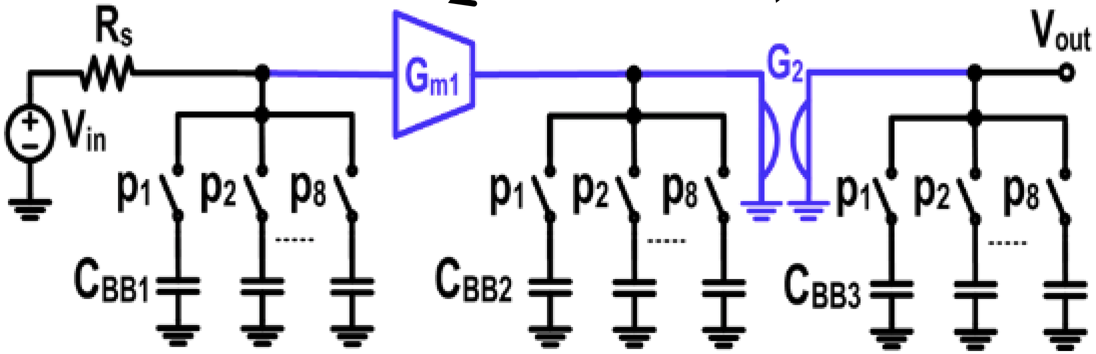
Note: extra harmonic responses

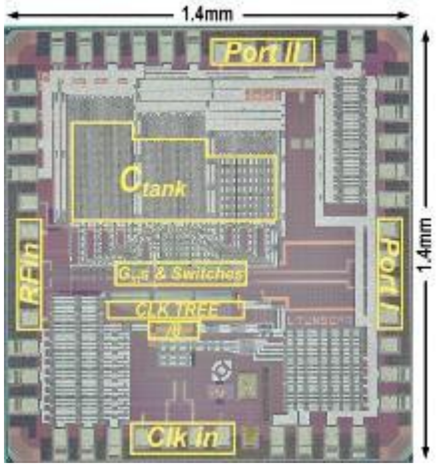
Higher-order N-path BPFs

- Use N-path filter as parallel LC tank
- Synthesize a high-order BPF with gyrator coupling
- All-pole singly-terminated 6th-order BPF

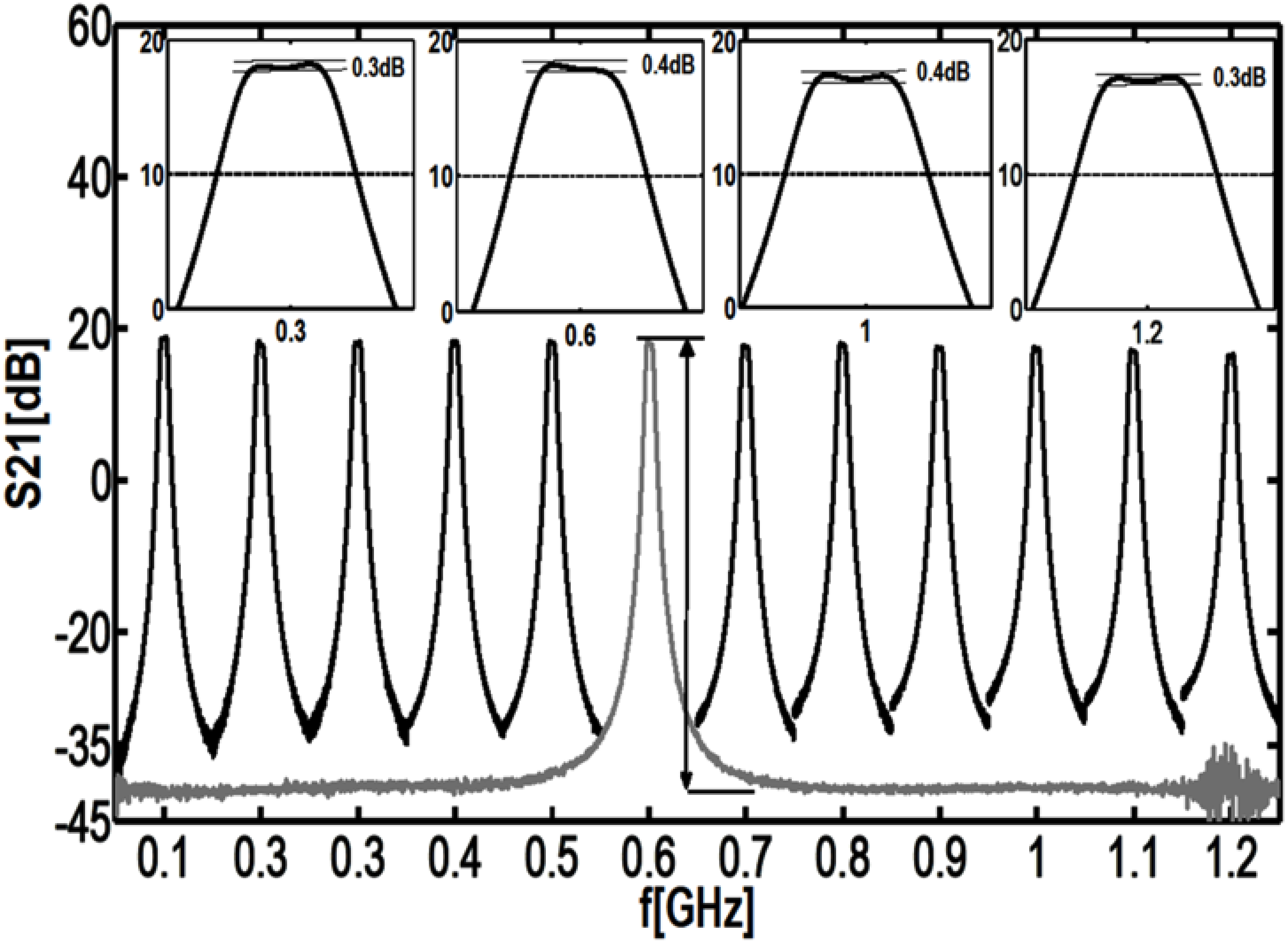


V-I by CMOS Inverters



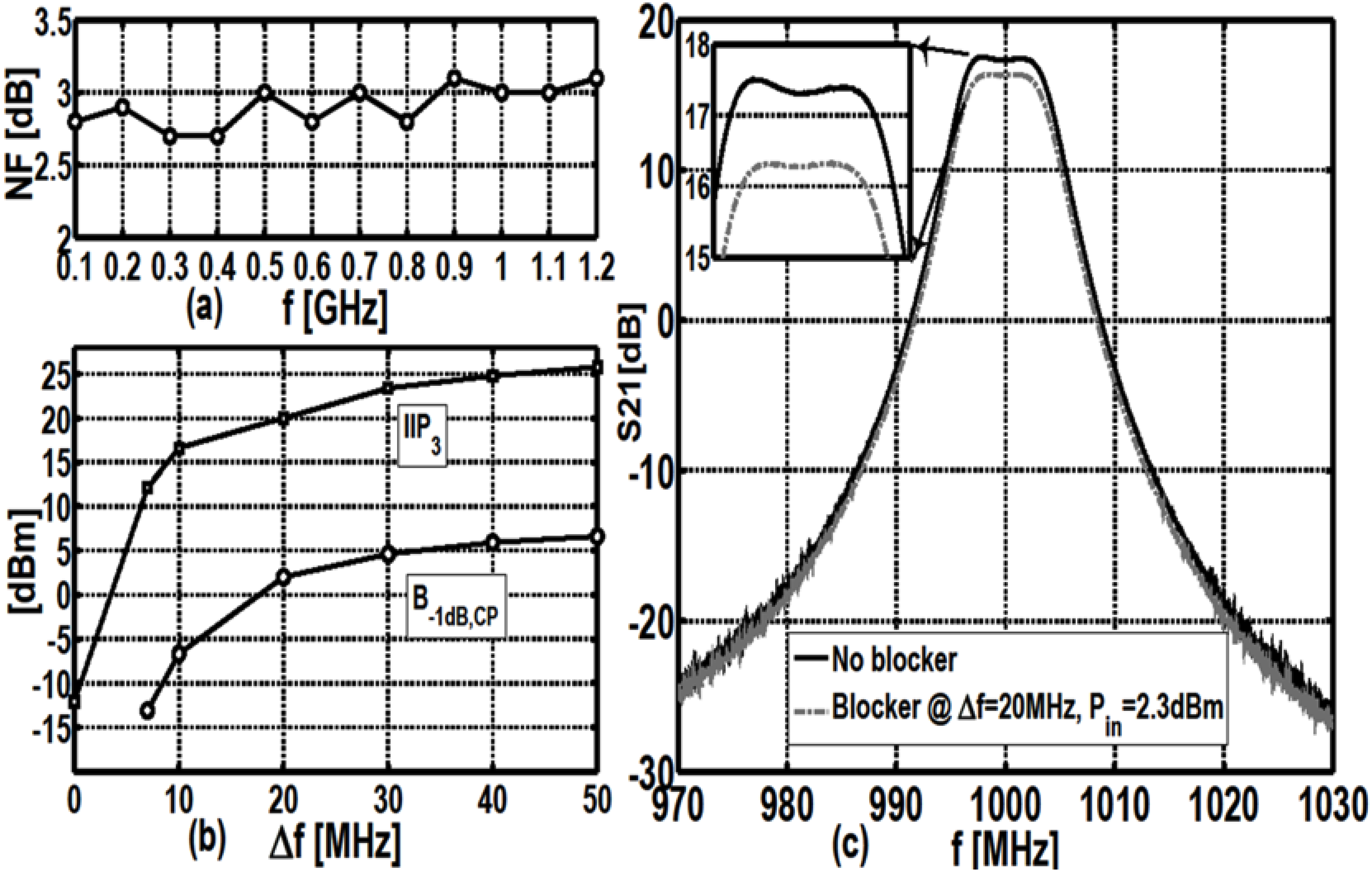


Filter Transfer Function



[Darvishi, ISSCC 2013]

Linearity and NF



[Darvishi, ISSCC 2013]

Conclusions

Cognitive Radio Transceivers:

- ☐ Put challenging new requirements:
  - Flexibility in frequency, bandwidth, modulation, ...
  - ⇔ key issue: less upfront filtering ⇔ huge challenge...
- ☐ Some recent ideas:
  - Polyphase Multipath: Agile clean TX
  - Cross-Correlation of 2 RX outputs: trade time for SFDR
  - N-path filter: linear high-Q filter, program f_c by clock
- ☐ Room for new ideas!

References

- ***[AndrewsJSSC10]*** C. Andrews and A. C. Molnar, "A Passive Mixer-First Receiver With Digitally Controlled and Widely Tunable RF Interface," *IEEE JSSC*, pp. 2696-2708, 2010.
- ***[BlaakmeerJSSC08]*** S. C. Blaakmeer, E. A. M. Klumperink, D. M. W. Leenaerts, and B. Nauta, "Wideband Balun-LNA With Simultaneous Output Balancing, Noise-Canceling and Distortion-Canceling," *IEEE JSSC*, pp. 1341-1350, 2008.
- ***[BlaakmeerBJSSC08]*** S.C. Blaakmeer, E.A.M. Klumperink, D.M.W.Leenaerts,B. Nauta, "The Blixer, a Wideband Balun-LNA-I/Q-Mixer Topology,"*IEEE JSSC*, pp.2706-2715, Dec. 2008.
- ***[BorremansJSSC2011]*** Borremans, J.; Mandal, G.; Giannini, V.; Debaillie, B.; Ingels, M.; Sano, T.; Verbruggen, B.; Craninckx, J., "A 40 nm CMOS 0.4–6 GHz Receiver Resilient to Out-of-Band Blockers,", JSSC, vol.46, no.7, pp.1659,1671, July 2011
- ***[BruccoleriJSSC04]*** F. Bruccoleri, E. A. M. Klumperink, and B. Nauta, "Wide-band CMOS low-noise amplifier exploiting thermal noise canceling," *IEEE JSSC*, pp. 275–282, Feb. 2004.
- ***[CookJSSC06]*** B.Cook, A.Berny, A.Molnar, S.Lanzisera, K.Pister, "Low-power 2.4-GHz transceiver with passive RX front-end and 400-mV supply", *IEEE JSSC*, pp. 2757–2766, Dec. 2006.
- ***[DarvishiJSSC13]*** M.Darvishi, R. van der Zee, B.Nauta, "Design of Active N-Path Filters," *IEEE JSSC*, vol.PP, no.99, pp.1,15, doi: 10.1109/JSSC.2013.2285852
- ***[GhaffariISSCC13]*** A.Ghaffari, E. Klumperink,F.E. van Vliet, B. Nauta, "Simultaneous spatial and frequency-domain filtering at the antenna inputs achieving up to +10dBm out-of-band/beam P1dB," *ISSCC*, pp.84-85, 2013.
- ***[KlumperinkPhD97]*** E.A.M. Klumperink, "Transconductance based CMOS Circuits; Circuit Generation, Classification and Analysis", *PhD Thesis University of Twente*, 1997, http://icd.ewi.utwente.nl/publications/icpub1997/Klumperink-PhD-Thesis.pdf
- ***[Liempd,JSSC2014]*** Soer, M.C.M.; Klumperink, E.A.M.; Nauta, B.; van Vliet, F.E., "3.5 A 1.0-to-2.5GHz beamforming receiver with constant-Gm vector modulator consuming < 9mW per antenna element in 65nm CMOS," ISSCC, pp.66,67, 9-13 Feb. 2014
- ***[LinISSCC15]*** Zhicheng Lin; Pui-In Mak; Martins, R.P., "2.4 A 0.028mm2 11mW single-mixing blocker-tolerant receiver with double-RF N-path filtering, S11 centering, +13dBm OB-IIP3 and 1.5-to-2.9dB NF," ISSCC, pp.1,3, 22-26 Feb. 2015
- ***[LinJSSC14]*** Zhicheng Lin; Mak, P.-I.; Martins, R.P., "A Sub-GHz Multi-ISM-Band ZigBee Receiver Using Function-Reuse and Gain-Boosted N-Path Techniques for IoT Applications," *IEEE JSSC*, vol.49, no.12, pp.2990,3004, Dec. 2014
- ***[LinTCAS14]*** Zhicheng Lin; Pui-In Mak; Martins, R.P., "Analysis and Modeling of a Gain-Boosted N-Path Switched-Capacitor Bandpass Filter," Circuits and Systems I: Regular Papers, IEEE Transactions on , vol.61, no.9, pp.2560,2568, Sept. 2014
- ***[MahrofJSSC14]*** D.H.Mahrof, E.A.M. Klumperink, M.S.Oude Alink, B.Nauta, "Cancellation of OpAmp Virtual Ground Imperfections by a Negative Conductance Applied to Improve RF Receiver Linearity", IEEE JSSC 2014.

References

- ***[MirzaeiTCAS11]*** A. Mirzaei, H. Darabi, "Analysis of Imperfections on Performance of 4-Phase Passive-Mixer-Based High-Q Bandpass Filters in SAW-Less Receivers," *IEEE TCAS-I*, pp.879,892, May 2011.
- ***[MensinkTCAS05]*** *E. Mensink, E.A.M. Klumperink and B. Nauta, “Distortion Cancelling by Polyphase Multipath Circuits”, IEEE, Tr Circuits. And Systems, September 2005.*
- ***[MirzaeiTCAS11]*** A. Mirzaei, H. Darabi, "Analysis of Imperfections on Performance of 4-Phase Passive-Mixer-Based High-Q Bandpass Filters in SAW-Less Receivers," *IEEE TCAS-I*, pp.879,892, May 2011.
- ***[MoseleyISSCC09]*** Moseley, N.A., Ru, Z., Klumperink, E.A.M., Nauta, B., "A 400-to-900 MHz Receiver with Dual-domain Harmonic Rejection Exploiting Adaptive Interference Cancellation“, ISSCC, Digest of Technical Papers, pp. 232-233, 2009.
- ***[MurphyJSSC12]*** D.Murphy, H.Darabi, A.Abidi , A.A.Hafez, A.Mirzaei, M.Mikhemar, and M.C.F. Chang, "A Blocker-Tolerant, Noise-Cancelling Receiver Suitable for Wideband Wireless Applications," *IEEE JSSC*, pp. 2943-2963, 2012.
- ***[ParkJSSC14]*** Joung Won Park; Razavi, B., "Channel Selection at RF Using Miller Bandpass Filters," Solid-State Circuits, IEEE Journal of , vol.49, no.12, pp.3063,3078, Dec. 2014
- ***[RuJSSC09]*** Z.Ru, N.A.Moseley, E.A.M.Klumperink, B.Nauta, "Digitally-Enhanced Software-Defined Radio Receiver Robust to Out-of-Band Interference, *IEEE JSSC*, pp.3359-3375, 2009.
- ***[SacchiCICC03]*** E. Sacchi et al., “A 15 mW, 70 kHz 1/f Corner Direct Conversion CMOS Receiver,” Proc. IEEE 2003 CustomIntegrated Circuits Conf. pp. 459–62, 2003.
- ***[SansenTCAS99]*** W.Sansen,"Distortion in elementary transistor circuits,“ *IEEE TCAS*, pp.315-325, Mar.1999.
- ***[ShresthaJSSC06]*** *R. Shrestha, E. A. M. Klumperink, E. Mensink, G. J. M.Wienk, and B.Nauta, “A Polyphase multipath technique for Software Defined Radio Transmitters,” in IEEE J. Solid-State Circuits, vol. 41, no. 12, pp. 2681–2692, Dec. 2006.*
- ***[SoerISSCC09]*** M.C.M.Soer, E.A.M.Klumperink, Z.Ru, F.E.van Vliet, B.Nauta,"A 0.2-to-2.0GHz 65nm CMOS Receiver Without LNA Achieving >11dBm IIP3 and <6.5dB NF," ISSCC, pp.222-223, 2009.
- ***[SoerTCAS10]*** M.C.M.Soer, E.A.M.Klumperink, P.T. de Boer, F.E.van Vliet, B.Nauta, "Unified Frequency-Domain Analysis of Switched-Series-RC Passive Mixers and Samplers," IEEE TCAS-I, pp. 2618-2631, 2010.
- ***[SoerISSCC14]*** M.C.M.Soer, E.A.M.Klumperink, F.E.van Vliet, B.Nauta, "A 1.0-to-2.5GHz Beamforming Receiver with Constant-Gm Vector Modulator Consuming < 9mW per Antenna Element in 65nm CMOS“, ISSCC, pp.66-67, 2014.
- ***[SubhanISCAS11]*** S.Subhan, E.A.M.Klumperink, B.Nauta, *“Towards Suppression of All Harmonics in a Polphase Multipath Transmitter”,* Proceedings of ISCAS, pp 2185-2189, May 2011.
- ***[SubhanJSSC14]*** S.Subhan, E.A.M.Klumperink, A.Ghaffari, G.J.M.Wienk, B.Nauta*, "A 100 – 800MHz 8-Path Polyphase Transmitter with Mixer Duty-Cycle Control achieving <-40dBc for ALL Harmonics“,* Solid-State Circuits, IEEE Journal of, vol.49, no.3, pp.595-607, March 2014.