SAND2022-5085C

IMS Connecting Minds. Exchanging Ideas.

ARFTG RFIC

WSJ-7

Receiver Design Techniques to Maintain Sensitivity in the Presence of Large Blockers

Travis Forbes

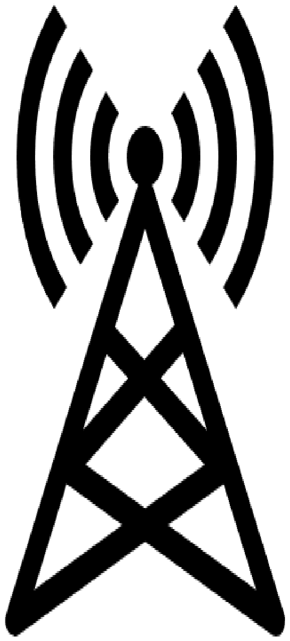
Sandia National Laboratories

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Outline

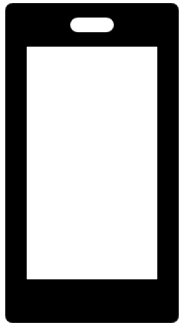
- Blockers in Wireless Systems: Where Do They Come From?
- Circuit Level Effects of Large Blockers
  - Saturation, Nonlinearity, and Mixing
- On-Chip Blocker Mitigation Approaches
  - Harmonic Rejection Receivers
  - N Path Filters and Mixer-First Receivers
  - Self-Interference Cancellation
- Conclusion

Wireless Signals Everywhere



- Radars
  - Weather
  - Altimeter
  - Automotive

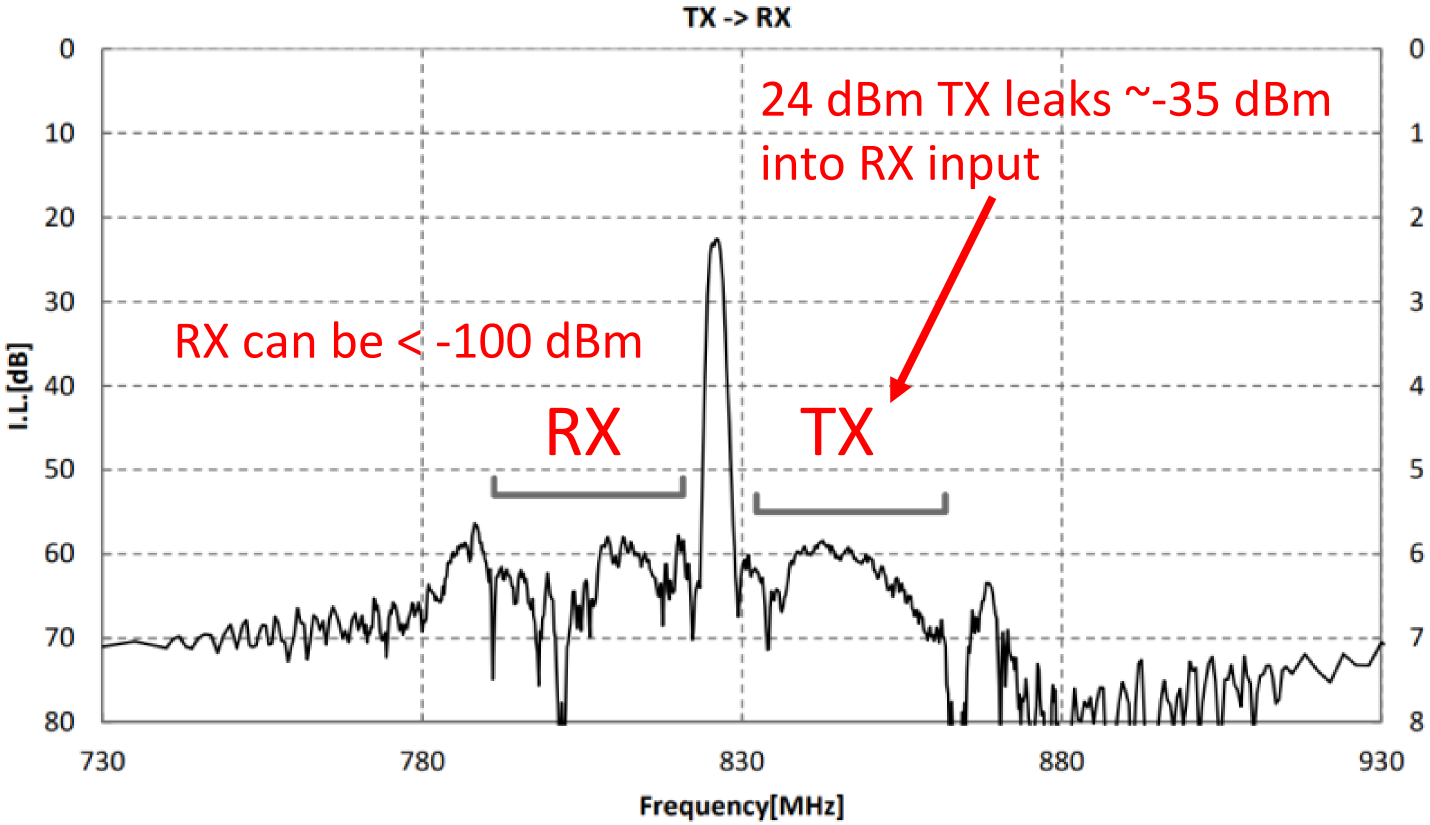
- Cellular (4G/5G/6G)
- Wifi
- Bluetooth
- TV/Satellite
- And more…



Blockers in a Device

Many radios in a device!

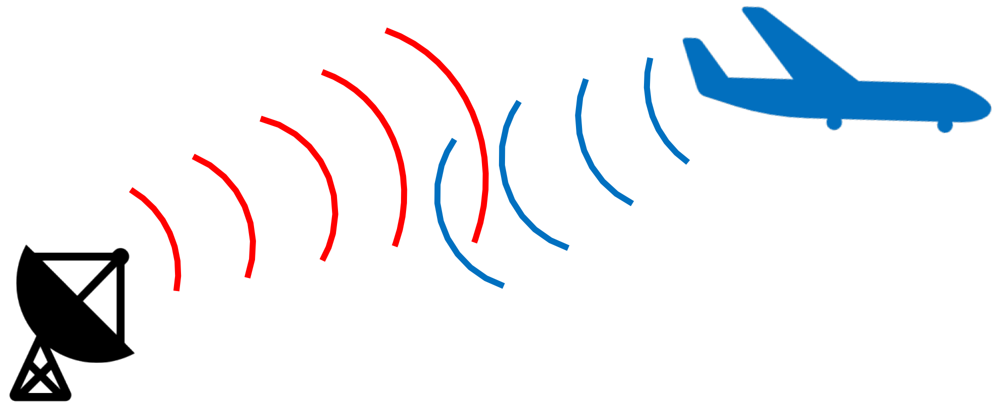
Frequency Division Duplex (FDD)



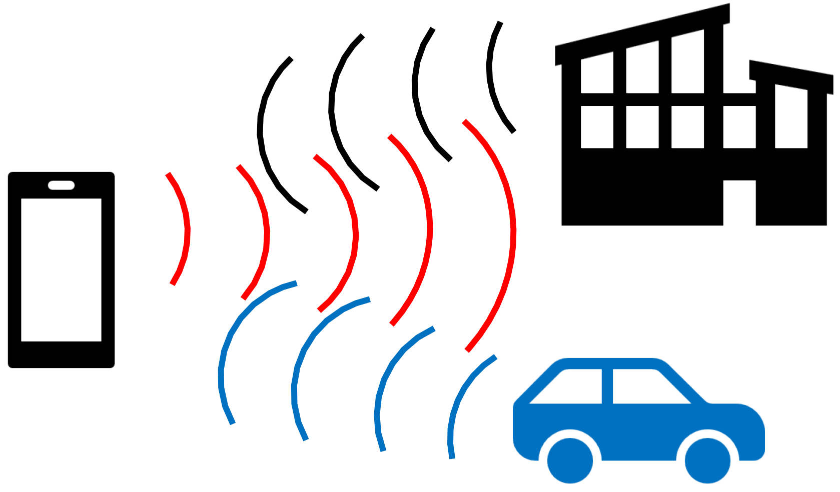
Example Murata SAYAP806MBA0C0A

Your Own Worst Enemy…

Radar Systems



Full-Duplex Communications



- Same frequency transmit/receive
  - TX-RX time delay in radar sets "blind range"
  - TX-RX same time in full-duplex
- In-band blocker!

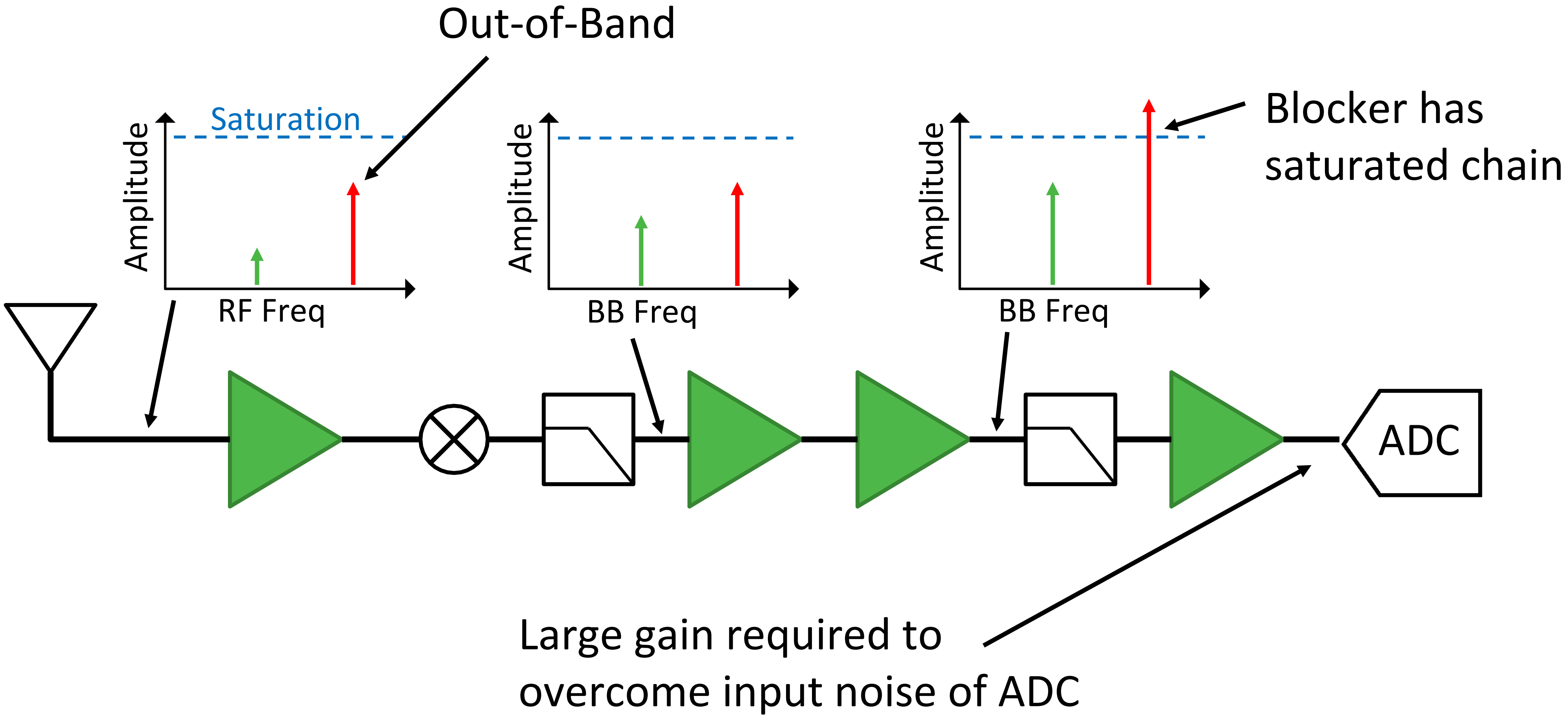
Simple Car Example

= 24 = 1 = 3

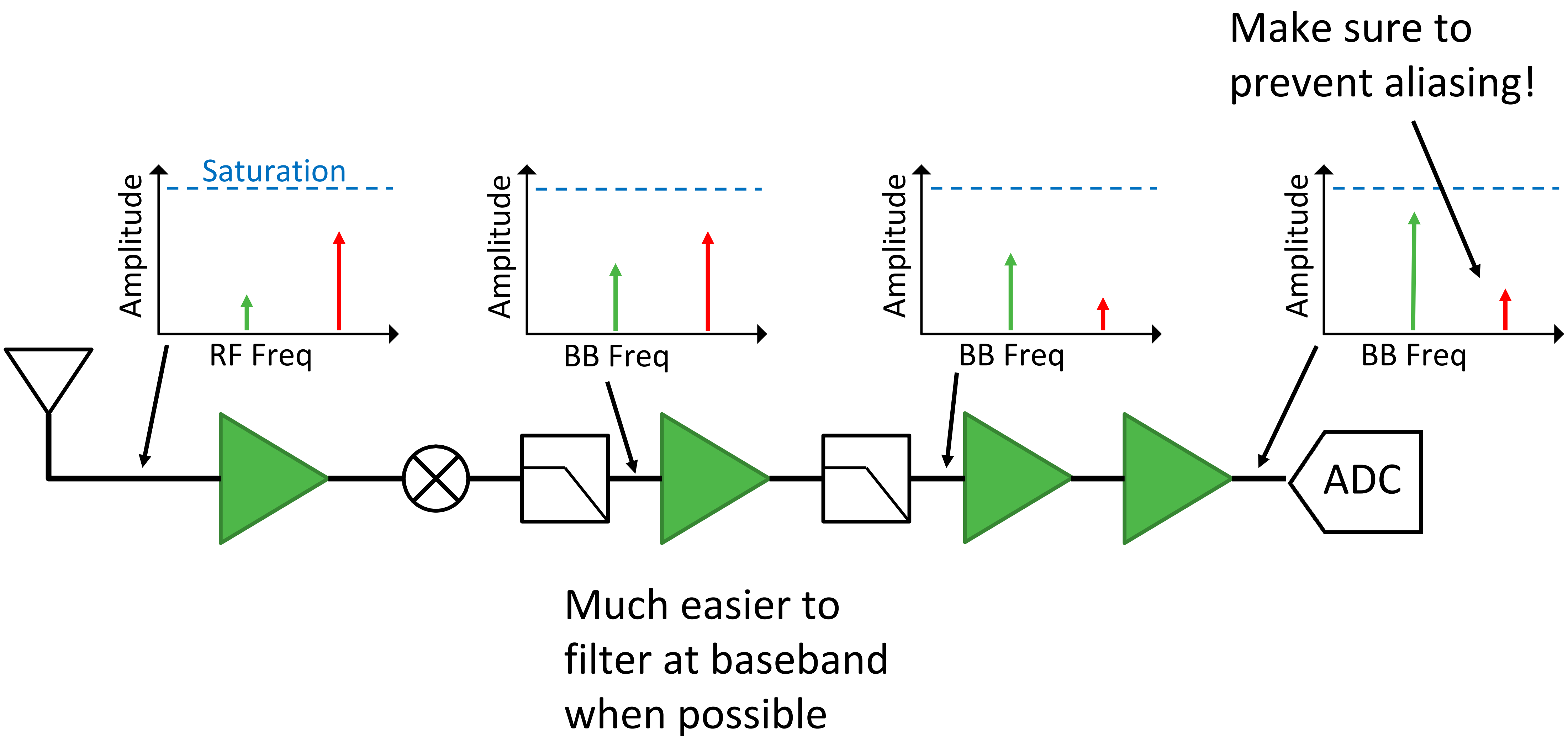
= 100 2 = 0.35 @ 850

$$P_{RX} = \frac{P_{TX} G_{ANT}^2 \lambda^2 \sigma_{CAR}}{(4\pi)^3 R^4} = -17\ dBm$$

Filtering: Order Matters

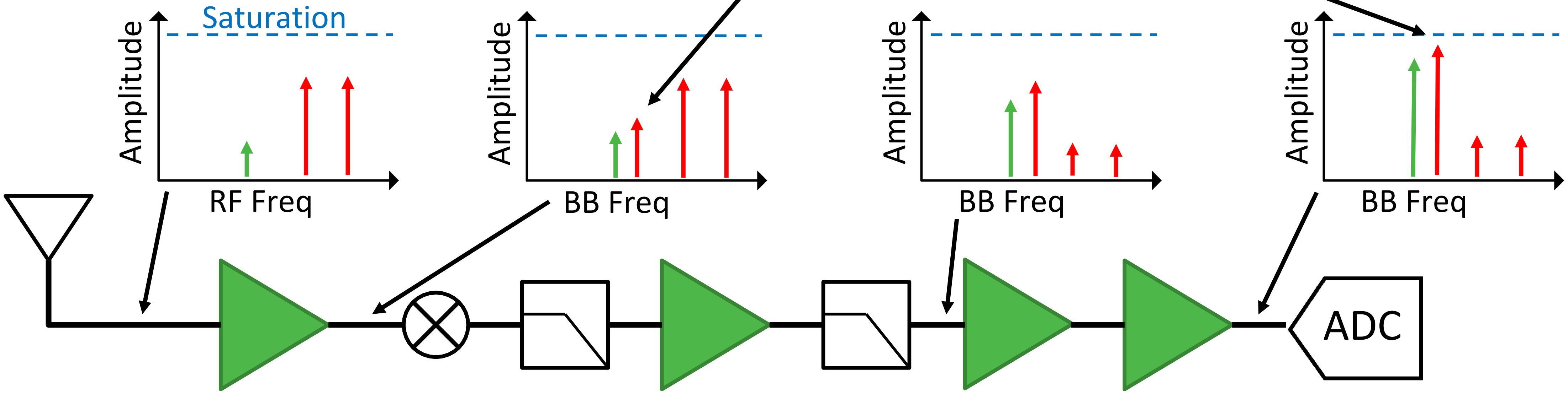


Filtering: Order Matters



Effects of Nonlinear Circuits

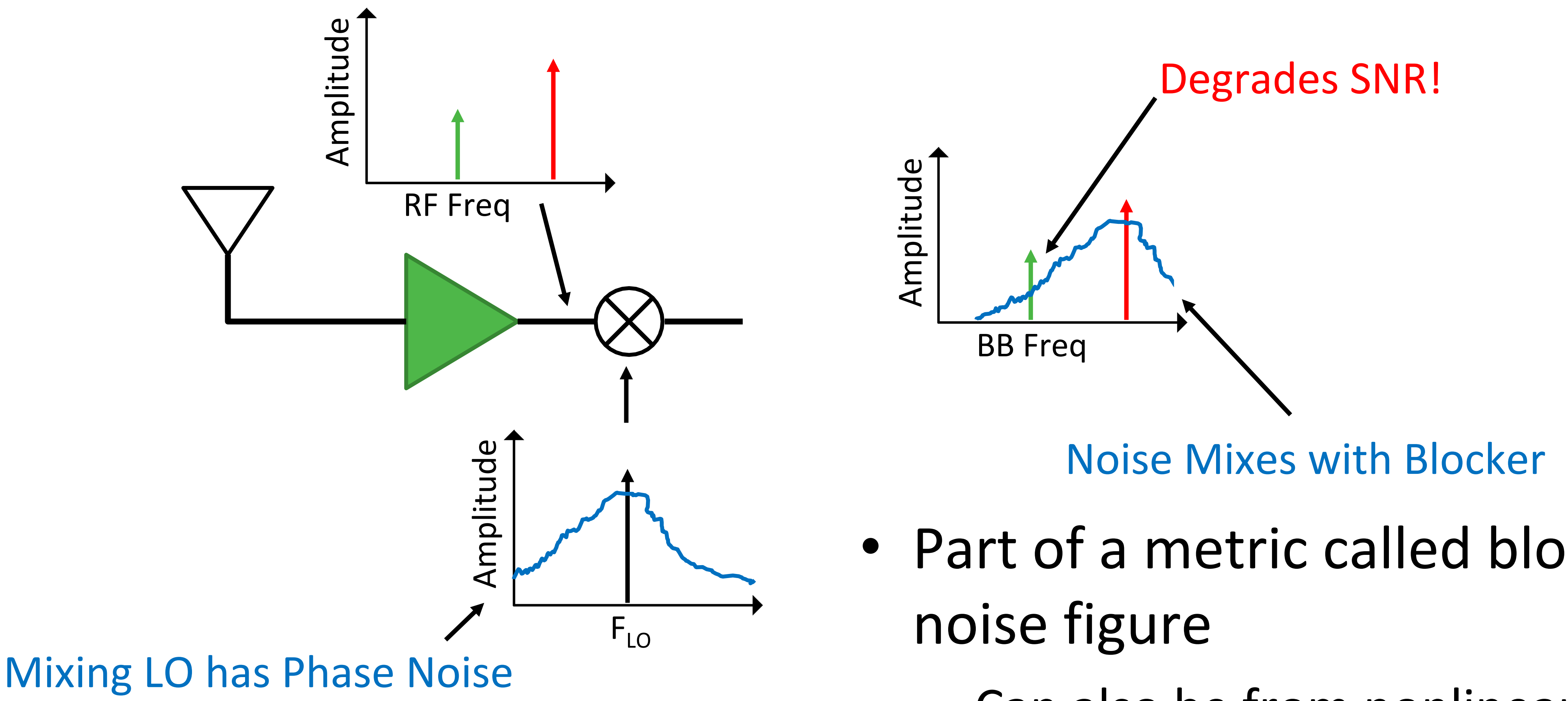
3rd order nonlinearity creates in-band blocker!



Consider 3rd order LNA nonlinearity

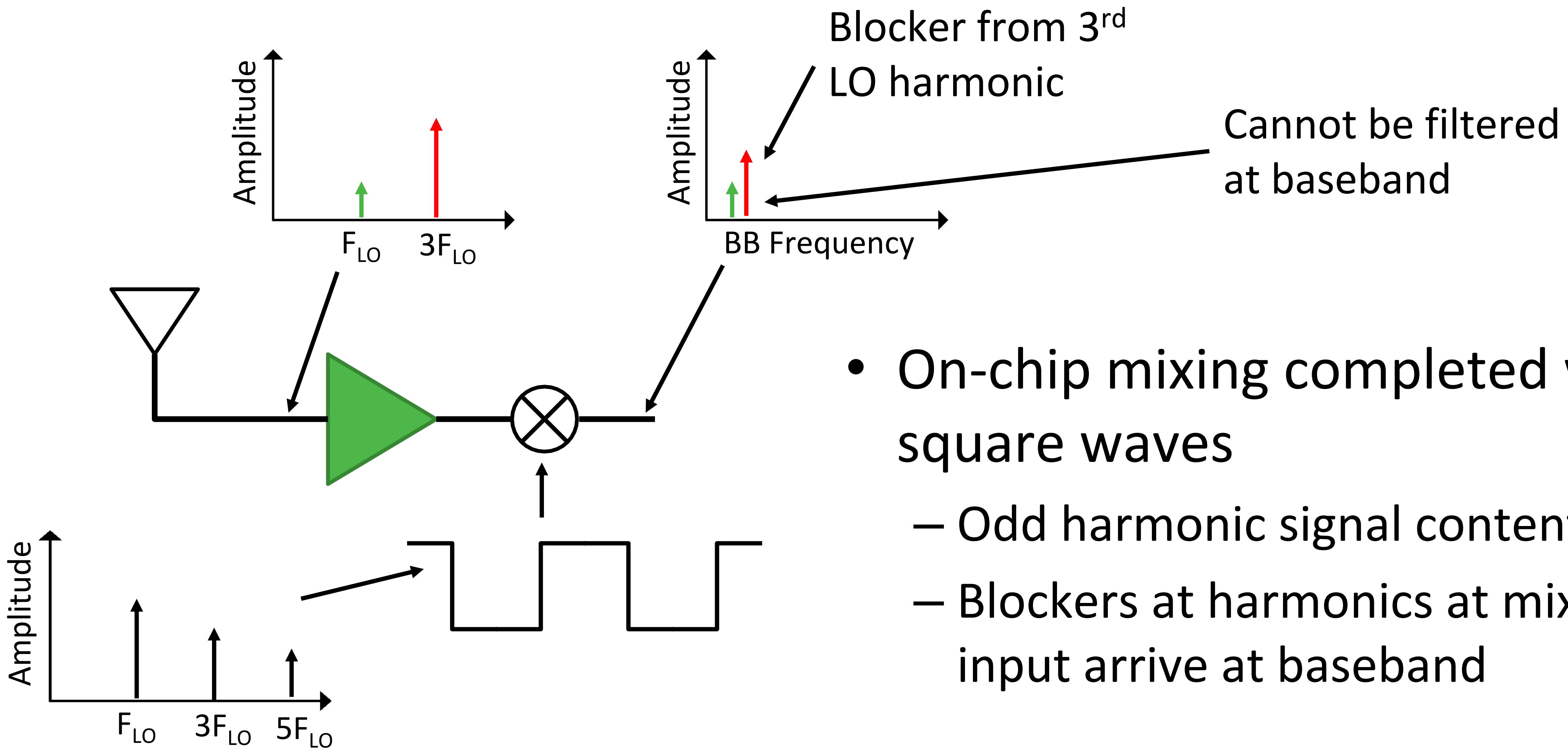
3rd order nonlinearity creates tones at $2f_1 - f_2$ (shown) and $2f_2 - f_1$

Reciprocal Mixing



- Part of a metric called blocker noise figure
  - Can also be from nonlinearity

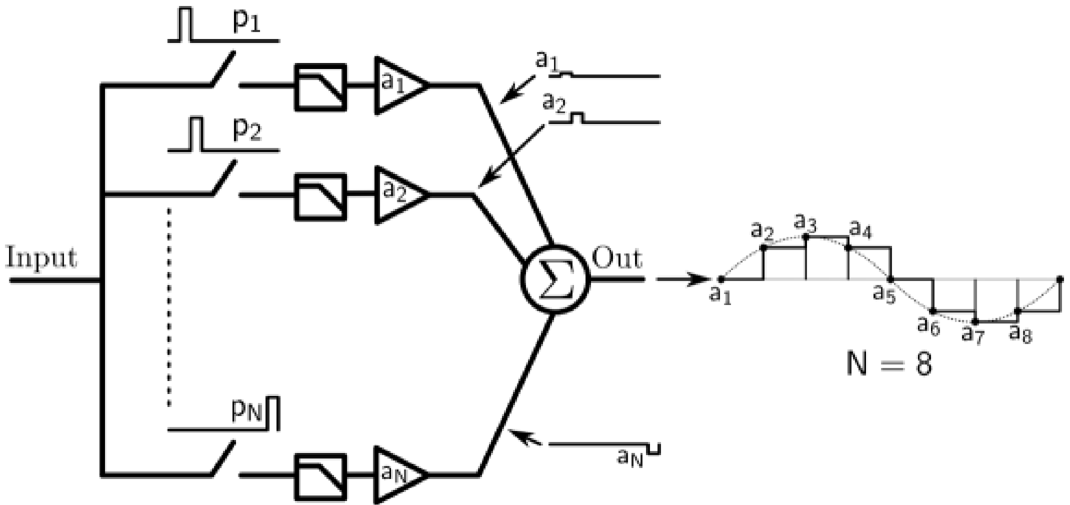
Harmonic Downconversion



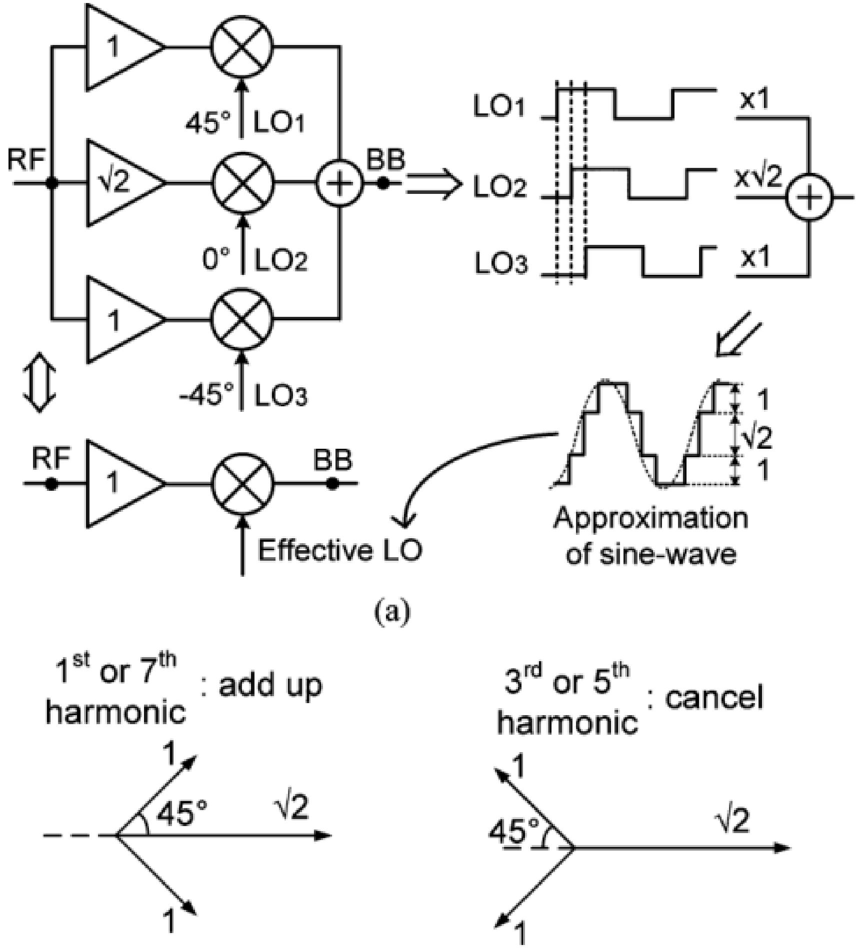
- On-chip mixing completed with square waves
  - Odd harmonic signal content
  - Blockers at harmonics at mixer input arrive at baseband

Harmonic Rejection Receivers

- Synthesize effective sinusoid
  - 3x 50% duty cycle paths with gains
  - 1/N duty cycle paths (N) with gains
  - Rejects N-2 harmonics



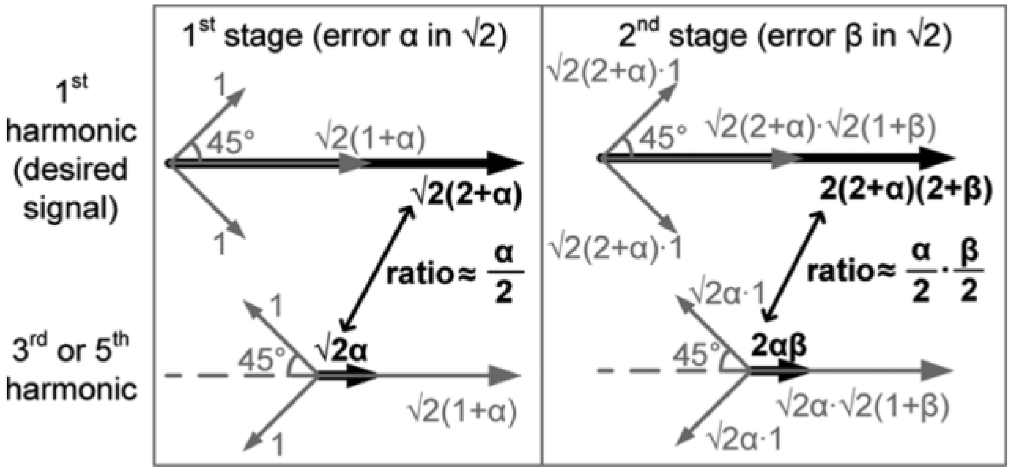
Molnar et al., CICC 2004
Fig from Forbes et al., JSSC 2014

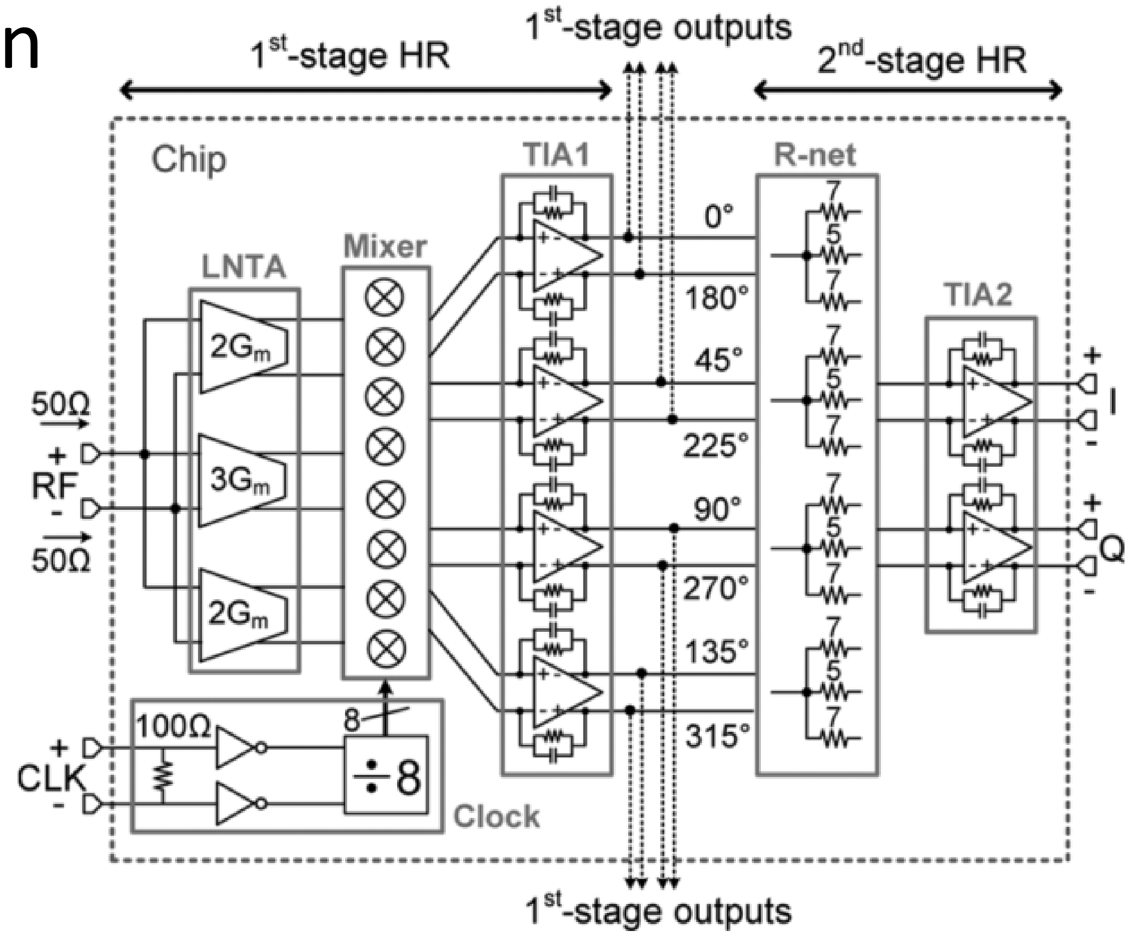


Weldon et al., JSSC 2001
Fig from Ru et al., JSSC 2009

Harmonic Rejection Receivers

- Phase/gain mismatch limits rejection
- RF + BB gains for better rejection
  - Two gain mismatches (<1) multiply
  - Baseband two stage does not do this



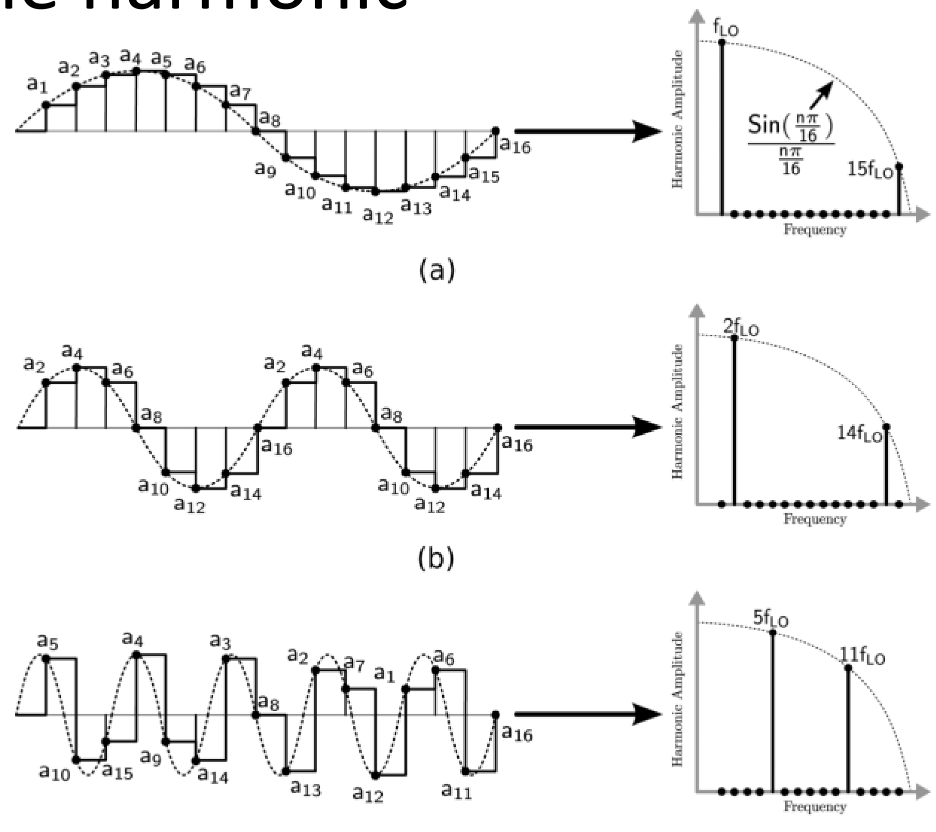


Ru et al., JSSC 2009

>60 dB HR3

Harmonic Rejection Receivers

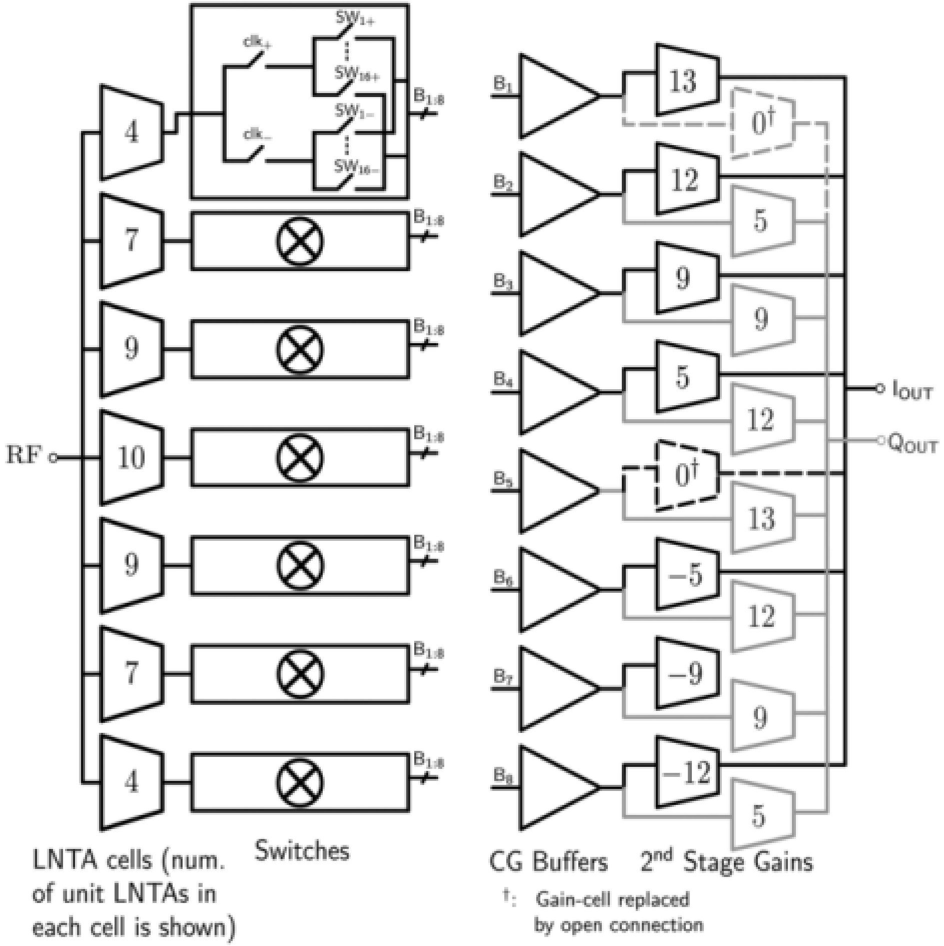
- You can synthesize more than one harmonic



(a)

(b)

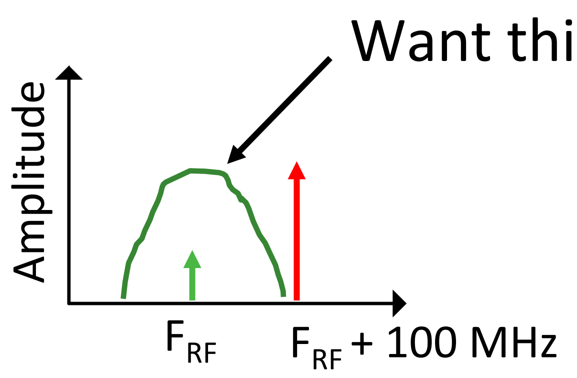
(c)



Forbes et al., JSSC 2013

>72 dB HR3

RF Filtering Challenges



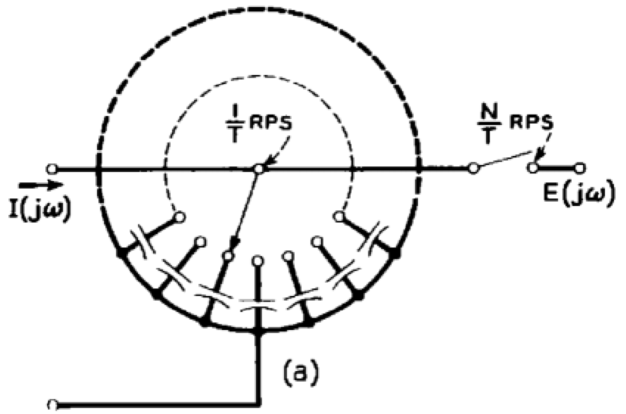
- Desire to move with operating band
- Very high Q!
- Can we do it on-chip?
  - Typically an acoustic technology

What Q for 20 MHz Filter?

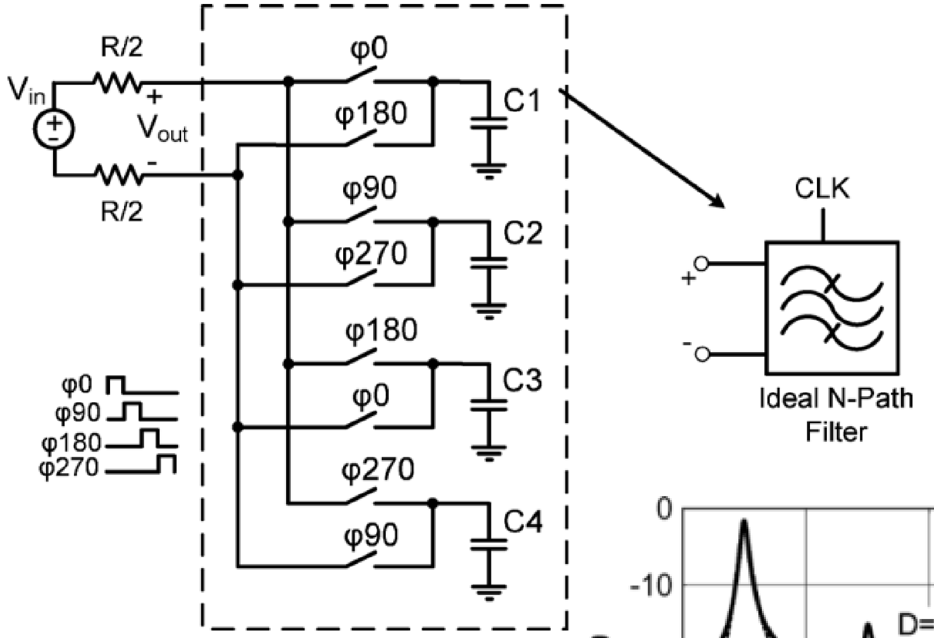
Frequency (GHz)	Quality Factor
0.5	25
1	50
3	150
6	300
24	1200
60	3000
100	5000

N Path Filters

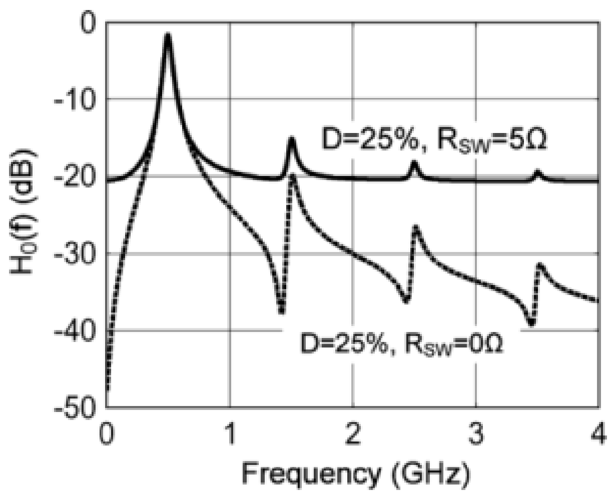
- Rotate input onto N capacitors in a cyclic period
  - Creates high-Z at the clocking frequency
  - High-Q programmable filter at



Franks and Sandberg, Bell Labs 1960



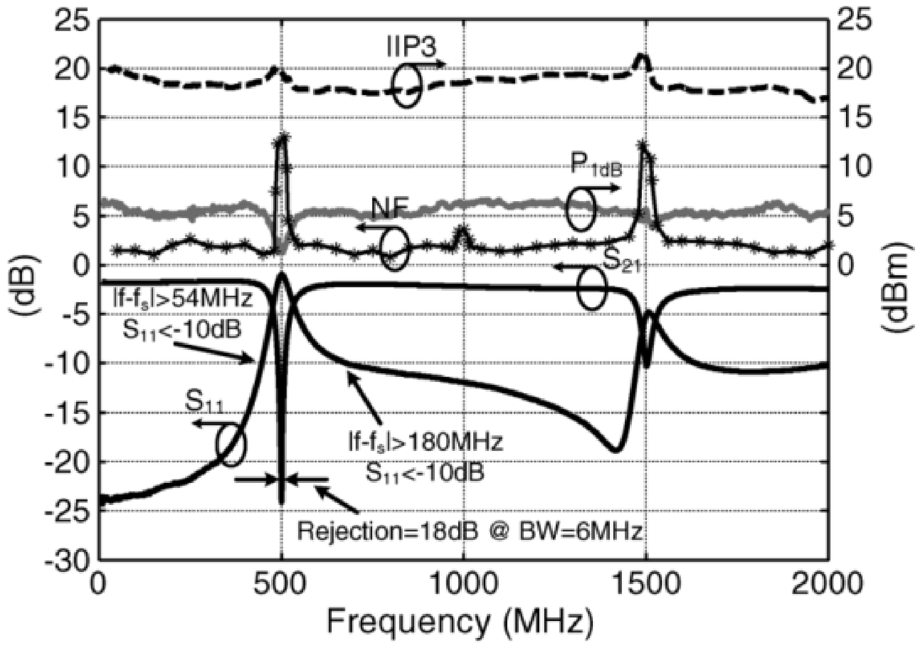
- Harmonic response still a challenge



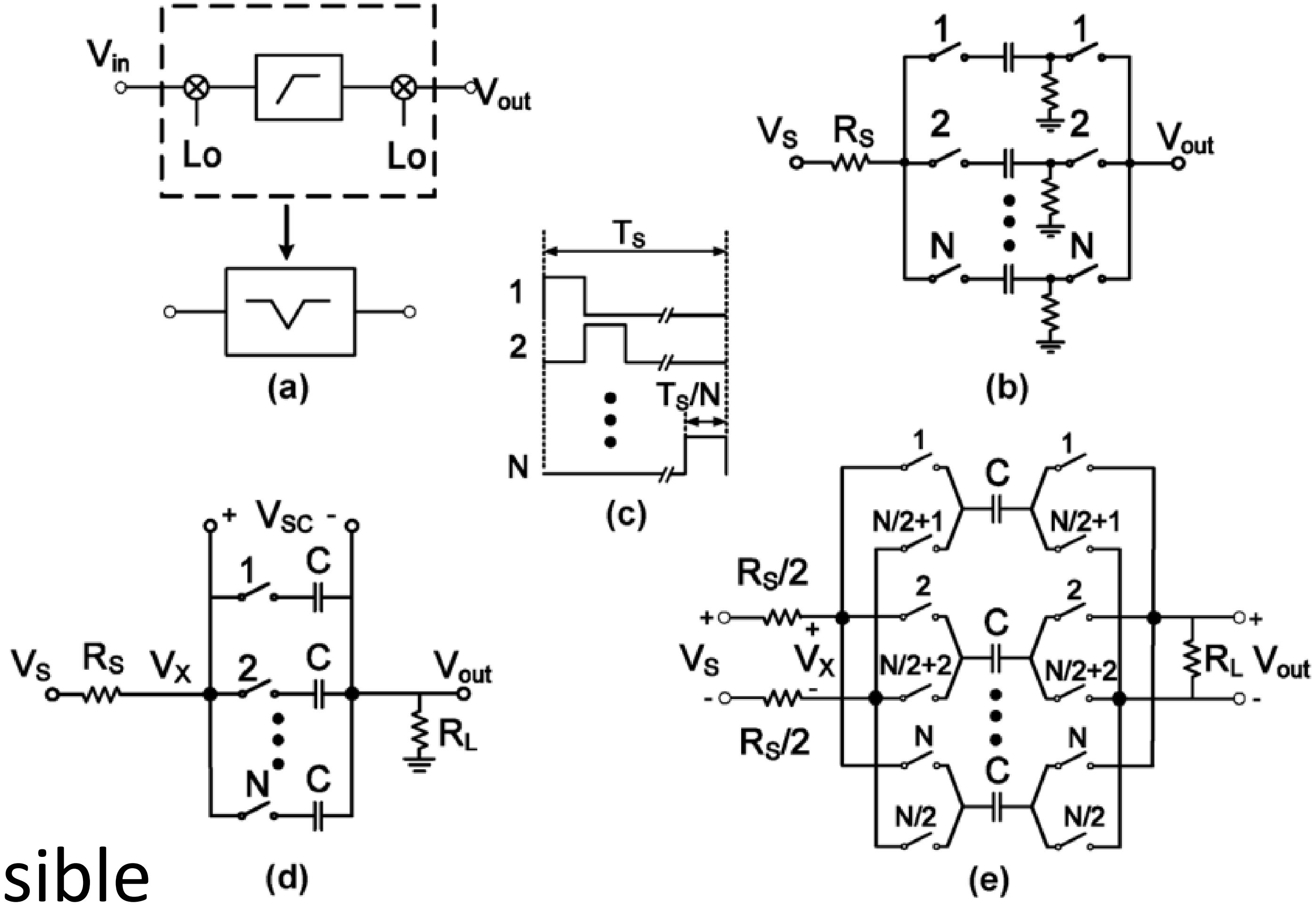
Ghaffari et al., JSSC 2011

N Path Filters

- Bandstop filters



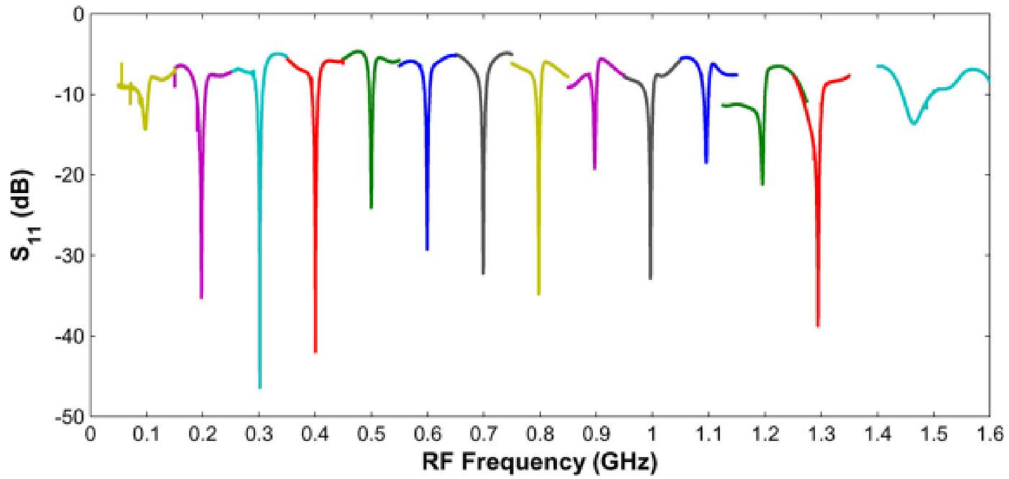
Ghaffari et al., JSSC 2013

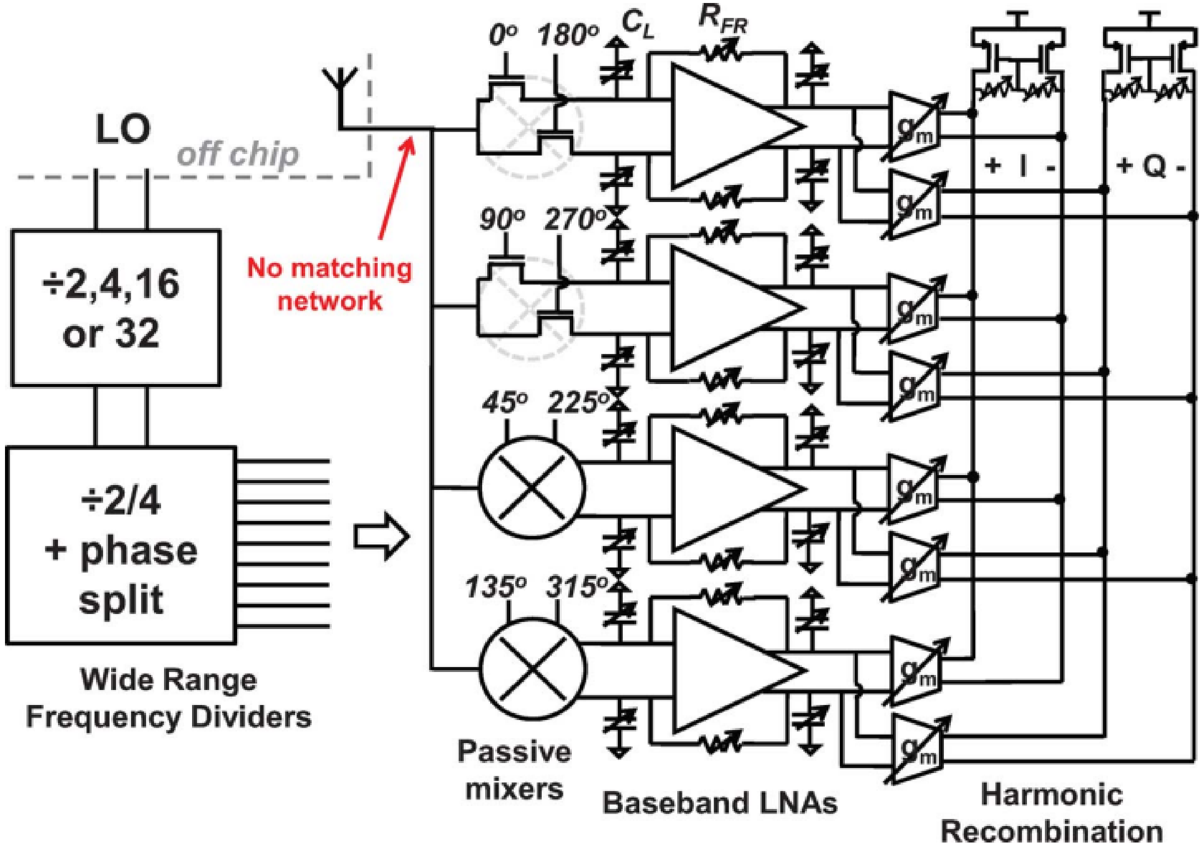


- Passive voltage gain also possible

Mixer-First Receivers

- Remove the input LNA
  - High linearity
  - Match through mixer
- Can include harmonic rejection
- Lo feedthrough challenge

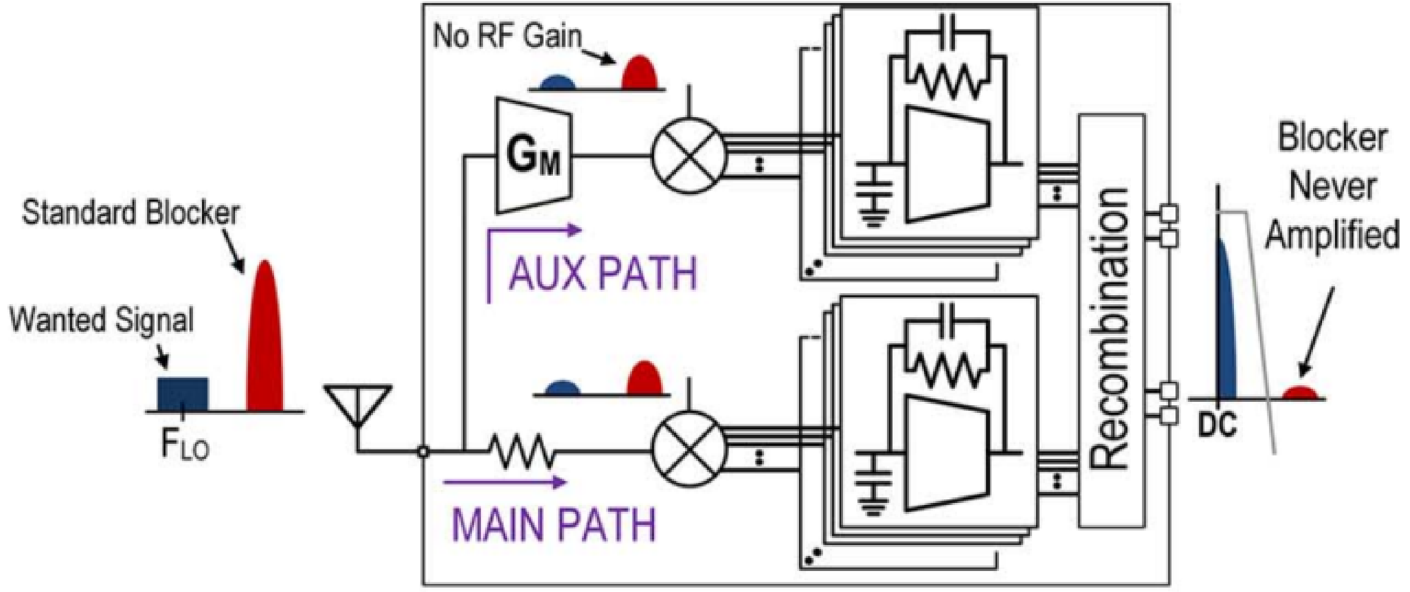




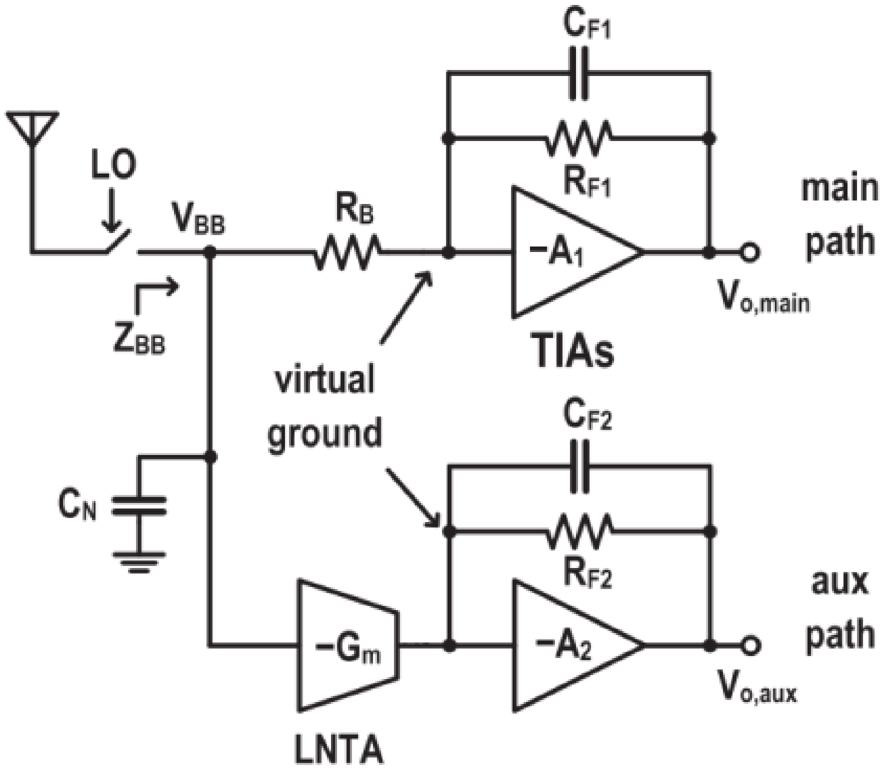
Andrews et al., JSSC 2010

Mixer-First Receivers

- Noise cancellation possible with 2 receive paths
  - Baseband or RF



Murphy et al., JSSC 2012



Bhat et al., JSSC 2021

Mixer-First Receivers

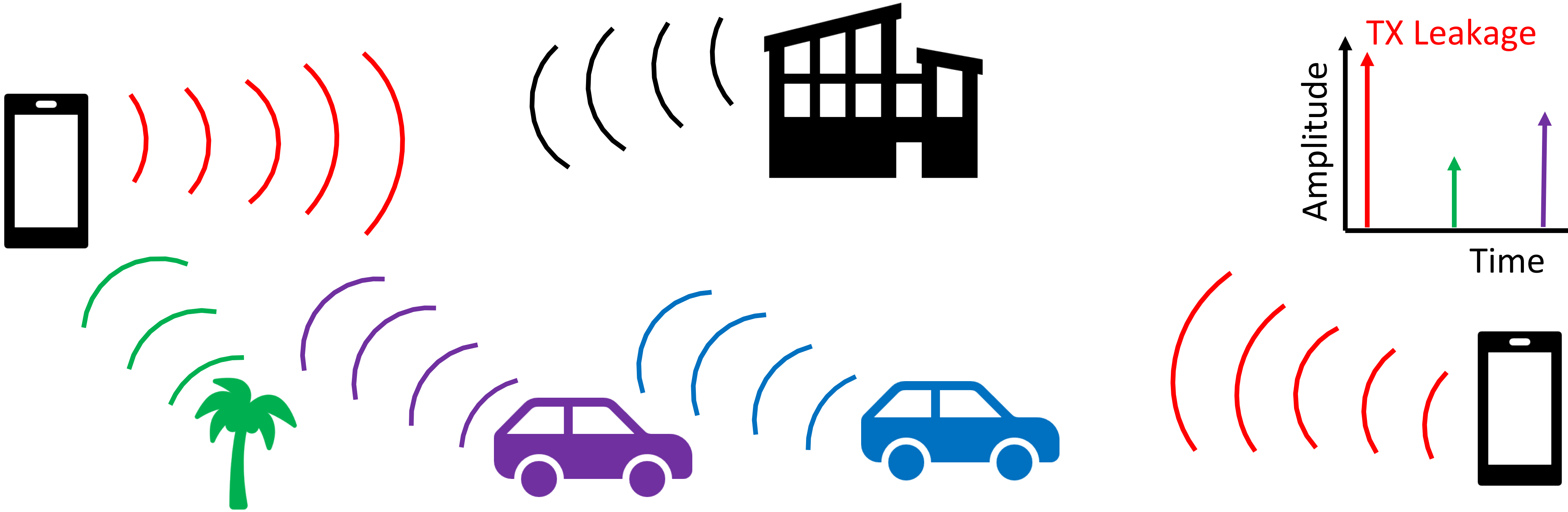
	Bhat JSSC 2021	Murphy JSSC 2012	Lien JSSC 2017	Andrews JSSC 2010	Krishnamurthy JSSC 2020
Architecture	MF BB NC	MF RF NC	MF Cap Fdbk	Mixer-First	MF 40 dB/dec
NF (dB)	2.5-5	1.9	2.3-5.4	3-5	4.3-7.6
Frequency (GHz)	1-6	0.3-2.9	0.2-8	0.1-2.4	0.2-2
Gain (dB)	22	72	21	40-70	13
OIP3 (dBm)	18	13.5	39	25	33.3
Power (mW)	172	35-78	56-290	37-70	147-179
Process Node	22 FDX	40 nm	45 nm SOI	65 nm	28 nm

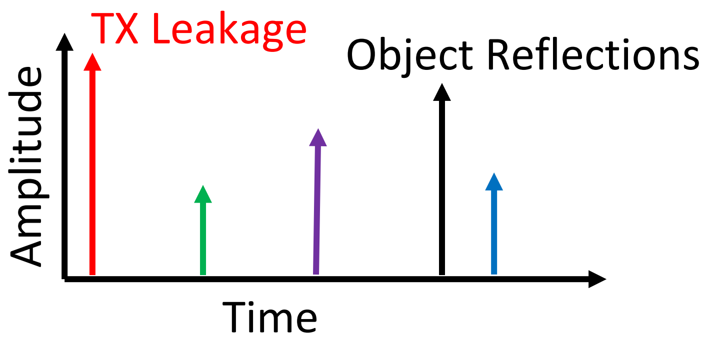
Significant out-of-band linearity!

Reasonable noise figure

Large bandwidth of operation

Full-Duplex Communications

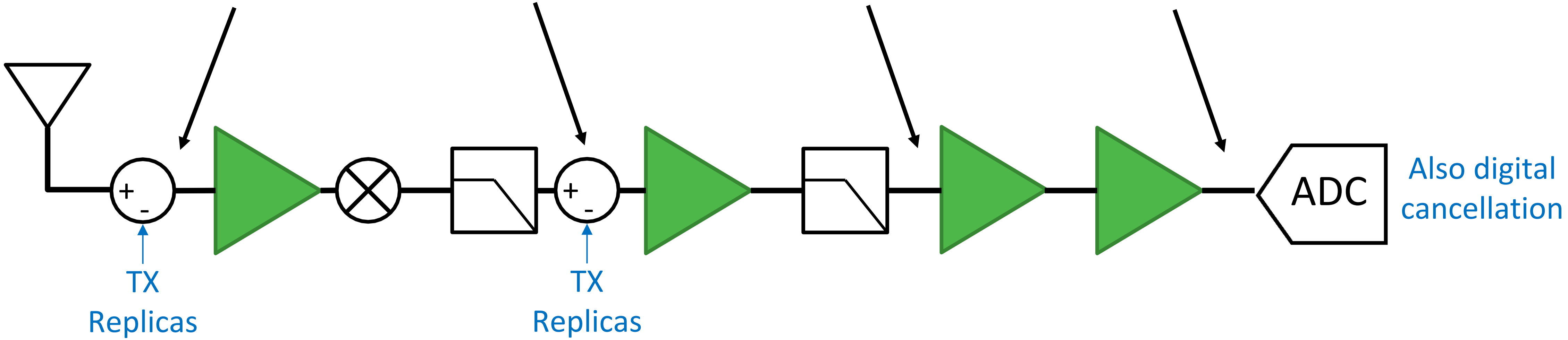


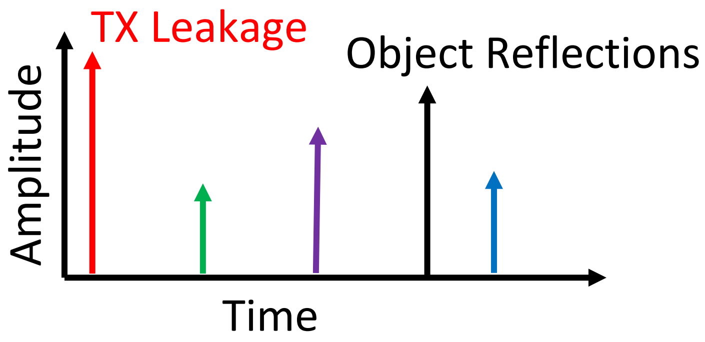


- Transmit and receive at the same frequency and time
  - Increase in spectral efficiency
- BUT you are your own worst blocker
  - In addition to traditional blockers

Full-Duplex Communications

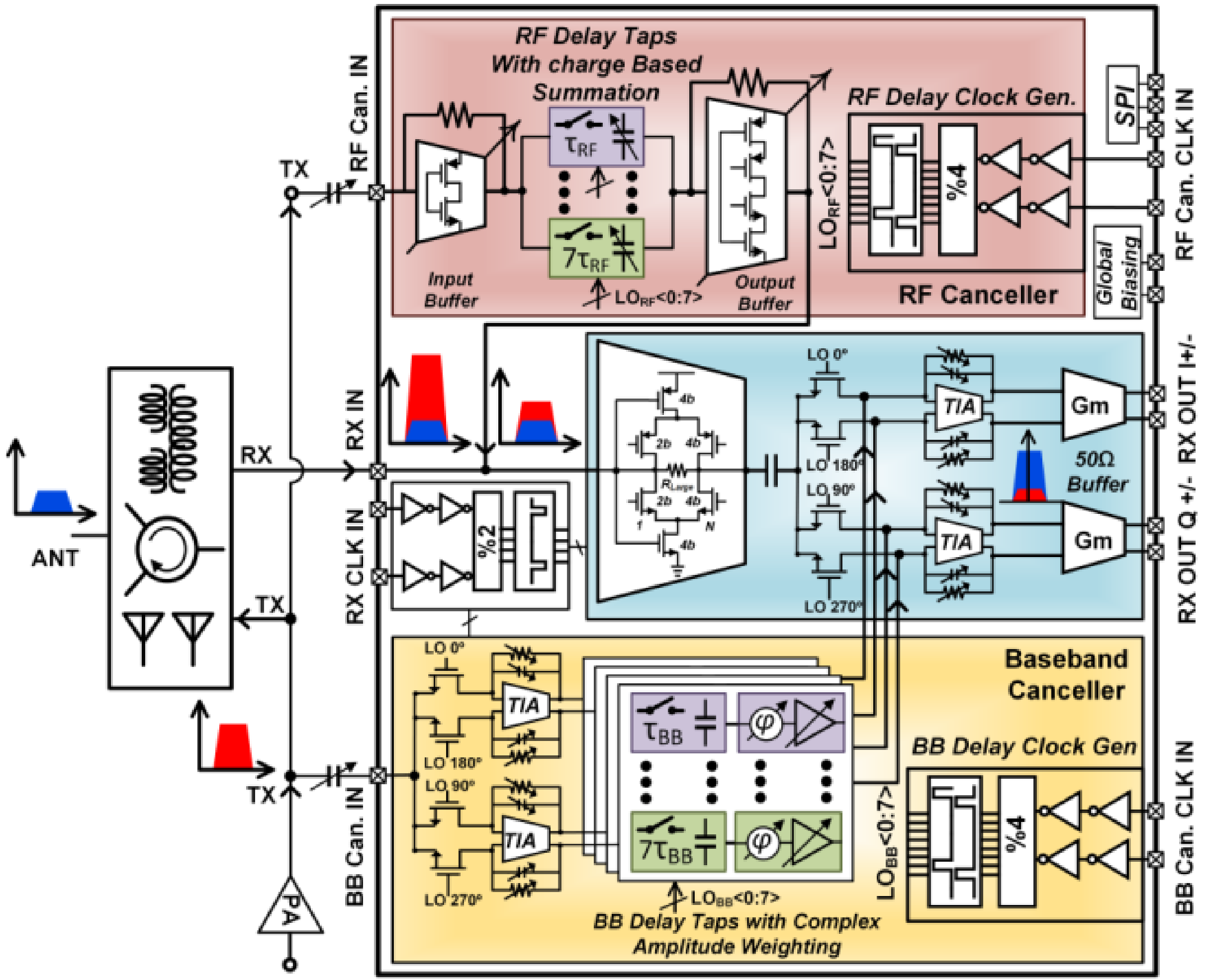
Must prevent saturation and nonlinear effects throughout the receiver

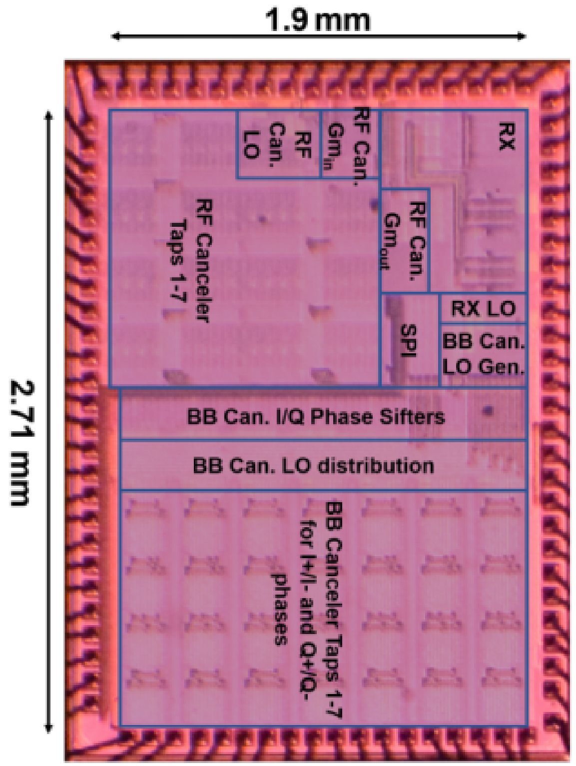




- TX replica for cancellation must include all leakage and reflections
  - Delay and amplitude must be matched
  - Objects in environment major challenge

Full-Duplex Communications





Chip Microphotograph

Nagaulu et al., JSSC 2021

Conclusion

- Blockers are present from other wireless devices and from contributions within a device
- Place filters in receive chain carefully to prevent saturation
- Mixer techniques can prevent harmonic downconversion
- N path filters and mixer first receivers enable high-Q filtering
  - Filtering follows mixing frequency
- Many research challenges to solve to make full-duplex a reality